Gearraidh Siar (Garry-A-Siar) and Baile Mhanaich (Balivanich), Benbecula

[NF 759 526]–[NF 760 535], [NF 761 542]–[NF 767 555]

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Introduction

The two coastal sections of Gearraidh Siar (Garry-a-siar) and Baile a' Mhanaich (Balivanich) on the west coast of Benbecula together comprise one of the best-documented and important geological sites in the Outer Hebrides. These low-lying rocky coastal exposures of Lewisian gneisses contain many members of the 'Younger Basic' Suite, mainly metadolerite dykes, which exhibit a wide variety of Laxfordian reworking effects. In the Gearraidh Siar section and the southern half of the Baile a' Mhanaich section the 'Younger Basic' dykes are little deformed and generally show a high degree of discordance reflecting relatively low levels of Laxfordian reworking. In contrast, in the northern half of the Baile a' Mhanaich section the dykes are thoroughly deformed and are generally concordant, reflecting high levels of Laxfordian strain. The change from the area of low strain to that of high strain occurs over about 1 m and can be observed on the ground.

The area of low Laxfordian reworking corresponds approximately to the broad antiformal hinge area in an anticline–syncline pair of some 4 km wavelength. These Laxfordian F3 structures fold the regional gneissose banding (Coward, 1973a,b). The folds are open to tight with upright axial planes and moderately NW-plunging axes. At the northern end of the Baile a' Mhanaich section an area of high strain lies in the core of the tight synform. The fold pair lies west of the main antiformal structure that governs the overall structural pattern on Benbecula (Coward, 1973b; Fettes *et al.,* 1992). The structural detail provided by the Gearraidh Siar and Baile a' Mhanaich sections, both on a regional scale, and along individual dykes, has allowed researchers to document the nature and variety of the Laxfordian event and of its component phases as well as pointing to the factors that control the pattern of deformation. These studies have provided an important basis for interpreting the regional patterns of Laxfordian reworking.

The sections also provide excellent examples of late-Laxfordian pegmatitic granite veins, which cut across the variously deformed 'Younger Basic' dykes and main Laxfordian structures and thus mark the end of the main Laxfordian events. Also present in the area are rare examples of the late-Scourian microdiorite sheets, and the only documented occurrence of a post-Laxfordian microdiorite dyke.

Although Jehu and Craig (1926) mapped the west coast of Benbecula, the first detailed work on the Gearraidh Siar and Baile a' Mhanaich coast sections was carried out by Dearnley and Dunning (1968). They studied the Laxfordian effects on the 'Younger Basic' dykes, and documented the variety of structural complexity and the associated metamorphism. Subsequently, Coward (1973a) carried out a detailed structural analysis of the sections, and Coward *et al.* (1970), Coward (1973b) and Fettes *et al.* (1992) have all discussed the regional context. The present account draws on these references and also on unpublished data held by the British Geological Survey in Edinburgh.

Description

The two coastal sections lie mostly in the intertidal zone on the westernmost part of Benbecula (Figure 2.17). The southern section runs from [NF 760 535] around the headland of Gearraidh Siar to [NF 760 526] and is separated from the Baile a' Mhanaich section to the north by the small sandy bay of Culla. The northern section extends from Quirnish [NF 757 544], north and then east for some 2 km to the fringes of the small town of Baile a' Mhanaich [NF 770 555]. Both sections are backed by storm beaches and sandy machair, and consist of low rocky outcrops, which provide almost continuous exposure except where interrupted by small inlets of shingle and sand. The exposure may extend west for up to 100 m from the shoreline at low tide. Because of its low-lying nature the sand and shingle banks do shift over time and alter the detailed pattern of exposed bedrock.

