The Dalradian rocks of the Shetland Islands, Scotland

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Keywords:
Geological Conservation Review
Shetland Islands
Dalradian Supergroup
Lithostratigraphy
Structural geology
Metamorphism

ABSTRACT

Metasedimentary and metavolcanic rocks to the east of the Walls Boundary Fault on Shetland have lithological similarities to those of the Dalradian Supergroup of the Scottish mainland. In particular, the middle part of the succession, termed the Whiteness Group, includes numerous metalimestones and associated pelites in a shallow-marine succession that recalls the upper parts of the Appin Group and the Argyll Group of mainland Scotland. Metavolcanic rocks within the deeper water turbiditic sequence of the succeeding Clift Hills Group might be broadly coeval with those of the Southern Highland Group of Scotland. Beyond that, correlations with the established Dalradian succession are tenuous and are not possible at formation level. A local succession immediately west of the Walls Boundary Fault is of even more-dubious Dalradian affinity.

The dominant structure is the regional-scale, downward- and east-facing East Mainland Mega-monocline. This has a vertical western limb, which youngs to the east, and an eastern top limb that dips to the north-west at 20–30°. Strata on the eastern limb are inverted on Mainland, Whalsay and Out Skerries but are right way up on the west side of Unst, having been folded around the tight Valla Field Anticline. The Shetland Ophiolite-complex has been thrust over the inverted limb of the Valla Field Anticline on the east side of Unst. The regional monocline folds earlier small- to
medium-scale, tight to isoclinal folds with associated planar and linear structures, which are all assigned to a single ‘Main Deformation’. It also post-dates the regional metamorphism, which ranges from chlorite to garnet grade, with localized development of staurolite-kyanite, gneissose fabrics, and the emplacement of schistose granitic sheets in the Colla Firth Permeation Belt.

The GCR sites have been selected mainly to be representative of the East Mainland Succession with its associated structures and metamorphism. Highlights include well-preserved sedimentary structures, high-grade gneisses permeated by granitic material, basaltic pillow lavas and serpentinized ultramafic rocks. Some of the latter contain enigmatic skeletal pseudomorphs after olivine and have been interpreted as former high-magnesium lavas.
1 INTRODUCTION

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The Shetland Islands lie about 165 km north-east of the Scottish mainland, and are almost half way between Scotland and Norway. The islands comprise an inlier of Caledonian and pre-Caledonian metamorphic rocks, which is completely surrounded by Devonian (Old Red Sandstone) and younger rocks (Figure 1). Correlation of the metamorphic rocks with those of the Scottish mainland has been based on lithological similarities, aided by some radiometric dating. For general summaries of the geology see Mykura (1976) and Flinn (1985).

The Walls Boundary Fault, a likely northward continuation from the Scottish mainland of the Great Glen Fault (Flinn, 1961) (Figure 1) divides the metamorphic rocks of Shetland into two mutually uncorrelatable successions associated with two distinct sets of post-metamorphic granites.

1.1 West of the Walls Boundary Fault

To the west of the Walls Boundary Fault, the overall tectonic arrangement is a series of structural slices, separated by thrusts and shear-zones that interleave pre-Caledonian basement gneisses with metasedimentary cover sequences (Flinn et al., 1979; Flinn, 1985). Many of the component slices exhibit similarities to parts of the Lewisian, Moine and Dalradian sequences of the Scottish mainland and Western Isles. Quartzofeldspathic orthogneisses contain hornblende gneisses that have yielded radiometric ages up to c. 2900 Ma and have been correlated with the Lewisian Gneiss Complex. The orthogneisses are in contact to the east with a belt of predominantly schistose psammites containing zones of coarse hornblende gneisses, which are locally blastomylonitized. The psammites have been tentatively correlated with the Morar Group of the Moine Supergroup, whereas the hornblende gneisses might correspond to the inliers of Lewisianoid rocks that are common in the Morar Group. A blastomylonite shear-zone, which separates the Moine-like rocks from the orthogneisses has been correlated with the Moine Thrust. GCR sites to represent these units are described in the Lewisian, Moine and Torridonian rocks of Scotland GCR volume (Mendum et al., 2009). The Moine-like rocks, with their Lewisianoid inliers, are limited to the east by the Virdibreck Shear-zone, along which low-grade phyllic to schistose metasedimentary and metavolcanic rocks of possible Dalradian affinity (the Queyfirth Group) have been thrust westwards.

1.2 East of the Walls Boundary Fault

On the mainland of Shetland, to the east of the Walls Boundary Fault, a dominantly metasedimentary sequence has been correlated with the Moine and Dalradian successions of the Scottish mainland and is referred to as the East Mainland Succession. This succession has been split into four major, lithostratigraphically
distinct 'divisions', now formally defined as groups (Figures 1 and 2; Flinn et al., 1972).

The oldest part of the East Mainland Succession, the Yell Sound Group, crops out in the west, where it has been truncated obliquely by the Walls Boundary Fault. It has a maximum exposed width of 10 km and possibly half as much again allowing for sea cover. It is composed of variably gneissose quartzofeldspathic psammites, alternating with major lenses of mica schist and quartzite. It also contains layers of garnet-studded hornblende schist together with half a dozen Lewisianoid inliers. This lithological assemblage distinguishes the Yell Sound Group from the rest of the East Mainland Succession and has allowed it to be correlated with the Loch Eil and Glenfinnan groups of the Moine Supergroup in Scotland (Flinn, 1967, 1992).

The Yell Sound Group is separated from rocks to the east by the 70 km-long and c. 1 km-wide Boundary Zone that extends across the islands of Mainland, Yell and Unst. The western margin of the Boundary Zone is marked by occurrences of a microcline-megacryst augen gneiss, the Valayre Gneiss (Flinn 1992, Flinn in Mendum et al., 2009), and its eastern margin by the Skella Dale Burn Gneiss. Between these two augen gneisses the Boundary Zone contains lenses of locally blastomylonitized Lewisianoid hornblende gneisses, basic metavolcanic rocks and a variety of other gneissose psammites and semipelites together with a metalimestone.

To the east of the Boundary Zone, the rocks of the East Mainland Succession have very general lithological similarities with the Dalradian succession of mainland Scotland and are the subject of this paper. They extend the length of Shetland from north to south and have been divided into three groups. From west to east and older to younger these are the Scatsta, Whiteness and Clift Hills groups.

Along part of the south-east coast of the Mainland, the Dalradian rocks have been overthrust, from the east, by a tectonic nappe containing gneisses and various metasedimentary lithologies. The nappe overlies an imbricate zone, containing some serpentinite that was termed a tectonic mélange by Flinn (1967). Some of the constituent rock types are similar to Dalradian lithologies seen farther west within the East Mainland Succession (e.g. in the Scalloway GCR site) but, despite these similarities, the tectonic style is distinct and this south-eastern fringe is recognized as the separate Quarff Nappe Succession. The emplacement of the 'Quarff Nappe' probably took place late in the Caledonian Orogeny, during the Scandian Event. Farther north, part of an Early Palaeozoic ophiolite crops out on the islands of Unst and Fetlar (Figure 1). This, the Shetland Ophiolite-complex, was tectonically emplaced at about 500 Ma above rocks of likely Dalradian affinity; its geology has been summarized by Flinn (2001, in press) and its GCR sites are described in the Caledonian Igneous Rocks of Great Britain GCR volume (Stephenson et al., 1999). Elsewhere, across much of the east and south of Shetland’s Mainland, the Dalradian rocks are unconformably overlain by sedimentary and volcanic rocks of the Old Red Sandstone Supergroup and are intruded by late-Caledonian granites.
1.3 The Dalradian of Shetland

Dalradian rocks crop out over an area of more than 400 km² on the Mainland of Shetland, but also form smaller islands to the east of the Mainland and parts of Unst and Fetlar (Figure 1). Their lithostratigraphy, structure, metamorphism and tectonic implications have been the subject of a comprehensive review by Flinn (2007). On most of the Mainland, the succession is continuous, with a total thickness of 10–12 km, is unfolded except for minor folds, dips vertically and strikes north-south. To the south of Scalloway, the western parts of the succession (Scatsta Group) are increasingly hidden by the sea. To the north of Scalloway the Scatsta Group crops out along strike for 30 km but the eastern parts of the succession (Clift Hills Group) pass eastward beneath the sea.

The Scatsta Group is between 1 and 2.5 km wide. It is dominantly composed of quartzites and impure quartzites, planar laminated by muscovite partings and with lensoid layers of schistose kyanite- and staurolite-bearing aluminium-rich pelites (chloritoid-bearing at lower grade). There is evidence of soft-sediment slumping.

