The Dalradian rocks of the Shetland Islands, Scotland

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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 7.1). 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 7.1) 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 Lewisianiod 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 phyllitic 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 ((Figure 7.1) and (Figure 7.2); 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 7.1). 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 km^2 on the Mainland of Shetland, but also form smaller islands to the east of the Mainland and parts of Unst and Fetlar (Figure 7.1). 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 7.2). 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 andLaxfirth 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 7.1). 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 7.2). 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, father 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 7.2).

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 7.3). 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 7.3), 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.

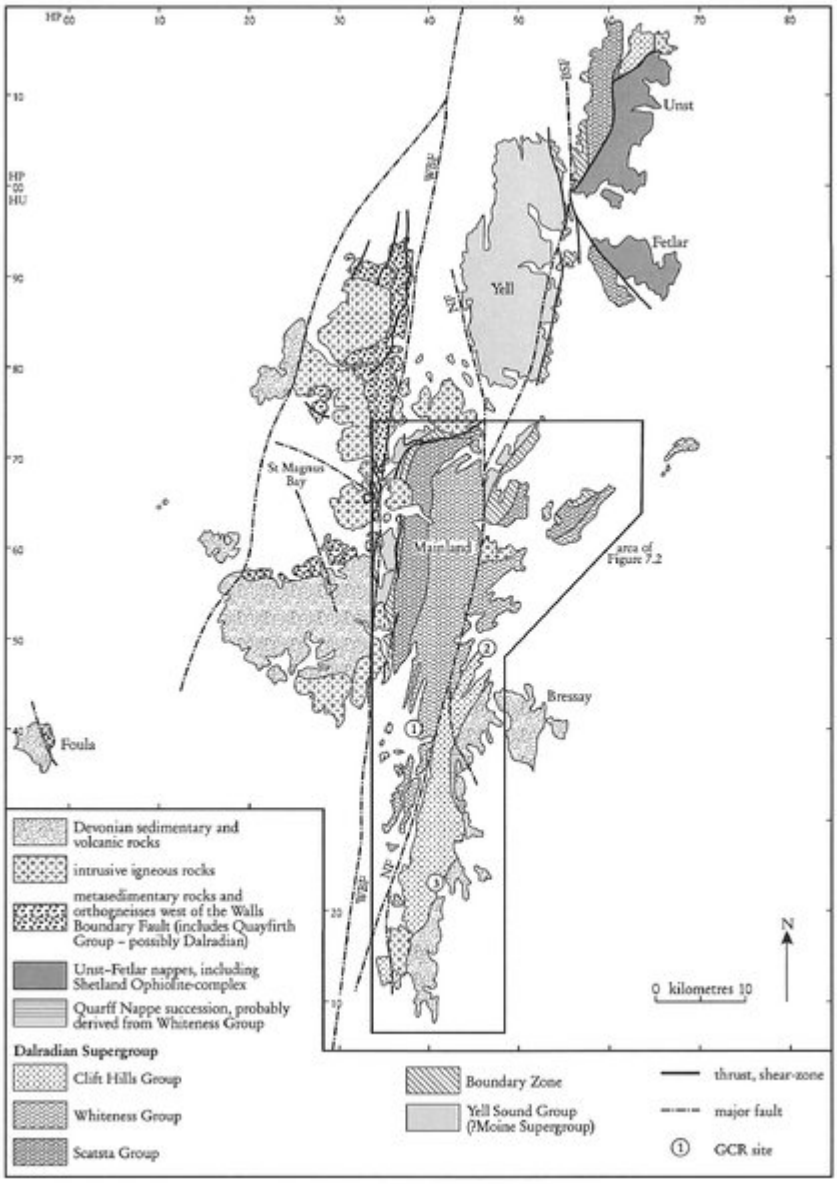
The main regional metamorphism in the Dalradian of Mainland Shetland was coincident with the Main Deformation (Flinn, 1967) but preceded the formation of the East Mainland Mega-monocline and has been attributed to burial metamorphism within the depositional basin (Flinn, 2007). As a result of this metamorphic 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 gneissose 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.