Gearraidh Siar (Garry-a-siar) section

The Gearraidh Siar section consists predominantly of grey to white granodioritic and tonalitic Lewisian gneisses. These are banded, but relatively homogeneous, coarse- to medium-grained rocks, with the gneissose banding defined by the quartzofeldspathic and biotite-and hornblende-rich layers. The banding and concordant Scourian fabrics vary in strike from NNW to north and north-east and dip generally at 50°–60° towards the west. Only minor 'Older Basic' bodies occur in the section. However, the gneisses contain many mafic dykes of the 'Younger Basic' Suite, mainly metadolerite, which are cut by a suite of late-Laxfordian pegmatitic granites. The original orientation of the dykes was predominantly north-west but a few lay at high angles to this trend. They vary in width from a few centimetres up to *c.* 25 m and can be traced for up to 100 m across the exposed section. Many of the dykes have small offshoots and apophyses that may lie at high angles to the trend of their parent dyke. The degree of reworking shown by the dykes varies considerably (Figure 2.18). Dearnley and Dunning (1968) erected four categories to define the deformational state, namely:

- type-1, dykes and small apophyses completely undisturbed and cutting sharply across the gneissose foliation;
- type-2, dykes showing signs of deformation but with the main contacts and apophyses still cross-cutting;
- type-3, dykes and offshoots locally parallel to the gneissose foliation with some folding and boudinage;
- type-4, dykes strongly deformed, commonly boudinaged and migmatized, and almost wholly concordant to the gneissose foliation.

Dearnley and Dunning (1968) also examined the mineralogy of the dykes. They showed that the cores of the bigger dykes exhibit granulite-facies assemblages characterized by garnet + clinopyroxene, whereas the margins and smaller dykes contain amphibolite-facies assemblages of hornblende + plagioclase. The former they attributed to an early-Laxfordian granulite-facies metamorphism; the latter to a later Laxfordian retrogressive phase.

Coward (1973a) related the Laxfordian reworking to four phases, $D1_L$–$D4_L$. He documented many examples of multi-phase deformation and demonstrated that the degree of reworking can vary from virtually absent to very high across transitional zones as narrow as 0.5 m. He showed that the deformation associated with his first and third phases is relatively intense but confined to narrow zones whereas the second phase also resulted in a more-widespread but moderate style of reworking. He regarded the amphibolite-facies assemblages as syntectonic and closely related to the deformational phases.

Throughout the section the many members of the 'Younger Basic' Suite illustrate this variation in the degree of reworking. Although regionally the degree of Laxfordian reworking is low, some narrow zones of high strain do occur. Strongly discordant and largely undeformed mafic dykes may exist within metres of concordant and deformed dykes. In some cases large dykes may be boudinaged although their apophyses are largely undeformed; in other cases the reverse occurs. The following localities illustrate these points, although many other examples also occur along the section (Figure 2.17), (Figure 2.18).

At [NF 756 535] a 2 m-wide vein of bright-red pegmatitic granite cuts two mafic dykes. This is locality G4 of Coward (1973a, fig. 6) and Dyke B of Dearnley and Dunning (1968, fig. 6). The two dykes are sub-parallel and trend roughly north-west; they are boudinaged and weakly folded with a locally prominent lineation that plunges 20°–40° to the north and NNW The dykes are discordant to the general trend of the gneissose foliation, but locally the foliation has been rotated into concordance with their margins. There are a number of small apophyses, which show a range of fold styles. The cores of the dykes have garnet + pyroxene-bearing assemblages, but the margins are amphibolitized. These dykes have been subject to a moderate degree of reworking and were classified as type-3 by Dearnley and Dunning (1968).

At [NF 756 535] an undeformed, markedly cross-cutting mafic dyke with numerous unmodified apophyses is exposed. Some 50 m to the west of this locality a weakly folded mafic dyke still shows narrow, largely undeformed, cross-cutting apophyses (G6 of Coward, 1973a). At [NF 756 533] a 1–1.5 m-thick Laxfordian pegmatitic granite vein cuts refolded isoclinal folds of apophyses on the north-east side of a large mafic dyke (G7 of Coward, 1973a, fig. 5). At [NF 756 532] a late-Laxfordian pegmatitic granite vein cuts a narrow zone of intensely deformed dykes where the dykes and their apophyses have been pulled into conformity with the gneissose foliation (G8 of Coward, 1973a, fig. 7).