The Whiteness Group is 6–7 km thick and is composed dominantly of planar laminated psammites with some granofelsic psammites and micaceous psammites, all of biotite grade. It contains four major metalimestones, up to 500 m thick, and several thinner beds. It also contains a 1 km-thick unit of gneisses, comprising the Colla Firth Permeation Belt, which extends the length of Shetland (see the Scalloway GCR site report).

The Clift Hills Group is 3–4 km thick and is the infill of an extensional basin containing turbiditic quartzites, mafic and ultramafic metavolcanic rocks, metagreywackes, phyllitic chloritoid pelites and metalimestones (see the Hawks Ness and Cunningsburgh GCR site reports).

This continuous succession is laid out to view across the middle of Mainland Shetland (Figure 2). It is assumed that the overall younging is from west to east, although this cannot be proved and intrafolial isoclinal folding precludes any general inference from sedimentary younging evidence. However, the regional metamorphism shows a progressive decrease from kyanite-, staurolite- and garnet-grade in the west to chlorite-grade in the east and the uninterrupted sedimentary succession shows a progression in the same direction from shallow- to deep-water deposition and eventual rifting.

There is an overall similarity to the Scottish mainland Dalradian succession and the following correlations were suggested tentatively (by J.L. Roberts and J.E. Treagus in Flinn et al., 1972):

Scatsta Group = the lower part of the Appin Group;
Whiteness Group = the upper part of the Appin Group and lower part of the Argyll Group;
Clift Hills Group = the upper part of the Argyll Group and the Southern Highland Group.
However a comparison with tables of the Scottish mainland Dalradian succession (Harris et al., 1994; Stephenson and Gould, 1995; Strachan et al., 2002) reveals no possibility of unequivocal correlation at formation level. The Asta Spilitic Formation at the base of the Clift Hills Group was originally matched with volcanic formations in the Easdale Subgroup, and the younger Dunrossness Spilitic Formation was therefore correlated with the Tayvallich volcanic rocks (i.e. by Flinn et al., 1972 as followed by Harris and Pitcher, 1975 and Johnson, 1991). However, more recently it has been suggested that the Asta Spilite and Laxfirth Limestone pair could be correlated with the lithologically similar Tayvallich Slate and Limestone Formation and Tayvallich Volcanic Formation, so that the Dunrossness Spilitic Formation would be equivalent to later volcanic events within the Southern Highland group, such as the Loch Avich lavas and the Green Beds (D. Flinn, personal communication in Harris et al., 1994; Flinn, 2007). On a broader basis it does seem reasonable to label the Clift Hills Group as equal to the topmost part of the Argyll Group and the Southern Highland Group, but the Whiteness Group lacks the deepening cycles of the Argyll Group and there is no tillite or any kind of ‘boulder bed’ to indicate a possible Appin-Argyll group boundary.

The correlations suggested by Flinn et al. (1972) have been indicated on Geological Survey maps, but should be regarded with caution. Current suggestions (in part after Flinn, 2007), also highly tentative but adopted in this paper, are indicated in Table 1. However, a more-radical overall interpretation by Prave et al. (2009a), based on C-isotope chemostratigraphy of metacarbonate rocks, has implied that the Dalradian volcanism on Shetland is younger than any on mainland Scotland or Ireland, being significantly later than 600 Ma and possibly post-550 Ma. This would cast doubt upon all previous correlations.

All three of the Dalradian GCR sites in Shetland lie within the outcrop of the East Mainland Succession, in the southern part of Mainland Shetland (Figure 2). Together they demonstrate the relatively rapid transformation of the long continuing Scatsta-Whiteness shallow depositional basin into the well-developed turbidite-volcanic Clift Hills deep extensional basin. The Scalloway GCR site demonstrates the regionally metamorphosed, locally gneissose and tectonized state of the sandstones and subordinate limestone of probable shallow-marine facies in the Colla Firth Formation in the central part of the Whiteness Group. The Hawks Ness GCR site, farther east, demonstrates the sudden deepening of the basin, following the deposition of the Laxfirth Limestone, with the immediate influx into the basin of the volcaniclastic Asta Spilitic Formation, followed by turbiditic quartzites, graded siltstones and greywackes of the Clift Hills Phyllitic Formation. The Cunningsburgh GCR site represents the top of the Clift Hills extensional basin in the south of Shetland, in an area of major eruptive magmatism involving ultramafic lava-breccias and locally pillowed mafic lavas.
1.4 Tectonics and Metamorphism

Only one period of intense deformation, referred to by Flinn (1967) as the Main Deformation, has been recognized as affecting the East Mainland Succession. It resulted in the formation of a tectonic fabric ranging from dominantly planar to dominantly linear. Small- to medium-scale, tight to isoclinal, intrafolial folds with wavelengths no more than a few metres are widespread, but there is little preserved structural or stratigraphical evidence for large-scale folds. The principal planar fabric is a schistosity defined mainly by micas that is parallel to any compositional layering, bedding or lamination traces that might still be evident. It is well defined in the more-micaceous, finer grained rocks, but is less precisely defined in the coarser grained gneisses, in which it encloses lenticular resistant relics. There has been widespread boudinage of rock layers that had a marked ductility contrast to their neighbours; hornblende schists (perhaps originally intrusive mafic igneous rocks) within phyllitic sequences have been particularly susceptible.

The north-south-striking, eastward-younging, vertical beds described in the previous section extend from the Walls Boundary Fault to the east coast of the Mainland. However, on the offshore islands to the north of Bressay the whole succession is upside down, dipping at 20–30° to the north-west, and farther south the rocks of the Clift Hills Group to the east of the Cunningsburgh CGR site are overturned and dip to the west at c. 20° (Figure 2).

The overall structure of the Dalradian on and around Mainland Shetland therefore takes the form of a north-south-striking, 10 km-thick vertical limb younging east, with an eastern limb of similar thickness inclined at 20–30° to the north-west and younging downwards. The hinge region is accessible in the Cunningsburgh CGR site and is well exposed in the cliffs south of Stava Ness. In between, it is hidden by the overlying Old Red Sandstone succession and the Quarff Nappe. The fabric lineation in the vertical limb plunges gently to the south at 10-20°, while the much more poorly developed lineation in the westerly inclined limb has a near-horizontal north-easterly trend. If the westerly inclined limb could be rotated into a vertical east-facing attitude about a fold axis plunging about 20° to the north, then approximate matching of both stratigraphy and lineation would take place. Hence, the implied structure is a very large-scale, downward-facing monocline, referred to as the East Mainland Mega-monocline (Figure 3). However, apart from that monocline and a large-scale swing in strike south of Stava Ness, deformation subsequent to the Main Deformation on Mainland Shetland was limited to cataclasis, faulting and the production of kink folds. The formation of the East Mainland Mega-monocline post-dates the main regional metamorphism and deformation, currently dated, albeit with poor precision, at c. 530 Ma (see below), and is considered to have occurred in an extensional regime accompanying rifting on the passive margin of Laurentia (Flinn, 2007). However, it pre-dates the obduction of the Shetland Ophiolite-complex at c. 498 Ma (Flinn et al., 1991), the emplacement of the Quarff Nappe, the deposition
of the Old Red Sandstone and the truncation of the East Mainland Succession to the west by the post-Devonian Walls Boundary Fault.

On Unst and Fetlar, structural relations are altogether different due to the emplacement of the Shetland Ophiolite-complex on top of inverted, shallow-dipping Scatsta Group rocks (Flinn, in press). On the west coast of Unst (the Valla Field Block) the Scatsta Group rocks have been folded back around the Valla Field Anticline to dip east at about 45° and are right way up (Figure 3), whilst in the north-east of Unst, a large tectonic lens of the Clift Hills Group (the Saxa Vord Block) has been inserted between the Scatsta Group rocks and the ophiolite.