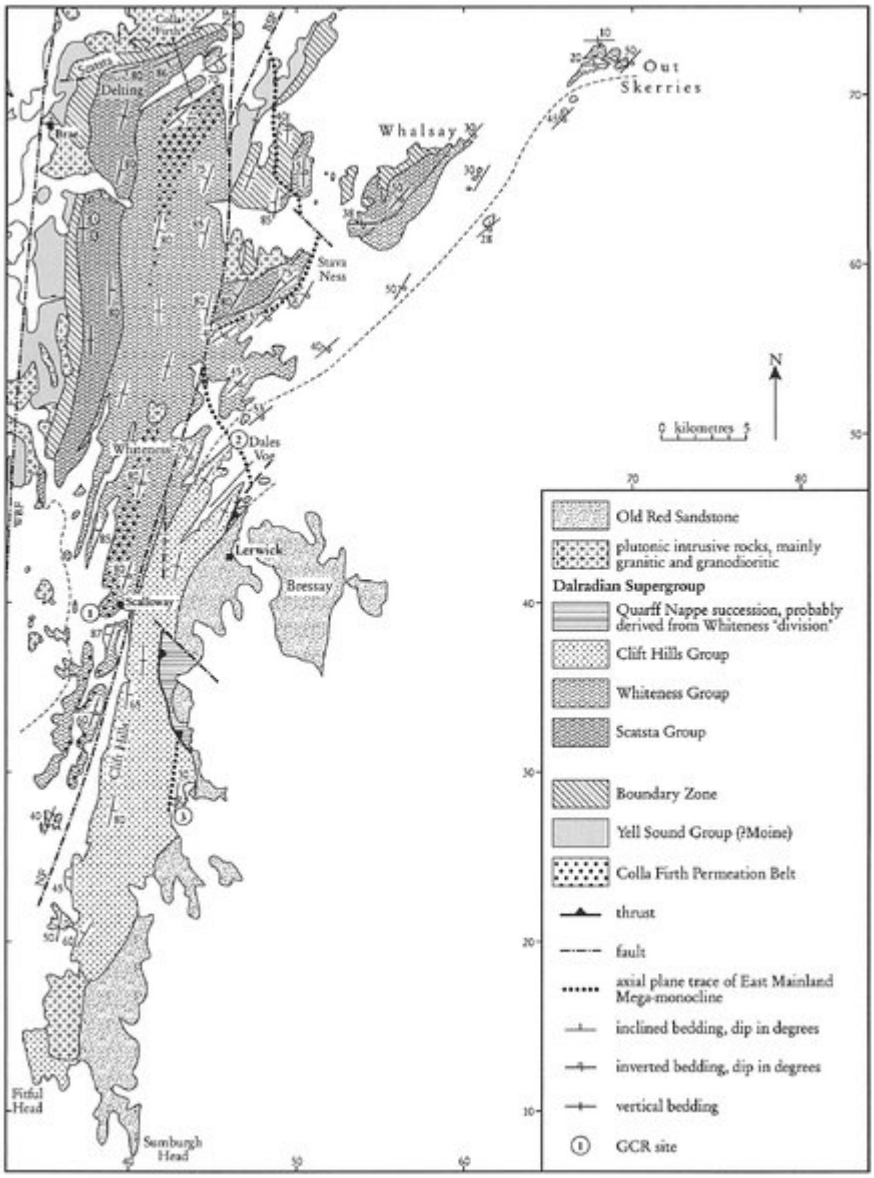
Somewhat later, development of porphyroblasts such as biotite, chlorite, staurolite, kyanite, chloritoid and garnet occurred, overprinting the tectonic fabrics in the less strongly tectonized rocks of the Clift Hills Group. In the Dalradian rocks beneath the Shetland Ophiolite-complex on Unst and Fetlar, 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.