At [NF 756 530] a 2 m-thick vein of pink pegmatitic granite with a core of white quartz cuts a strongly discordant 3 m-wide mafic dyke. This is locality G12 of Coward (1973a) and Dyke A of Dearnley and Dunning (1968, fig. 4). The mafic dyke is *c.* 10 m wide and can be traced for nearly 100 m. It lies at a high angle to the gneissose foliation and shows virtually no trace of Laxfordian deformation as evidenced by a lack of internal planar fabrics and small undeformed and cross-cutting apophyses. The dyke is largely composed of garnet + clinopyroxene-bearing assemblages with amphibolite-facies assemblages confined to narrow marginal zones. Dearnley and Dunning classified this dyke as type-1. Some 80 m to the SSW, near the low-tide mark at [NF 7557 5291], a concordant to slightly discordant thin microdiorite sheet is tightly folded and locally podded. It lies adjacent to thin, folded but markedly discordant mafic dykes (G13 of Coward, 1973a). The microdiorite sheet is thought to be late-Scourian in age.

At [NF 758 526] an irregular *c.* 1.5 m-wide pegmatitic granite vein with a quartz core cuts a 5 m-wide mafic dyke. This is locality G15 of Coward (1973a) and Dyke C of Dearnley and Dunning (1968, fig. 5). The dyke trends northeast but is highly discordant to the gneissose foliation. Several apophyses also cut the foliation in the adjacent gneisses. Dearnley and Dunning classified the dyke as type-2, partly on the presence of a marginal lineation, which, they argued, signified weak Laxfordian deformation.

At [NF 758 535] a 3 m-wide foliated microdiorite dyke cuts across the gneissose banding and across a 1 m-wide late-Laxfordian pegmatitic vein. Some 12 m to the east the same pegmatitic vein cuts a 0.5 m-wide 'Younger Basic' mafic dyke. Two biotites from the microdiorite dyke have given a K-Ar minimum age of intrusion of 1421 ± 25 Ma (Fettes *et al.,* 1992).

NNW-trending Palaeogene dolerite dykes occur sparsely in the section, for example at [NF 7593 5350] where a 2 m-wide dyke cuts a 20 m-wide pegmatitic vein. These are easily recognized as sharp-edged, undeformed, partly vesicular, dark-grey dolerites with igneous textures. Inland, they weather to a mid-grey and rusty-brown colour.

Baile a' Mbanaich (Balivanich) section

The Baile a' Mhanaich section has similar lithological elements to that at Gearraidh Siar, except for the additional presence of large 'Older Basic' masses in its northern part (Figure 2.17). The Scourian felsic and subsidiary mafic gneisses generally trend north-east to east and dip at 35°–45° to the north-west and north. A prominent complex synformal zone occurs in the northern part of the section, adjacent to the 'Older Basic' bodies (Coward, 1973a). These bodies are generally strongly banded, defined by variations in the amounts of hornblende, plagioclase feldspar, garnet, and more rarely by quartz or clinopyroxene. They are pervasively metamorphosed and recrystallized. Normally, quartz-feldspar pegmatite veins cross-cut the 'Older Basic' bodies, and lenticular and irregular pegmatitic concentrations occur at their margins. This reflects the considerable competency contrast between the felsic gneisses and the mafic bodies. The smaller 'Older Basic' bodies occur as boudinaged sheets and disaggregated masses, typically heavily veined, either by the host gneisses or by pegmatitic felsic material. In places agmatitic textures are common. Ultramafic pods, now coarse hornblendite, also occur sparsely in the gneisses. Metadolerite dykes of the 'Younger Basic' Suite occur throughout the section; in the northern part they exhibit high degrees of Laxfordian reworking, but in the southern part the degree of reworking falls dramatically. The 'Younger Basic' dykes are cut by late-Laxfordian granite veins, which themselves are locally cross-cut by pegmatitic granite veins (e.g. at [NF 7582 5493]). A few NNW-trending Palaeogene dolerite dykes also occur (e.g. at [NF 7562 5435]).