The main regional metamorphism in the Dalradian of Mainland Shetland was coincident with the Main Deformation (Flinn, 1967) but preceded the formation of the East Mainland Mega-monocline and has been attributed to burial metamorphism within the depositional basin (Flinn, 2007). As a result of this metamorphic episode, the Whiteness and Scatsta group rocks range generally from biotite grade in the former to garnet grade in the latter. The rocks are all well crystallized, with the platy and elongate minerals defining the dominant regional schistose foliation and linear fabric. This was followed, whilst thermal gradients were still high, by the localized imposition of gneissic fabrics on the metasedimentary rocks to form the Colla Firth Permeation Belt and by the emplacement of a series of schistose granitic veins and sheets. In a slightly different interpretation of the evidence May (1970) compressed the tectonometamorphic history, suggesting that the fabrics in the granitic veins and those affecting the regionally metamorphosed rocks had formed at the same time, coincident with intrusion of the veins. From either viewpoint, the age of the granitic veins is critical, as it is much closer to a minimum age for the main deformation and metamorphism than the c. 498 Ma provided by the obduction age of the Shetland Ophiolite-complex (see above). A Rb-Sr whole-rock date of 530 ± 25 Ma from one of the veins (Flinn and Pringle, 1976), although imprecise and possibly inaccurate by modern standards, did seem to indicate that the metamorphic peak in Shetland might have occurred earlier than in the Dalradian of mainland Scotland, where the peak of Caledonian deformation and metamorphism occurred at about 470 Ma during the intense but relatively short-lived Grampian Event (e.g. Soper et al., 1999). However, U-Pb monazite ages from pelites beneath the Shetland Ophiolite-complex range from 462-451 Ma and have been interpreted as confirming that both the obduction and the regional metamorphism on Shetland were broadly synchronous with the Grampian Event (Cutts et al., 2011). The Scalloway GCR site is therefore of particular importance in establishing regional tectonometamorphic relationships and dating there by modern radiometric methods is an obvious need.

Patches of staurolite-kyanite-grade pelitic rocks occur locally within the Colla Firth Permeation Belt. Flinn (1954) interpreted these as ‘hot spots’ within the gneiss, whereas May (1970) interpreted them as relics of an early, relatively high-grade metamorphic event.

Somewhat later, development of porphyroblasts such as biotite, chlorite, staurolite, kyanite, chloritoid and garnet occurred,
overprinting the tectonic fabrics in the less strongly tectonized rocks of the Clift Hills Group. In the Dalradian rocks beneath the Shetland Ophiolite-complex on Unst and Fetlar, there is evidence of a later retrograde regional metamorphic event, chiefly involving chloritoid but not easily related to emplacement of the ophiolite (this is the ‘second metamorphism’ of Read, 1934).

The final metamorphic effect observed in the Dalradian rocks was the formation of thermal aureoles around the post-tectonic Spiggie, Channerwick and Cunningsburgh granite intrusions at about 400 Ma. In pelitic rocks this involved the development of such minerals as staurolite, chloritoid, andalusite, kyanite, sillimanite, garnet and muscovite.

2 SCALLOWAY (HU 396 389–HU 389 408)

D. Flinn and P. Stone

2.1 Introduction

The sea cliffs and rocky foreshore west from Scalloway, around Point of the Pund and northwards into Bur Wick, provide a continuously exposed and accessible traverse across the gneissose Colla Firth Permeation Belt and the non-gneissose rocks on either side. The belt of gneisses has developed within the psammitic Colla Firth Formation of the Whiteness Group and extends from Colsay (north of Fitful Head), northwards for 20 km to Scalloway and then for another 30 km north to Delting where it is cut off by the Nesting Fault. The belt varies between one and two kilometres wide, while the outcrop of the Whiteness Group is about 6 km wide. The layering throughout the outcrop is approximately vertical and strikes north-north-east. The gneisses and their adjacent areas are very variably intruded by granitic sheets, which are characteristically less than a metre thick but in several places they form substantial bodies.
The importance of the Scalloway GCR site is that it provides the only complete traverse across the Colla Firth Permeation Belt and illustrates its relationship with the non-gneissose rocks of the Whiteness Group to either side. The relative timing of gneiss development and intrusion of the granitic sheets is of great importance in assessing the wider tectonometamorphic history of the Shetland Dalradian and the radiometric age of the granitic sheets was investigated by Flinn and Pringle (1976). A detailed account of the geology of this area was given by May (1970) and it is included within the Geological Survey’s one-inch Sheet 126 (Southern Shetland, 1978). Other parts of the Colla Firth Permeation Belt, included within the Geological Survey’s one-inch sheet 128 (Central Shetland, 1981), have been described by Flinn (1954, 1967).

### 2.2 Description

The easily accessible coastal section to the west of Scalloway, exposes about 1.5 km of strata, part of the Colla Firth Formation of the Whiteness Group, much of which has been rendered gneissose during the development of the Colla Firth Permeation Belt (Figure 4). Throughout the section, granitic sheets are intruded into both the gneissose and non-gneissose rocks, and they merge into a more substantial foliated granitic mass at the eastern margin of the gneiss belt.

Between the edge of the built-up area of Scalloway and the headland of Maa Ness, the first c. 100 m of section is composed of rather flaggy or laminated and lineated, fine-grained semipelitic rocks alternating with sheets of pinkish or white aplitic microgranite that have both a clear schistose foliation and a lineation. The sheets are up to a metre thick and are mostly conformable with or obliquely cross-cut the metasedimentary layering. They are accompanied by pegmatitic streaks. A 300-m-wide outcrop of granite follows, in which there are only very minor semipelitic screens. Granitic sheets occur the length of the gneiss belt, both within it and for up to 100 m or more on either side. Exposure is poor inland, but elsewhere they seem to be very unevenly distributed, very rarely as closely packed as here and generally less than a metre thick.

Gneissose development is first seen on the east side of Maa Ness, to the west of the large granite sheet. It takes the form of a coarsening of the grain size resulting in a loss of sharpness of the schistosity, the lineation and the muscovitic laminations of the flaggy semipelites. The rocks are also homogenized, so that all evidence of bedding is lost and minor compositional differences are destroyed. The transformation is very patchy and generally partial in the east, but by the Point of the Pund the rock is a magnificent example of the homogenous granoblastic gneiss that is characteristic of the permeation belt as a whole (Figure 5). However, even here it is just possible to find ghostly patches of gneiss that retain traces of their original semipelitic character. Such ‘semigneiss’ relics serve to distinguish this paragneiss from orthogneiss, which it closely resembles.
North of Point of the Pund, granitic sheets and pegmatitic veins cut both the gneisses and relics of psammite and semipelite and also cut across small folds associated with local shears. Beds and lenses of metalimestone and calcsilicate rock become more common, together with bands of fine-grained hornblende schist. The gneiss formation has had no apparent effect on the non-psammitic rocks, although pelitic beds, which become more common to the north and west, tend to develop an array of small quartzofeldspathic leucosomes. Where the coast turns west at Burwick, areas of non-gneissose semipelite and of semipelite with only streaks and areas of partial recrystallization (‘semigneiss’) become increasingly common. The western edge of the island of Burwick Holm and the rock supporting the Burwick Broch (HU 3880 4058) are barely affected by the recrystallization. The western edge of the gneiss belt is just offshore to the west of the Ness of Burwick, and intersects the coast a kilometre or so to the north of Burwick.

The first deformation episode to affect the rocks (the so-called ‘Main Deformation’) resulted in the formation of minor folds and a strong fabric, which ranges from planar to linear (Flinn, 1967). Small, tight to isoclinal, intrafolial folds of bedding are common but no larger scale folds are seen. The foliation of the rock is determined by the schistosity, which is parallel to lithological banding and lamination (bedding). The foliation encloses lenses of hornblende schist. Most of the rocks display a prominent rodding or mineral lineation that plunges to the south-south-west at about 40° in the area of the GCR site but at lesser angles to the north and south.

The development of the gneissose fabric in the permeation belt was controlled locally by the nature of the protolith, which was generally banded and laminated with layers of mica-rich pelite and mica-poor semipelite and psammite. Pelitic layers have been almost entirely converted to gneisses by the segregation of diffuse quartzofeldspathic leucosomes and the development of a strong schistose fabric enclosing microaugen of large andesine crystals, 1-3 mm across. An inclusion of deformed kyanite in one of these microaugen was suggested by May (1970) to be evidence for an early phase of metamorphism prior to the development of gneisses (see below). By contrast, in the dominant more-psammitic lithologies the coarsening of the texture weakens the preferred orientation of the mica flakes and hence weakens the schistosity, so that the rocks are generally transformed into homogeneous granofelsic gneisses; quartzofeldspathic leucosomes locally give a lit-par-lit appearance and tend to merge with the cross-cutting granitic sheets in places.

Important features of the Colla Firth Permeation Belt that are not immediately obvious from field inspection are the mineralogical effects of the gneiss formation. These have been described by May (1970) for the area of the Scalloway GCR site and by Flinn (1954, 1967) for areas to the north and south. Microscope examination has shown that, although minerals of higher grade than biotite, blue-green amphibole, epidote etc are extremely rare in the Whiteness Group of the Scalloway area, microcline and diopside occur in calcsilicate bands and metalimestones within and adjacent to the permeation belt. May (1970) has also found a kyanite-staurolite-
bearing rock within the belt to the south of Scalloway, and both Flinn (1954) and May (1970) have reported fibrolite and garnet as present within the belt, in particular in Delting and also in a small area some 10 km south of Scalloway. It is apparent that the formation of the gneisses took place at a higher temperature than the metamorphism in the adjoining parts of the Whiteness Group. Late-stage, retrogressive effects include sericitization of feldspar and chloritization of biotite.