References



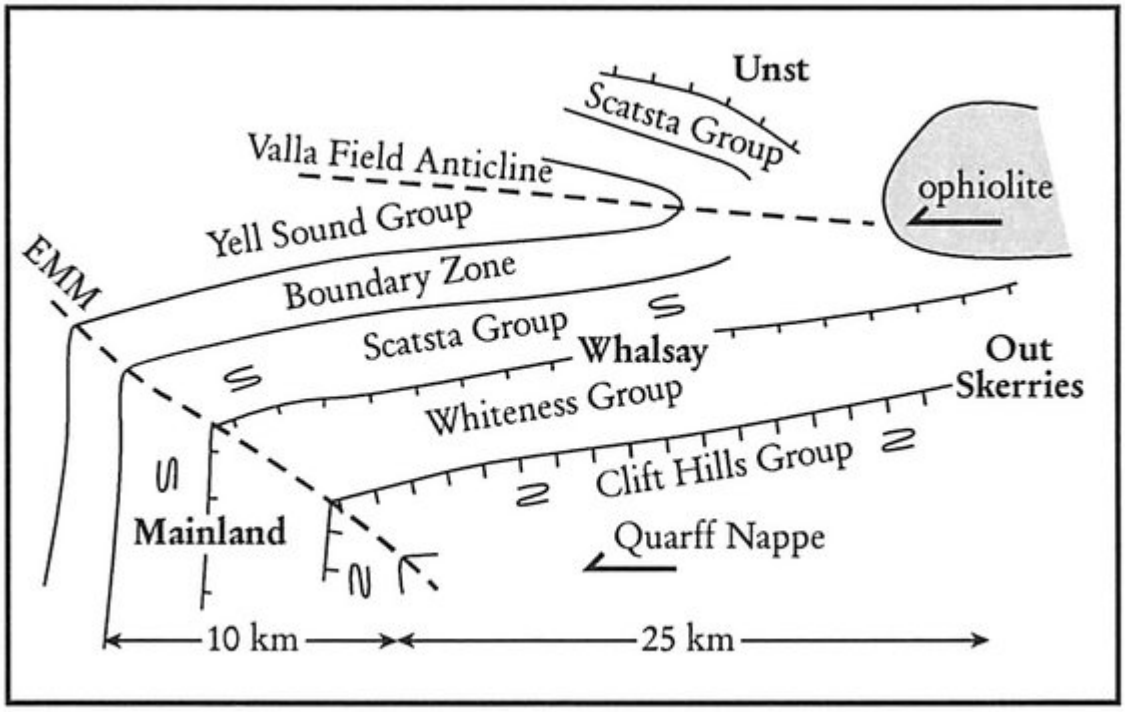
(Figure 7.1) Map of the Shetland Islands showing the outcrops of the Moine and Dalradian 'divisions' and overlying structural units. From Flinn et al. (1972) with modifications taken from the BGS 1:50 0000 sheet 131 (Unst and Fetlar, 2002). Proposed GCR sites: 1 Scalloway, 2 Hawks Ness, 3 Cunningsburgh. BSF Bluemull Sound Fault, NF Nesting Fault, WBF Walls Boundary Fault.



(Figure 7.2) 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.

SHETLAND			GCR	SCOTLAND	
group	formation	member	site	formation	group
Clift Hills	Dunrossness Spilitic		3	Loch Avich Lavas/Green Beds	Southern Highland
	Dunrossness Phyllitic				
	Clift Hills Phyllitic				
		Dales Voe Grit			
	Asta Spilitic		2	Tayvallich Volcanic	Argyll
Whiteness	Laxfirth Limestone			Tayvallich Slate and Limestone	
	Wadbister Ness				
	Girlsta Limestone		1		??????????
	Colla Firth	host rocks of the Colla Firth Permeation and Injection Belt			??????????
		Nesbister Limestone			
		Whiteness Limestone			Appin
	Weisdale Limestone				
Scatsta	Scatsta Quartzitic				Grampian
Boundary Zone	Skella Dale Burn Gneiss				??
	Valayre Gneiss				
Yell Sound					?Loch Eil + Glenfinnan

(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.



(Figure 7.3) 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.