At the eastern end of the section around Calligeo [NF 769 556] there are many scattered small exposures of felsic gneiss with both concordant and tightly folded 'Younger Basic' amphibolitic sheets. West from here, as far as Clachan-garbh [NF 760 553], the gneisses contain some large mafic bodies of the 'Older Basic' Suite. Members of the 'Younger Basic' Suite are also common, again concordant with the gneissose foliation (type-4 deformation *sensu* Dearnley and Dunning, 1968). A good example of a 12 m-wide mafic dyke cut by a late-Laxfordian pegmatitic granite is exposed at [NF 7580 5515]. Here, the host quartzofeldspathic gneiss is fine- to medium-grained, biotite-rich and locally garnetiferous, and may be a metasedimentary enclave. About 100 m to the south a 7 m-thick concordant mafic sheet exhibits a flattened fabric marked by bands of retrogressed garnet. Southwards, on the headland immediately south of Geodha Ban, there is a dramatic reduction in the degree of Laxfordian strain. At [NF 7575 5488], a thin basic dyke may be followed across this transition. South of the transition, the dyke, which is *c.* 30 cm thick, trends roughly north-west to WNW and is markedly

discordant to the gneissose foliation, which strikes roughly ENE and dips to the north. Traced northwards the dyke suddenly swings into concordance and develops a strong planar fabric. Coward (1973a) recorded the transition zone as merely 0.5 m wide. South from this point discordant contacts between the mafic dykes and gneissose foliation are common, for example at [NF 7580 5478], where an 80 cm-wide discordant dyke is cut by two granite veins; at [NF 7563 5435], just south of Eilean Chrossain, where there are 2–10 cm-thick discordant mafic dykelets; and at [NF 7568 5430], where a 13 m-wide 'Younger Basic' dyke is demonstrably discordant. The deformational state of the southern part of the section is broadly comparable with that present in the Gearraidh Siar section to the south. The Baile a' Mhanaich section thus contains a regional-scale boundary between an area of high Laxfordian strain (and degree of reworking) and one of low strain.

Interpretation

Dearnley and Dunning (1968) documented the variable Laxfordian reworking within the Gearraidh Siar and Baile a' Mhanaich sections but suggested that overall the two areas lay in a regional zone of low finite Laxfordian strain. They noted that the Laxfordian reworking within the two areas is concentrated in relatively narrow zones. They also interpreted the granulite-facies assemblages present in the cores of the larger dykes as a product of an early-Laxfordian granulite-facies metamorphism, subsequently partially retrograded by the later pervasive Laxfordian amphibolite-facies metamorphic event, which broadly accompanied the main deformation. Although it was subsequently shown that the granulite-facies mineralogy related to post-consolidation recrystallization in hot country rocks at mid-crustal levels (see Fettes *et al.,* 1992), the main observations of Dearnley and Dunning (1968) laid the grounds for the currently accepted interpretation of the nature of Laxfordian reworking.

Coward *et al.* (1970) noted that, on the regional scale, the areas of low Laxfordian strain, such as Gearraidh Siar and the southern part of the Baile a' Mhanaich section, occupy broad regional F3 antiformal cores that close to the west; the fold axes plunging to the north-west at moderate angles. In contrast, the regional high-strain zones, such as at the northern end of the Baile a' Mhanaich section, are coincident with the axial zones of pinched-in F3 synforms. Coward (1973a) showed that the broad anti-formal F3 hinge zones are relatively rich in basic rock-types and suggested that these areas may have acted as more highly competent blocks compared to those with fewer mafic bodies. He concluded that such a contrast might well have influenced the development of the regional $D3_L$ fold pattern.