The most widespread effect of deformation subsequent to the main phase is cataclastic faulting and locally prominent kink folding. Rare lamprophyre dykes are entirely post tectonic and post metamorphic.

2.3 Interpretation

The original sedimentary protoliths to the now-metamorphosed Scalloway succession were sandstones, mudstones and subordinate limestones of probable shallow marine facies. No definitive examples of sedimentary structure are preserved but the micaceous partings, regularly spaced at intervals of a few millimetres through some psammite units, and the regular division of the rocks into bed-like units, commonly of slightly different composition, are probably original sedimentary features. Mineralogically the psammites and pelites now consist of varying proportions of biotite, muscovite, quartz and plagioclase; garnet, kyanite and staurolite are accessories. These minerals and others mentioned above all developed during prograde metamorphism.

Three stages have been recognized in the formation of the Colla Firth Permeation Belt. May (1970) recognized an earlier stage in which kyanite and staurolite were formed, but since the kyanite and staurolite occur only within the permeation belt they, like the garnet and sillimanite elsewhere, might have formed during the gneiss development. The first undisputed stage recognized in the metamorphism of the area as a whole is the regional metamorphism with coincident tectonizing deformation. In the second stage some of the rocks within the area of the permeation belt were partially or completely transformed into gneiss (Figure 5). The presence of partially transformed rocks ('semigneisses') and even unaltered rocks among the gneisses proves that their formation followed regional metamorphism. The third stage involved the emplacement of granitic and pegmatitic sheets into the folded gneisses of the permeation belt and the adjacent rocks on either side.

The three stages are closely connected by having similar fabrics; foliations, schistosities and lineations are all parallel where they exist, although some of the granitic sheets are structureless. There have been slight differences in the detailed interpretation of this evidence. In the opinion of May (1970), the textural evidence preserved within this GCR site confirms that the granitic sheets were intruded as the gneissose fabric formed; the constituent minerals in the granite have been granulated and recrystallized to produce a fabric continuous with that in both the gneissose and non-gneissose country rocks. May therefore considered that the regional metamorphism, the gneiss development and the emplacement of the granitic sheets were all ‘syn-tectonic
and broadly synchronous’. In contrast, Flinn (1954, 1967) considered that the gneissies formed in a distinct event immediately after the regional metamorphism, while the thermal and stress structure was still in place. The two events could however have overlapped and the granitic sheets were probably emplaced very soon afterwards. The radiometric (Rb-Sr) date of 530 ± 25 Ma, obtained by Flinn and Pringle (1976) for the granitic sheets should therefore indicate a minimum age for the main deformation and peak metamorphism of the Shetland Dalradian. However, it is neither precise nor accurate by modern standards and needs to be repeated using modern techniques.

The possible causes and/or mechanisms of gneiss development have been discussed by Flinn (1954, 1967, 1995). The metamorphic minerals and grades involved are so low (below garnet grade in the Scalloway area) that there can be no question of the gneissies having formed by partial melting. He considered that the gneissies are most likely the result of recrystallization in which their grain size was doubled or trebled. This was brought about with little or no change of composition by the percolation (permeation) through the rocks of hot watery solutions from below, controlled by the pre-existing vertical layering and schistosity in the Whiteness Group. The water initiated the grain growth by grain-boundary migration and also supplied the heat for the diopside thermal aureole that occurs along the length of the belt. The granitic sheets are of S-type and probably formed by melting of the crust at depth. It is possible that they supplied some heat but it is notable that the aureole is continuous and is entirely confined to the gneissies, whereas the granitic sheets are irregularly distributed and extend beyond the aureole. May (1970), however, attributed the presence of diopside porphyroblasts in calc-silicate rocks to a late period of post-tectonic static metamorphism that is represented by the growth of various porphyroblasts elsewhere in Mainland Shetland (Flinn, 1967; see the Hawks Ness GCR site report).

### 2.4 Conclusions

The Scalloway GCR site provides a well-exposed and instructive section through part of the Colla Firth Permeation Belt, which is of national and possibly international significance. At the GCR site, this gneissose zone is developed within a sequence of semipelitic to psammitic metasedimentary rocks forming part of the Colla Firth Formation in the Whiteness Group of the Shetland Dalradian. The psammites and pelites have been recrystallized to a homogeneous granoblastic gneiss with a fabric parallel to that in the adjacent rocks outside the belt, which have been regionally metamorphosed and deformed but are not gneissose. Numerous granitic sheets and veins were intruded into both the gneiss belt and the adjacent non-gneissose rocks and these too have a schistose fabric.

Textural evidence preserved within the rocks of this GCR site confirms that the regional metamorphism and gneiss formation, although possibly originating from distinct events, were both broadly coincident with the principal deformation and that all of
these events only shortly preceded or overlapped with the intrusion of granitic sheets. The age of the granitic sheets is therefore of great national importance as an indicator of the minimum age of deformation and peak metamorphism in the Shetland Dalradian. A radiometric, Rb-Sr date of 530 ± 25 Ma is imprecise, probably inaccurate and dating by a modern, more-precise method is clearly desirable. However, the date does suggest that the deformation might be radically different in timing to the deformation affecting the Dalradian sequence elsewhere (e.g. peaking at c. 470 Ma in the Grampian Highlands). It follows that an understanding of these tectonometamorphic relationships is crucial for the wider interpretation of the Dalradian succession both in Shetland and in the Scottish mainland.

3 HAWKS NESS
(HU 447 477–HU 458 491–HU 458 473)

P. Stone and D. Flinn

3.1 Introduction

The sea cliffs and rocky foreshore around the promontory of Hawks Ness provide extensive exposure through a metasedimentary sequence extending from the top of the Whiteness Group through the lower part of the Clift Hills Group of the Shetland Dalradian. The lithologies present range from metacarbonate rocks of probable shallow-water origin, to metavolcanic rocks and deep-water turbidites. Sedimentary structures preserved in the turbiditic strata show locally opposed younging directions which, together with the exposure of fold closures, confirm the presence of isoclinal folds. Deformation has also produced a pervasive foliation, a linear fabric and a recrystallized, phyllitic mineral assemblage. Post-tectonic regional metamorphism led to the subsequent growth of staurolite and garnet porphyroblasts.

The regional importance of the Hawks Ness GCR site lies in the unusually wide range of sedimentary, tectonic and metamorphic features preserved in a succession that was deposited in an extensional basin setting. An understanding of the processes and sequence of events involved allows for a more-informed regional interpretation of an otherwise poorly known part of Scottish geology. A detailed account of the geology was given by Flinn (1967) whilst an overview of the regional geological setting was provided by Flinn and May (in Mykura, 1976); the GCR site area is included in the Geological Survey’s one-inch Sheet 128 (Central Shetland, 1981).

3.2 Description

Around the promontory that culminates in Hawks Ness, steeply inclined strata strike north-north-east. The stratigraphical sequence commences with the Laxfirth Limestone (the top of the Whiteness Group) on the west side of the promontory, and proceeds upwards and eastwards through the Asta Spilitic Formation and Clift...
Hills Phyllitic Formation (the lower part of the Clift Hills Group) (Figure 6). The Asta Spilitic Formation has been correlated with the Easdale Subgroup in the Dalradian succession of the Scottish mainland (Flinn et al., 1972) but more-recently a possible correlation with the Tayvallich volcanic rocks, at the top of the Argyll Group, has found more favour (Harris et al., 1994; Flinn, 2007).

The Laxfirth Limestone crops out as a thin strip along the strike-parallel eastern coast of Lax Firth, although the full outcrop extends to the western side of the firth and the thickness probably exceeds 500 m. It is a crystalline, calcite metacarbonate rock containing scattered coarse grains of quartz, and with small quantities of epidote, zoisite, white mica and pyrite concentrated into fairly continuous laminae. On a larger scale, there is a faint, millimetre- to centimetre-scale colour banding through shades of pale grey and pale pink. Overall, the Laxfirth Limestone is relatively fine grained compared to some other Dalradian metatlimestones. At its eastern boundary, it is intimately associated with conformable sheets of hornblende schist up to about a metre thick.