Coward (1973a,b) recognized four Laxfordian deformational phases ($D1_L$–$D4_1$), which affected the rocks of the site area and postulated that the first three phases were coaxial. Coward (1973a) argued that the effects of the first deformation phase were relatively minor and the main reworking was accomplished during the $D2_L$ and $D3_L$ phases. He also argued that the pattern of reworking established during $D2_L$ effectively controlled the nature of $D3_L$, with the later strain concentrated in the areas of high $D2_L$ deformation, thus reinforcing the areas of maximum reworking. The majority of the 'Younger Basic' dykes originally trended northwest, an orientation normal to the maximum compression direction during $D1_L$ and $D3_L$. As a result, the deformation during $D1_L$ largely resulted in boudinage of the dykes and the development of flattening fabrics and zones of intense strain parallel to the dyke margins. Only those dykes and apophyses lying at high angles to the maximum compression direction were folded. However, during $D2_L$, the maximum compression direction lay at a low angle to the majority of dykes. This resulted in a broader more-uniform deformational style with relatively open folds whose axial planes trend between north-east and north. A prominent gently to moderately NNW-plunging lineation is widely developed. F2 folds of $D1_L$ boudinaged dykes dominate the outcrop at locality G4 of Coward (1973a, fig. 6, see above). During $D3_L$, as in $D1_L$, the strain was concentrated in localized strongly deformed zones. Coward (1973a) argued that the $D3_L$ strain was focused in $D1_L$ deformation zones, increasing the intensity of deformation in these areas. The $D4_L$ event resulted in open to tight and even isoclinal folds, generally with east–west subvertical axial planes. The folds affected zones already strongly reworked by the Laxfordian $D1_L$–$D3_L$ events as well as previously little-deformed areas.

Coward (1973a) also noted cuspate structures at the margins of the basic dykes and dykelets and the host gneisses. He interpreted them as reflecting the ductility contrast between the rock types during deformation, the pinched-in areas between the cusps pointing to the lithology with the lower ductility. He noted that the relative ductility of the dykes and gneisses changed during Laxfordian reworking, particularly where the rocks suffered amphibolitization or

deformation-induced recrystallization. This resulted in a considerable variation in the ductility contrast between the gneisses, the large dykes and the small dykelets and, in consequence, in the style of the accompanying deformation. Coward cited, for example, virtually undeformed dykes hosted by strongly deformed and more-ductile gneisses, but with amphibolitized apophyses behaving as more-ductile elements within the gneisses. He noted that the concentration of $D1_L$ and $D3_L$ strain in specific zones promoted recrystallization and hence increased ductility in these zones, thus predisposing them to act as the focus of further strain. Hence, the ductility contrasts and the variety of orientations of the 'Younger Basic' dykes were major factors determining the heterogeneous nature of the overall Laxfordian deformation and varied pattern of Laxfordian strain across the section.

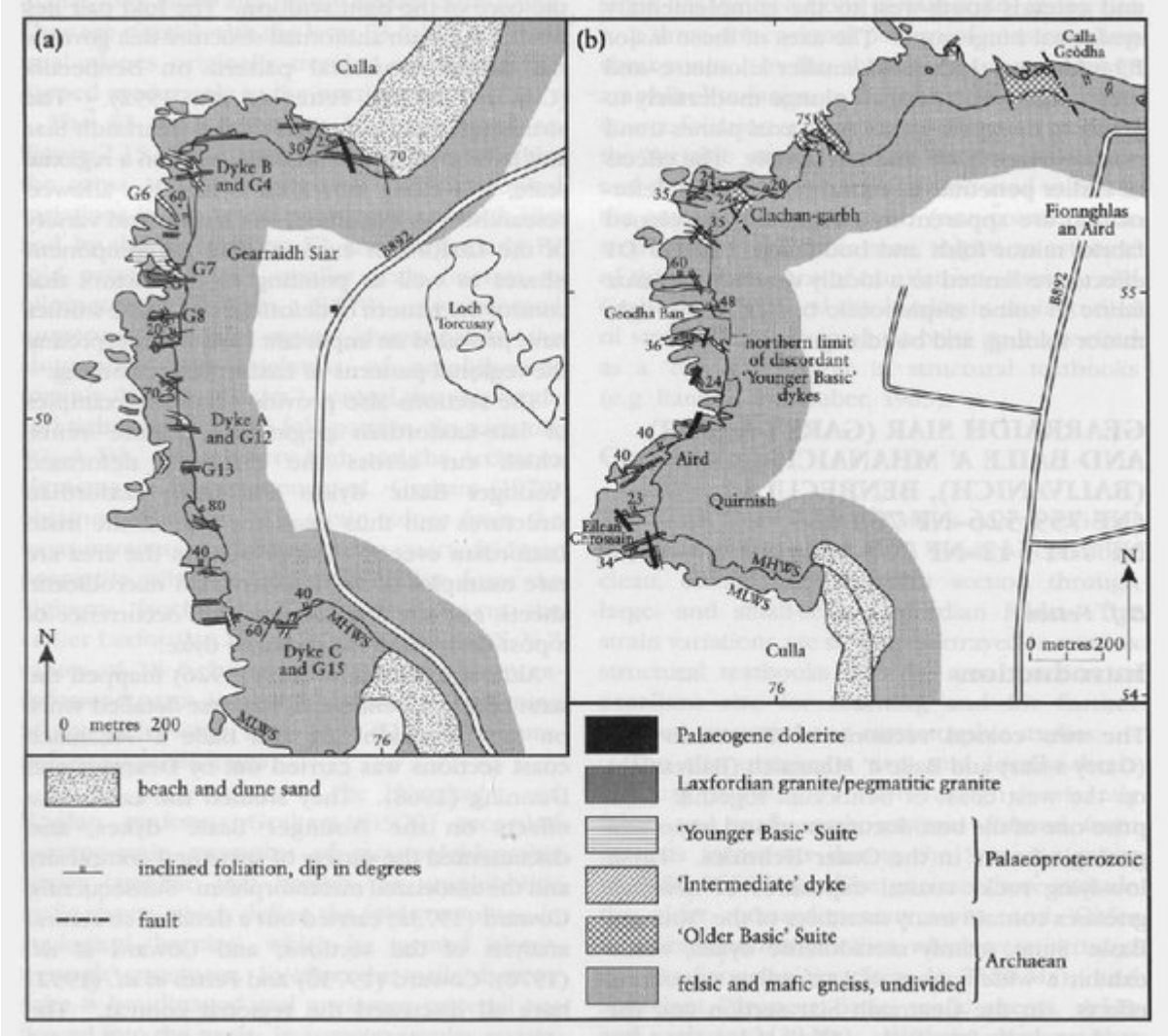
Conclusions

The coastal sections of the Gearraidh Siar to Baile a' Mhanaich GCR site illustrate the detailed nature of Laxfordian reworking of the earlier Archaean-age Scourian gneisses and the meta-dolerite dykes of the Palaeoproterozoic 'Younger Basic' Suite in one of the best-studied areas in the Outer Hebrides. The rocks form an upright antiform-synform fold pair some 4 km in wavelength that lies on the western limb of a larger-scale antiform that covers most of Benbecula. In simple terms, the southern part of the section exhibits a low degree of Laxfordian reworking where the mafic dykes strongly cross-cut the gneissose foliation and largely preserve their early-formed metamorphic fabrics. However, in the north, Laxfordian strains are high and the dykes have been strongly deformed and rotated into concordance with the gneissose foliation. The accompanying recrystallization has also modified their original mineralogy and fabrics in the mafic dykes so that they are now amphibolites. The boundary between the two zones is very sharp, locally occurring over less than a metre. However, internally, local strain variations and detailed deformation patterns have been studied based on the nature of the 'Younger Basic' dykes.