Conformably above the metalimestone is the Asta Spilitic Formation, which crops out along the north-west coast of Hawks Ness in a narrow zone no more than a few tens of metres wide. These largely pyroclastic rocks range from phyllitic fine-metatuffs to pyroclastic metabreccias and are generally thinly interbanded with feldspar-phyrnic hornblende schists and phyllitic pelites. Adjacent to the Laxfirth Limestone, and corresponding with the pyroclastic rocks, a narrow positive ground-magnetic anomaly of about 1000 nT can be traced continuously, southward to the sea at Scalloway and to the north-east almost as far as the Out Skerries. The pyroclastic rocks are succeeded by a zone, 10–20 m wide, in which beds of turbiditic gritty quartzite alternate with thin beds of laminated and graded, dark semipelite. Some hornblende schists commonly form boudinaged pods.

The north-east coast of Hawks Ness presents a continuous section through more than 300 m of the Clift Hills Phyllitic Formation. This unit contains phyllitic metagreywackes, thin beds of gritty quartzite, phyllitic gritty psammite, pelite, calcsilicate rock and sporadic lenses of hornblendic schist similar to those seen in the underlying Asta Spilitic Formation. The phyllitic rocks are laminated on a millimetre scale, the darker, more-micaceous laminae representing metamorphosed mudstone, while the paler laminae are probably derived from sandstones and siltstones. It is possible to detect small-scale cross-bedding in places, usually with the appearance of low-amplitude ripples (Figure 7). They have a strong foliation and are pervasively recrystallized to fine-grained quartz, feldspar and muscovite, together with biotite and/or chlorite; some are graphitic. Staurolite, biotite and chlorite porphyroblasts post-date the imposition of the tectonic foliation (Flinn, 1967). Inland, in the southern part of the Hawks Ness promontory, are large intrusions of hornblende metagabbro, containing ophitic blue-green hornblende and recrystallized primary albite. Smaller lenticular bodies of hornblende schist containing
relict phenocrysts of plagioclase also attest to an igneous protolith.

On the south-east side of the Hawks Ness promontory, the top part of the Clift Hills Phyllitic Formation is the Dales Voe Grit Member, which comprises 1.5 km of turbiditic gritty quartzites. Excellent exposures are provided by the rocky headlands of Brim Ness and Fora Ness. In this well-layered sequence, units of impure quartzite, with bed thickness ranging from several centimetres up to several metres, alternate with subordinate units of thinly bedded laminated and graded semipelite. At Brim Ness there is a thin, conformable interbed of granular calcisilicate rock, whilst thin metalimestones and lenses of Asta Spilite-like rock occur sporadically. Within the quartzite units, many individual beds show normal, upwards grading from coarse, locally pebbly bases, through coarse-grained, gritty quartzite to finely laminated semipelite. Cross-bedding is seen in the upper parts of many beds, whilst evidence of channelling and current scour is preserved on basal bedding planes. This abundance of sedimentary younging evidence demonstrates local reversals that can be attributed to tight folding; many hinges are spectacularly preserved (Figure 8a). These are dominantly single-bed intrafolial isoclinal folds most of which face eastwards and upwards, but a minority face westwards and downwards.

On the eastern side of the Dales Voe Grit, on the opposite side of Dales Voe, there is an upward transition from the gritty metasandstone back into chloritic phyllites. These then continue eastwards, and stratigraphically upwards until, farther south, they are seen to underlie the pelitic Dunrossness Phyllitic Formation, which in turn underlies the volcanic Dunrossness Spilitic Formation, part of which crops out in the Cunningsburgh GCR site.

Post-tectonic lamprophyre dykes, one of which can be seen to the south of Brim Ness, are probably of Early- to Mid-Devonian age.

### 3.3 Interpretation

At the base of the succession within the GCR site, the thick metacarbonate unit of the Laxfirth Limestone suggests sedimentation in relatively shallow water. The subsequent volcanicity recorded in the Asta Spilitic Formation, and the closely associated turbiditic metasedimentary rocks of the Clift Hills Phyllitic Formation, then suggest a phase of rapid subsidence and the establishment of a deep-water depositional environment. The following Dales Voe Grit beds have all the characteristics of deep-water turbidites. The individual beds are graded in their lower parts, passing up into a laminated and sporadically cross-bedded upper sector that is either abruptly overlain by the coarse base of the succeeding bed or passes up into a unit of thinly bedded, graded siltstones. The thicker, sandstone beds were deposited from large-volume and high-density turbidity flows, whereas the sequences of more thinly bedded, graded siltstones derive from a series of smaller, low-density flows. The bases of the thicker beds commonly carry flute and groove casts from which Flinn (1967) was able to calculate an original current flow from the north.
The array of sedimentary features that are preserved also allows the local sedimentary younging direction to be established. Throughout the GCR site area, the beds strike 030° and, in general, they dip steeply to the north-west in the west and to the south-east in the east. The overall stratigraphical trend is for successively younger units to crop out sequentially towards the south-east. This situation is confirmed by some of the localized sedimentary younging evidence but is contradicted in places by unequivocal examples of younging towards the north-west (Figure 7). Flinn (1967) recognized this phenomenon and related it to short wave-length isoclinal folding, which is shown by individual beds (Figure 8a). This was linked to the main tectonic deformation, which produced a steep schistosity and a lineation plunging at c. 20° to the south (Figure 8b); a similar fabric and orientation to that in the rocks of the Scalloway GCR site to the south-west. However, while the fabric lineation plunges at 20° or so to the south, the axes of the folded turbidite beds plunge at 20–30° to the north (Figure 6, inset).

The local syn-tectonic metamorphic mineral assemblage is dominated by muscovite, biotite, chlorite, quartz and plagioclase. Post-tectonic regional metamorphism has led to the porphyroblastic growth of staurolite, garnet, biotite and chlorite.

### 3.4 Conclusions

The Hawks Ness GCR site provides a well-exposed and instructive representative section through a metasedimentary sequence extending from the top of the Whiteness Group (the Laxfirth Limestone) through the lower part of the Clift Hills Group (the Asta Spilitic Formation and the Clift Hills Phyllitic Formation) in the Dalradian succession of Shetland. These units are currently thought to be broadly equivalent to the Tayvallich Subgroup of the Scottish mainland succession. The sequence demonstrates deposition in a progressively deepening marine environment with sub-marine volcanism marking the onset of rapid subsidence.

Structural and metamorphic features within the GCR site make a significant contribution to interpretation of the deformational and metamorphic history of the Shetland Dalradian. Deep-water turbiditic strata (in the Dales Voe Grit) preserve sedimentary structures from which opposing stratigraphical younging can be deduced, confirming that the sequence has been affected by short-wave-length, isoclinal folding, which is commonly shown by individual beds. A phyllitic mineral assemblage (muscovite-biotite-chlorite-quartz-plagioclase) formed during deformation-related metamorphism and staurolite, garnet, biotite and chlorite were produced during post-tectonic, regional metamorphism.
4 CUNNINGSBURGH
(HU 439 280–HU 421 274–HU 432 264)

D. Flinn, P. Stone and D. Stephenson

4.1 Introduction

This GCR site is named after the collection of hamlets on the south-east coast of Mainland Shetland, some 13 km south-south-west of Lerwick, that is generally known as Cunningsburgh (Figure 9). There, despite relatively intense metamorphism, an unusual and regionally important geological assemblage can be recognized. The east-west foreshore between South Vosker and Mail provides sections through the uppermost part of the Dunrossness Spilitic Formation, at the top of the Clift Hills Group. The rocks are dominantly sub-marine, basic pillow lavas with interbedded volcanlastic material and intrusive bodies of hornblende metagabbro. To the south of Mail the north-south trending sea cliffs and the hillside between the cliffs and the road are composed of metalavas alternating with layers of metavolcaniclastic material and beds of metasedimentary rock. The rocks are pervasively foliated and are difficult to interpret in the field due to the intensity of metamorphism and their general dark-coloured and fine-grained nature. Inland from the north-south cliff section, the hillside drained by the Burn of Catpund is underlain by a large body of variably altered serpentine, notable for its local development of highly unusual and controversial spinifex-like texture, which could be of considerable international interest (Figure 10). Along its western margin the serpentine is in direct contact with a sequence of phyllitic chloritoid-kyanite-chlorite pelites, known as the Dunrossness Phyllitic Formation. These stratigraphically overlie the Clift Hills Phyllitic Formation that is displayed so comprehensively in the Hawks Ness GCR site. The Dunrossness Phyllitic Formation is seen to overlie the serpentine structurally at the southern end of the GCR site, although it underlies it stratigraphically in the accepted order of Shetland succession.

This assemblage of rocks, following on from the sequence seen in the Hawks Ness GCR site, provides an illustration of the final stages in the development of a late-Dalradian extensional basin, when crustal disruption culminated in deep-seated intracontinental to oceanic magmatism. An understanding of the processes and sequence of events involved allows for a more-informed regional interpretation of an otherwise poorly known sector of the Scottish Dalradian. Detailed accounts of the local geology were given by Flinn (1967), Flinn and Moffat (1985) and Moffat (1987) and the area is covered by the Geological Survey’s one-inch Sheet 126 (Southern Shetland, 1978). The rock assemblage was discussed in its regional context by Flinn (1985, 1999).

An additional feature of this GCR site stems from its considerable archaeological interest. Areas of very soft talc-magnesite schist (steatite), arising from low-temperature hydrothermal alteration of the serpentine, were exploited in Norse times to be worked-up
into various artefacts. Numerous tool-marked recesses have been left behind by the Norse workings and it has been suggested by archaeologists that there was considerable trade in steatite products from these and from other such quarries in Shetland.

### 4.2 Description

The Dunrossness Spilitic Formation forms the stratigraphically highest part of the Dalradian succession exposed in Shetland (Flinn et al., 1972). It is almost entirely composed of mafic and ultramafic, lavas and volcaniclastic rocks formed in a sub-marine environment. The formation has been correlated broadly with either the lavas and tuffs of the Tayvallich Subgroup at the top of the Argyll Group (Flinn et al., 1972), or possibly with part of the slightly later Southern Highland Group (Harris et al., 1994; Flinn, 2007).

The formation dips consistently to the west at between 25° and 45°. There is no local way-up evidence but, accepting that the overall younging of the Shetland Dalradian succession is to the east, as discussed in the Introduction to this paper, the sequence here must be overturned. The outcrop width and dip suggest a formation thickness of about 1 km, with the ultramafic component, a large body of serpentinite, occupying upwards of one half of that, in the topographically highest but stratigraphically lowest part in the west. For the most part, the sequence is thinly foliated with some thicker and more-massive, less well-foliated units that are probably relics of the original bedding. The metamorphic foliation is generally parallel to the igneous and sedimentary layering. Folding is rare but locally the layering and foliation are intensely deformed by a series of small, strongly asymmetrical, tight to isoclinal folds. Fold hinges are subhorizontal but show a range of orientations, possibly in association with minor faulting, which complicates the structure locally. Garnet appears to have grown in two phases of metamorphism, before and after imposition of the foliation. Overall, the rocks stratigraphically above the serpentinite have been metamorphosed to lower to medium amphibolite facies. This is a significantly higher grade than is seen in the rocks of the Clift Hills and Whiteness groups to the west (see the Hawks Ness GCR site report).

The serpentinite occupies most of the hillside above the road to the west of the coastal sections. Its basal contact with the metasedimentary, chloritoid-bearing Dunrossness Phyllites is exposed only in the sea cliffs at the southern end of the GCR site, immediately north of Lamba Taing. There, despite the complication of minor but complex faulting, the contact appears to lie parallel to the bedding traces and dominant foliation in the phyllites; there is no evidence for a significant tectonic break. A major lens of serpentinite, separate from the main body, crosses the road and intersects the coast in the middle of the GCR site and wedges out on the hillside south of the Burn of Catpund. This large lens of serpentinite also lies parallel to the foliation in the spilitic and volcaniclastic rocks.

The serpentinite has been variably steatitized and veined by talc. From several hundred metres north of the Burn of Catpund to the
south end of the GCR site, the steatitization is sufficiently intense for a quarry to have been opened recently in the expectation of exploitation. The surrounding hillside is scarred by small pits opened during the Norse occupation of Shetland, a thousand years ago, for the manufacture of utensils. Some Norse pits along the Burn of Catpund have been re-excavated by the burn and one has been opened by archeologists for display purposes.

The steatite rock is about half talc and half magnesite. Where the steatitization is not too intensively developed, the rock is seen to be a clast-supported breccia composed of blocks up to about 30 cm in diameter, thoroughly cemented by the serpentinization. Broken blocks within the breccia that have been little affected by steatitization, have in places been weathered and etched to reveal that they are composed of a mass of needle-like, parallel to subparallel crystal pseudomorphs forming a distinctive spinifex-like texture (Figure 10). The 'spinifex' textured rocks can be traced intermittently from about 300 m north of the Burn of Catpund as far as the Burn of Mail, in a zone a hundred metres or so west of the contact of the serpentinite body with the spilitic rocks (Figure 9). Thin sections show that the pseudomorphs have the characteristic crystal terminations of spinifex-textured olivines, but that they are serpenitized or steatitized, as is the matrix that contains them. As is discussed below, the recognition of the spinifex-like texture provides crucial support for the interpretation of the serpentinite as an original quickly chilled, ultramafic lava, possibly a komatiite.

Also present within the serpentinite outcrop are several major lenticular layers of fine-grained non-serpentinite rocks that possibly separate individual ultramafic lavas. These are mainly metavolcaniclastic rocks, best seen on the beach at Mail and in the nearby road cutting. They also include interlayered lenses of metasedimentary rocks including very fine-grained, often graphitic gritty psammites, quartzites and pelites; one such lens crops out on the coast about 200 m south of Sands of Mail. The minerals present include biotite, garnet, chlorite, chloritoid and hornblende. The quartzites might be recrystallized cherts and there is at least one 2 m-thick bed with a melange-like texture showing tectonic stretching of the clasts within the plane of the foliation (Figure 11).

Sporadically distributed through the serpentinite are many near-spherical to sublenticular bodies of hornblende gabbro, 10–20 m across and forming prominent smoothly rounded knolls. Also widely scattered in this area are intrusive veins and lenses, centimetres to several metres in width, of a white to greyish rock with a siliceous patina. The rock is composed of minute aligned crystals of albite with sparse accessory hornblende and biotite. It contains 10% Na₂O and 0.5% K₂O and has been interpreted as a sodic 'keratophyre' (an albite felsite). It also contains abundant micron-sized zircons and an analysis shows 1000 ppm Zr, but it has not as yet been dated and relationships with the host serpentinite cannot be determined.

To the east of the serpentinite, between the road and the sea, are metamorphosed basic lavas alternating with volcaniclastic rocks. In thin section the lavas are seen to be composed dominantly of
blue-green hornblende with epidote. Some are aphyric, others contain relict phenocrysts of plagioclase (now corroded albite), and many are amygdaloidal. The rocks are variably tectonized with phenocrysts broken and displaced in some examples and acting as microaugen within the foliation in others. They are tholeiitic Mid-Ocean-Ridge-Basalt (MORB), probably derived from a relatively enriched mantle source (Fettes et al., 2011). The volcaniclastic rocks are black and commonly very fine grained. Their nature is largely indeterminable in the field except where they have been polished by sand along the Mail coast; identification has been assisted greatly by thin-section examination (Flinn, 1967).

Eastwards along the coast from the Sands of Mail, the rocks are exceedingly difficult to interpret. Most are black and fine grained, but in thin section they prove to be basic metavolcaniclastic rocks. Some weathered exposures reveal faint cross-sections of pillow structures (e.g. at HU 441 282) and the sequence might be largely composed of fragmented pillow lavas. Also present, especially adjacent to the Old Red Sandstone to the east of Aith Voe, are exposures of graphitic quartzite and phyllitic pelite. Inland there are a number of hornblende gabbro bosses with the same appearance as those seen to the west within the serpentinite; although here some are schistose and boudinaged, Flinn (1967) reported the preservation of an ophitic texture. An unusually large example crops out on the coast at The Pows (HU 437 278). They might have originated as intrusions into the volcanic sequence.

4.3 Interpretation

The interpretation of the origin of the serpentinite is crucial in any assessment of the wider geological significance of the Cunningsburgh GCR site in relation to the late history of the Dalradian basin in Shetland. When it was first mapped in the late 1950s, the serpentinite was interpreted as comprising one or more sub-marine, ultramafic lava flows (Flinn, 1967). However, this interpretation was regarded as petrologically impossible at the time and was not published until the recognition of the spinifex-like texture by Flinn and Moffat (1985) suggested the possibility of a komatiitic protolith for the serpentinite.

The term ‘komatiite’ was introduced by Viljoen and Viljoen (1969) to describe ultramafic lavas from the Baberton Mountain Land, South Africa. They are now known to be fairly widespread in Archaean greenstone belts but are rare in younger geological assemblages; for an overall review see Arndt and Nisbet, (1982). The high concentration of magnesium (up to 32% MgO) and related elements in komatiitic lavas indicates a high temperature (c. 1600°C), a high degree of melting of mantle material and consequently an unusually high heat flow and/or the tapping of an exceptionally deep and hot mantle source. Hence the presence of the ultramafic lava within the Shetland Dalradian has potentially profound implications for the tectonic development of the depositional basin.