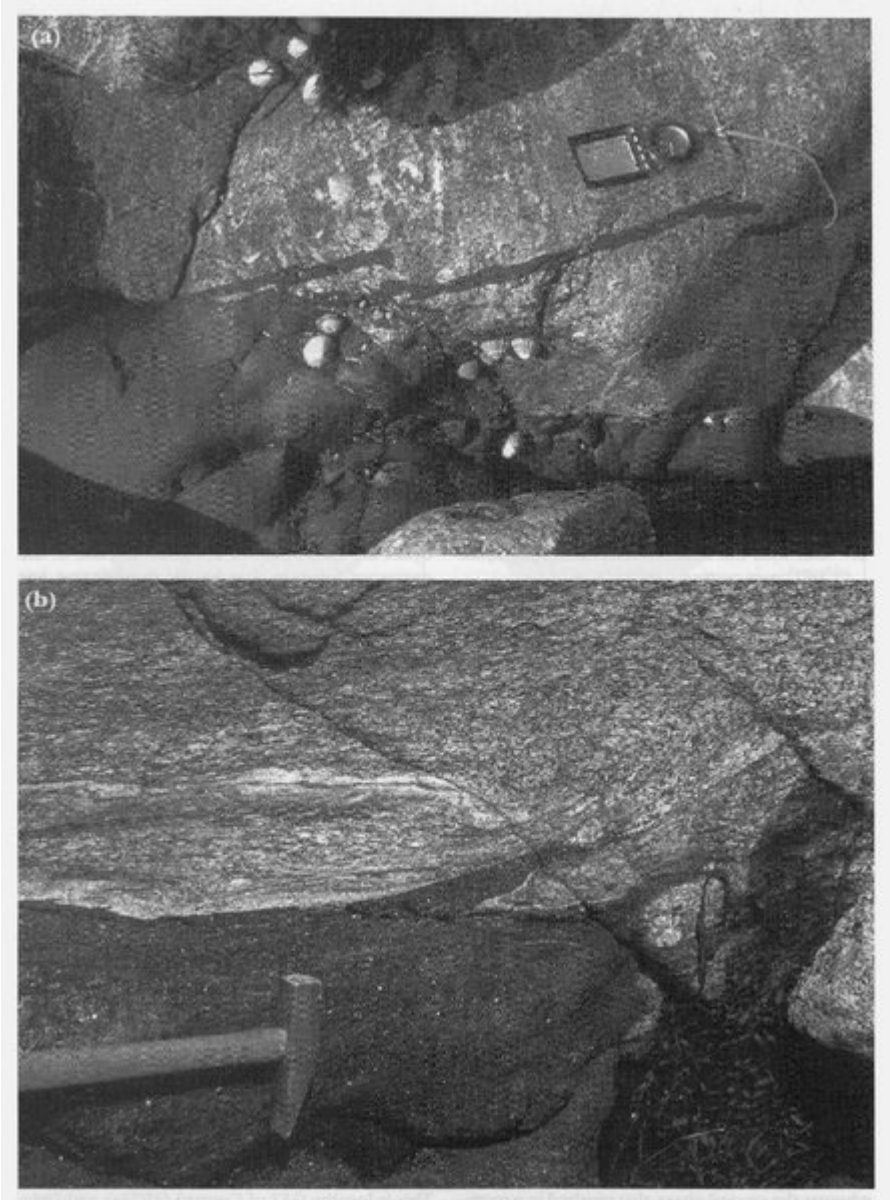
Variations along the section in the style and geometry of deformation allow conclusions to be drawn about the amount of strain, mechanisms of deformation, the ductility contrasts between the different rock-types, and the original orientation of the 'Younger Basic' dykes. The distribution and intensity of the early-Laxfordian deformation was controlled by the relative abundance of the mafic dykes of the 'Younger Basic' Suite. Where the dykes are abundant the overall competence of the rocks was high, and hence structural and metamorphic reworking was concentrated in areas of relatively few basic intrusions. Successive deformational phases were then focused in zones of already highly deformed rocks, thus reinforcing the structural pattern and emphasizing the boundaries between the zones.

This GCR site is of international importance as one of the keys to unlocking the history of the Laxfordian event in the Outer Hebrides. It is an excellent and readily accessible teaching site, both for Hebridean and Lewisian geology, and it demonstrates features commonly found in other ancient crystalline basement rocks.

References



(Figure 2.17) Simplified geological maps of Gearraidh Siar (Garry-a-siar) and Baile a' Mhanaich (Balivanich), Benbecula. Based on Dearnley and Dunning (1968), Coward (1973a) and BGS mapping. (G4, etc. — locality numbers from Coward (1973a); Dyke A, etc. — locality from Dearnley and Dunning (1968); see text for details.)



(Figure 2.18) Gearraidh Siar. (a) Discordant 'Younger Basic' dyke apophyses unaffected by Laxfordian strain. The compass is 18 cm long. (b) Foliated 'Younger Basic' dyke apophyses in an area of moderately strong Laxfordian strain. The hammer head is 14 cm long. (Photos: J.R. Mendum.)