Apart from the high MgO values, the most distinctive feature of komatiitic lavas is the common primary crystallization of olivine as long intermeshed crystals in a glass matrix, to produce what is
known as ‘spinifex texture’ (after the spiny intermeshed leaves of Australian Spinifex grass). However, the spinifex nature of the texture in the Cunningsburgh rocks was disputed by Nesbitt and Hartman (1986) who thought it more likely to be an example of the well-documented ‘pseudo-spinifex’ or ‘jackstraw’ texture that develops through the regrowth of olivine during prograde metamorphism of serpentinite (Collerson et al., 1976). The distinction between this pseudo-spinifex and true spinifex texture is best based on examination of thin sections of fresh samples. However, the Cunningsburgh rocks are both serpentinized and steatitized, destroying these distinctive thin-section features. The distinction in this case has to be based on the study of the textural patterns revealed on suitably weathered rock surfaces (Figure 10).

Nesbitt and Hartmann (1986) presented various arguments against the presence of komatiitic lavas at Cunningsburgh and elsewhere in the Caledonian–Appalachian Orogen, possibly influenced by the fact that occurrences in post-Archaean rocks were at that time regarded as exceedingly rare or non-existent. Proterozoic and Phanerozoic komatiitic occurrences are no longer regarded as quite so rare, but it is difficult to reach any conclusions about original magmatic liquid compositions from rocks that are as altered as the Cunningsburgh serpentinites, and the origin of the spinifex-like texture remains somewhat enigmatic. However, even if the Cunningsburgh rocks were not originally komatiites, it is still possible that they originated as basaltic lavas, in which Mg concentrations even higher than those of typical komatiites can arise by olivine fractionation and accumulation (see the Ardwell Bridge GCR site report).

In a robust defence of their original interpretation, Flinn and Moffat (1986) pointed out that the complex metamorphic history implied by the Nesbitt and Hartmann interpretation of the origin of the spinifex-like texture does not fit the known geology of the Cunningsburgh area. In particular, there is no evidence in Shetland for a high-grade metamorphic event (of at least upper amphibolite facies) that would have been necessary to produce prograde olivine growth after one episode of serpentinization but before the brecciation and the final serpentinization and steatitization. They re-iterated their belief that a volcanic origin for the serpentinite in the top of an extensional basin requires the fewest assumptions, creates the fewest problems and fits the observed structural and metamorphic history most simply.

Consequently, the Dunrossness Spilitic Formation, including the serpentinite, is regarded as the final volcanic infill to the late-Dalradian extensional basin that is still preserved in Shetland. Following the deposition of the Laxfirth Limestone, early sedimentation in the basin was interrupted by a series of relatively minor volcanic eruptions giving rise to the Asta Spilitic Formation (see the Hawks Ness GCR site report). But the later volcanism that created the Dunrossness Spilitic Formation was an event on an altogether different scale. Not only is the formation a kilometre or more thick, but it commenced suddenly with the eruption of a thick sequence of ultramafic lavas. This unusual event is most readily explained by a rapid acceleration of crustal
rifting beneath the extending basin, causing adiabatic melting in
the mantle immediately below with generation and emplacement of
high-temperature, magnesium-rich magmas (Flinn, 2007). The
spinifex-like texture, the brecciation and the serpentinization
could all be due, in part at least, to sub-marine emplacement of
the ultramafic magma; certainly they are all early-formed features.
The emplacement of the ultramafic magma was followed by the more-
usual eruption of basaltic magma of tholeiitic Mid-Ocean Ridge
affinities in the form of lavas, volcanioclastic material and
eventually pillow lavas. Their higher grade of metamorphism than
any of the rocks in the Clift Hills and Whiteness groups to the
west might have been caused, at least in part, by residual heat
associated with the ultramafic magmas. The intrusion of small
globular masses of the same magma in the form of hornblende gabbro
would seem to require special conditions or circumstances that are
not fully resolved.

Apart from the sub-marine lavas and volcanioclastic deposits, the
original protoliths for the sedimentary components of the
Dunrossness Spilitic Formation were interbedded mudstones and
sandstones of deep-marine, probable turbiditic facies. Accessory
lithologies present possibly included chert and a melange-type rock
that might have originated by sedimentary slumping before being
tectonized.

The onshore outcrop of the Dunrossness Spilitic Formation is given
additional importance by a substantial offshore extension beneath
Old Red Sandstone strata, as indicated by major coincident gravity
and aeromagnetic anomalies. These anomalies continue as far north
as the island of Unst, suggesting that the extensional basin
eventually developed into an intracontinental rift on the edge of
Laurentia at the time of the opening of the Iapetus Ocean (Flinn,
2007). It has even been suggested by Flinn (2001) that the
Shetland Ophiolite could have been obducted from this basin at
about 500 Ma.

A possible ophiolitic association of the serpentinite and pillow
lava sequence in the Cunningsburgh area was noted by Garson and
Plant (1973) and was further hinted at by Nesbitt and Hartmann
(1986). This interpretation invoked limited sea-floor spreading
during basin extension, but also invited consideration of cold
serpentinite diapirism into growing oceanic fracture zones.
However, apart from the presence in the Cunningsburgh area of
serpentinite and pillow lavas, no convincing evidence has been
adduced which in any way suggests the presence of an ophiolite-
complex. At the time that these suggestions were made it was still
common for all serpentinite occurrences to be interpreted
automatically as ophiolites.

**4.4 Conclusions**

The coast to the east and south of Mail and the hillside inland
from the coast at the Cunningsburgh GCR site, provide excellent
exposures of the Dunrossness Spilitic Formation, the youngest
Dalradian unit present in Shetland. It is largely metavolcanic in
origin and comprises sub-marine lavas and various volcanioclastic
rocks, interbedded with minor metasedimentary lithologies of deep-
water facies. The volcanic succession has been intruded by comagmatic hornblende gabbro and by albite felsite ('sodic keratophyre') of unknown affinity. All of the rocks have been deformed and metamorphosed, up to middle amphibolite facies in places; some of the finer grained rocks have a phyllitic texture.

The metavolcanic rocks include basaltic pillow lavas and brecciated ultramafic rocks that are interpreted as high-magnesium lavas. Clasts within the latter have spectacular and highly distinctive elongate pseudomorphs after crystals of olivine, which have been likened to the spinifex texture characteristic of unusual high-temperature lavas known as komatiites. Unfortunately later serpentinization has obliterated details of the texture and its origin has been the subject of debate, but the presence of komatiites in post-Archaean rocks is rather unusual, and the possibility of their presence in Shetland is highly significant and of international interest.

The rock assemblage illustrates the final phase in the development of the Dalradian extensional basin in the Shetland area. An abrupt increase in the rate and depth of extensional faulting is considered to have caused generation of the highly unusual ultramafic lavas, followed by eruption of more-typical, within-plate basaltic lavas. A considerable thickness of the basaltic lavas and associated volcaniclastic rocks built up as the basin filled; since many of the lavas are pillowed, sub-marine eruption is confirmed. The volcanic sequence can be traced offshore by geophysical methods as far north as the island of Unst, and it might have formed the floor of an intracontinetal basin on the edge of Laurentia from which the Shetland Ophiolite was obducted. Hence, the geological features preserved within the Cunningsburgh GCR site have profound implications for the wider interpretation of the Dalradian succession both in Shetland and in the Scottish mainland.

ACKNOWLEDGEMENTS

This paper has been compiled by D. Flinn and edited by D. Stephenson. Sadly, Derek Flinn died whilst it was being prepared for publication. His lifelong contribution to all aspects of the geology of Shetland can never be surpassed. The GCR editor was P.H. Banham and the referee was M.R.W. Johnson, who also provided valuable editorial suggestions. The project was cofunded by the Joint Nature Conservation Committee (JNCC) and the British Geological Survey (BGS) and has been managed by N.V. Ellis for JNCC and D.J. Fettes and M. Smith for BGS.

Since the initial site selection and site documentation for the Dalradian block of the Geological Conservation Review, additional sites to represent the Dalradian of Shetland were suggested by D. Flinn and F. May. The necessary amendments to the GCR documentation were greatly facilitated by R. Wignall (for Scottish Natural Heritage).

Diagrams were drafted for publication by S.C. White (JS Publications, Newmarket) and photographs were scanned and prepared by B.M. McIntyre (BGS, Edinburgh). Photographs from the BGS
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27).

The first complete draft of the Dalradian GCR was submitted to the
JNCC in June 2009. In 2010, the JNCC terminated its involvement in
Earth Science conservation and abandoned its contractual agreements
to publish the remaining GCR volumes. So, the authors are greatly
indebted to Diarmad Campbell, Chief Geologist Scotland for the BGS,
for funding the drafting of remaining figures and to the
Geologists’ Association and Elsevier, for ensuring that this volume
is published as a Special Issue of their Proceedings. We are
particularly grateful to Neil Ellis of the JNCC for his efforts to
secure a new publisher and to Professor James Rose, Editor in Chief
of the PGA, for making it all happen.

Finally, on behalf of all of the site authors, we would like to
record our thanks to the owners and managers of land and quarries
who have allowed access to the sites, either during previous work
or specifically for the GCR exercise.

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**Figure 1** Map of the Shetland Islands showing the outcrops of the Moine and Dalradian 'divisions' and overlying structural units. From Flinn et al. (1972) with modifications taken from the BGS 1:50 0000 sheet 131 (Unst and Fetlar, 2002).

Proposed GCR sites: 1 Scalloway, 2 Hawks Ness, 3 Cunningsburgh. BSF Bluemull Sound Fault, NF Nesting Fault, WBF Walls Boundary Fault.

**Figure 2** Map of the 'divisions' of Moine and Dalradian rocks on Mainland Shetland, east of the Walls Boundary Fault (the so-called 'East Mainland Succession'), showing main structural features and the location of the proposed GCR sites: 1 Scalloway, 2 Hawks Ness, 3 Cunningsburgh. BSF Bluemull Sound Fault, NF Nesting Fault, WBF Walls Boundary Fault.

**Figure 3** Schematic cross-section of the East Mainland Mega-monocline and Valla Field Anticline, Shetland (after Flinn, 2007). EMM East Mainland Mega-monocline axial plane trace.

**Figure 4** Map of the area around the Scalloway GCR site.

**Figure 5** Typical homogeneous granoblastic gneiss of the Colla Firth Permeation Belt, Whiteness Group, viewed normal to the lineation and parallel to the foliation. Point of the Pund, Scalloway (HU 3873 3889). Hammer shaft is 33 cm long. (Photo: D. Flinn, BGS No. P 574422.)

**Figure 6** Map of the area around the Hawks Ness GCR site. Inset is an equal-area stereographic projection showing the relationship between poles to bedding, axes of prominent isoclinal folds in individual quartzite beds and fabric lineations.

**Figure 7** Ripple cross-lamination preserved within the Dales Voe Grit Member of the Clift Hills Phyllitic Formation. Brim Ness (HU 4606 4825). Hammer head is 16.5 cm long. (Photo: F. May, BGS No. P 726605.)

**Figure 8** Structures in the Clift Hills Phyllitic Formation (see stereoplot inset in Figure 6).

(a) Isoclinal synform in beds of turbiditic psammite of the Dales Voe Grit Member. Houbie (HU 4572 4807).

(b) South-west-plunging lineation caused by tectonic elongation of clastic grains in a bed of coarse, schistose psammite. North-west tip of Hawks Ness (HU 4583 4909). Coin is 30 mm diameter. (Photos: F. May, BGS Nos. P 726606 and P 726607.)

**Figure 9** Map of the area around the Cunningsburgh GCR site.

**Figure 10** Spinifex-like texture preserved as pseudomorphs after olivine in a block of brecciated and then serpentinized ultramafic rock. Hillside south-west of Sands of Mail, Cunningsburgh (HU 4261...
2744). Coin is 26 mm in diameter. (Photo: D. Flinn, BGS No. P 550134.)

**Figure 11** Tectonically stretched clasts within a debris-flow deposit, probably volcaniclastic, interbedded with spilitic lavas of the Dunrossness Spilitic Formation on the coast south-west of Mail, Cunningsburgh (HU 429 278). Hammer shaft is 28 cm long. (Photo: P. Stone, BGS No. P 726608.)

**Table 1** The East Mainland Succession of Shetland, showing tentative informal correlations with the Moine and Dalradian supergroups of mainland Scotland. Stratigraphical ranges exhibited by the GCR sites are also shown: 1 Scalloway, 2 Hawks Ness, 3 Cunningsburgh.
Table 7.1  The East Mainland Succession of Shetland, showing tentative informal correlations with the Moine and Dalradian supergroups of mainland Scotland.
Stratigraphical ranges exhibited by the GCR sites are also shown: 1 Scalloway, 2 Hawks Ness, 3 Cunningsburgh.
Devonian sedimentary and volcanic rocks

intrusive igneous rocks

metasedimentary rocks and orthogneisses west of the Walls Boundary Fault (includes Quayfirth Group – possibly Dalradian)

Unst–Fetlar nappes, including Shetland Ophiolite-complex

Quarff Nappe succession, probably derived from Whiteness Group

Dalradian Supergroup

Clift Hills Group

Whiteness Group

Scatsta Group

Boundary Zone

Yell Sound Group (?Moine Supergroup)

thrust, shear-zone

major fault

GCR site in this volume
Figure 7.2

The image contains a geological map of an area, showing various geological layers and features. The map includes symbols for:
- Old Red Sandstone
- Plutonic intrusive rocks, mainly granitic and granodioritic
- Dalradian Supergroup
- Quarff Nappe succession, probably derived from Whiteness Group
- Clift Hills Group
- Whiteness Group
- Scatsta Group
- Boundary Zone
- Yell Sound Group (?Moine)
- Colla Firth Permeation Belt

Key symbols used in the map:
- Thrust
- Fault
- Axial plane trace of East Mainland Mega-monocline
- Inclined bedding, dip in degrees
- Inverted bedding, dip in degrees
- Vertical bedding
- GCR site in this volume
Figure 7.3

[Diagram showing geological features such as Unst, Scatsta Group, Whiteness Group, Clift Hills Group, Boundary Zone, Valla Field Anticline, Yell Sound Group, EMM, Valla Field Anticline, Whalsay, Out Skerries, Quarff Nappe, and ophiolite. The diagram includes scale markers of 10 km and 25 km, and an arrow indicating the overall direction of younging.]
Figure 7.4

Dalradian Supergroup, Whiteness Group

- Laxfirth Limestone Formation
- Wadbister Ness Formation
- Girlsta Limestone Formation
- hornblendite, fine-grained
- metalaminate, calcisilicate rock and/or hornblendite
- semipelite and psammitic, fine-grained, laminated
- gneiss, homogeneous and granoblastic
- semipelite and psammite, partially recrystallized ("semigneiss")
- schistose pelite, micaceous

- fault
- inclined bedding or foliation, dip in degrees
- vertical bedding or foliation
- rodding or mineral lineation, plunge in degrees

lamprophyre dyke (Caledonian)

areas with abundant sheets (20–300 metres-wide) of schistose microgranite and granite and non-schistose pegmatitic veins; larger bodies are shown individually
phyllitic semipelite and psammite
calcisilicate granofels
metavolcaniclastic rocks
turbiditic gritty quartzite, interbedded with cm-banded and graded semipelite
feldspar-phyric hornblende metagabbro
phyllitic gritty semipelite and psammite, locally hornblendic
metavolcaniclastic rocks, locally hornblendic; some agglomerate metacarbonate rocks and hornblende schists
Dales Voe Grit Member
Clift Hills Phyllitic Formation
Asta Spilitic Formation
Laxfirth Limestone Formation

Figure 7.6
Middle Old Red Sandstone
Dalradian Supergroup, Clift Hills Group
very fine-grained metavolcaniclastic rocks
hornblende gabbro
fine-grained metavolcaniclastic rocks with some hornblendic agglomerates and metabasaltic lavas
serpentinite
graphitic metasedimentary rocks
gritty quartzite
psammite and pelite ± chloritoid
hornblende gabbro
metavolcaniclastic rocks
serpentinite
phyllitic chloritoid-kyanite-chlorite pelites
phyllitic semipelites

Dunrossness
Spilitic Formation
Dunrossness Phyllitic Formation
Clift Hills Phyllitic Formation

Fault, tick on downthrow side
Inclined bedding or foliation, dip in degrees
Vertical bedding or foliation
Lineation, plunge in degrees
Horizontal lineation

Norse steatite quarry
Modern steatite quarry

Albite felsite (keratophyre)
Lava
Pillow lava, poorly defined
Serpentinite, brecciated and partly steatitized
Talc-rich steatite
Spinifex-like texture in serpentinite