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# Millenderdale

[NX 177 905] and [NX 177 906]

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## Introduction

Mafic dykes rich in hornblende and pyroxene and with a granular texture are seen intruded into foliated gabbro in a series of rocky knolls about 500 m east of Millenderdale Farm. The foliation in the gabbro is generally steeply inclined with a variable, approximately NE–SW trend. The dykes range up to about 3 m across and comprise about 25% of the outcrop; for the most part they cross-cut the gabbro foliation but locally they swing into a parallel orientation. The relationships seen are unique within the Ballantrae Complex and are controversial in terms of its interpretation as an ophiolite assemblage.

The unusual characteristics of the gabbro-dyke assemblage were first described by Teall (in Peach and Horne, 1899) and discussed in some detail by Balsillie (1932) and Bloxam (1955) before its interpretation by Church and Gayer (1973) as representing a part of the sheeted-dyke component seen in an ideal ophiolite sequence. However, that interpretation has not been widely accepted and the problem has been summed up by Bluck (1978a) as follows.

'These outcrops have been interpreted as part of a sheeted dyke complex... but the proportion of dykes to country rocks is considerably lower than is found in other ophiolites, e.g. 90–100% of the sheeted dyke complex is dyke rock at Troodos.... Dyke intrusion in a tectonically active regime where gabbroic rocks were forming and cooling might well fit the model of a spreading ridge, but on the exposed evidence the outcrop is merely gabbro cut by a few dykes... a sheeted dyke complex is either poorly represented or not present at all in the Ballantrae ophiolite.'

Despite the sheeted-dyke controversy the Millenderdale gabbro-dyke assemblage preserves unusual textures and relationships that probably originated at an oceanic spreading ridge. Of particular interest is the granofels texture in the dykes and their apparent lack of chilling against the gabbro.

## Description

Variably foliated and flasered gabbro, cut by mafic dykes, crops out to the east of Millenderdale Farm. The gabbro has been pervasively hornfelsed and in places is altered to a dark, granular-textured mafic rock consisting essentially of plagioclase, pyroxene and amphibole; the dykes were probably doleritic originally but have been almost entirely altered to a similar lithology. The Millenderdale gabbro lies at the NE end of the Southern Serpentinite Belt within the Ballantrae Complex but its relationship with the surrounding ultramafic rock is uncertain since no contacts are exposed; it may form a very large tectonic inclusion. The gabbro is a pale-coloured, medium- to very coarse-grained rock with extremely variable textures ranging from those produced by normal igneous crystallization to those developed during high-temperature metamorphism. That some of the apparent foliation must be a primary feature due to igneous crystallization differentiation is indicated by cryptic variation in pyroxene composition and the presence in some mafic bands of relict olivine.

The dykes are medium grained and dark-grey, locally weathering to a rusty-brown colour. Most have a granular, saccharoidal texture and are not chilled against the host gabbro, indicating that it was still hot at the time of dyke intrusion. The dykes have a very wide range of orientations and no dominant trend is evident; indeed, cross-cutting relationships between dykes are fairly common, perhaps indicating a protracted period of intrusion. Some dykes follow a meandering and anastomosing path and may enclose xenoliths of foliated gabbro, whereas others cut straight across the gabbro foliation (and earlier dykes) with no deviation.

Most dykes that lie parallel to the NE–SW gabbro foliation are foliated themselves, with augen structure developed in places, so that their margins appear gradational with the gabbro. The foliated dykes may then be cut by either of two further dyke varieties. Completely non-foliated dykes generally cross-cut the foliation at a high angle but a considerable range of intersections are seen and some non-foliated dykes lie parallel to the gabbro foliation; in some examples the gabbro foliation bends to become conformable with the dyke margin. A few of the dykes have a very faint internal foliation that bears no simple relationship to the main gabbro fabric; this variety may cut either foliated or non-foliated dykes but may in turn be cut by other non-foliated dykes.

The metamafic texture and composition of the dykes and some zones within the gabbro is a striking feature shared with numerous other doleritic enclaves within the Southern Serpentine Belt. However, only at Millenderdale can the range of intrusive relationships be seen. The metamafic dyke rocks were described as beerbachites by Bloxam (1955) and this name has remained in common usage although beerbachite (*sensu stricto*) is a leucocratic hornfels dominated by plagioclase and containing little or no amphibole. The Millenderdale 'beerbachites' have a fine-grained (0.1–0.3 mm), equidimensional and polygonal granofels texture with only rare porphyroclasts of plagioclase or pyroxene, which results from the almost complete recrystallization of original igneous minerals ((Figure 2.31)a). They are high-grade, thermally metamorphosed rocks. Plagioclase, generally andesine, makes up between about 30% and 60% of the rock accompanied by variable quantities of pyroxene and brown amphibole, the latter forming by alteration of the former. The pyroxene is variously salite, diopside or hypersthene, the amphibole is Ti-rich ferroan pargasite, and olivine is a very rare accessory. A detailed mineralogical and chemical description is given by Jelínek *et al.* (1980). With the development of a foliation in the beerbachite' dykes the distribution of the different minerals becomes increasingly heterogeneous until the development of discrete mafic and leucocratic domains gives the rock a streaky appearance ((Figure 2.31)b).

## Interpretation

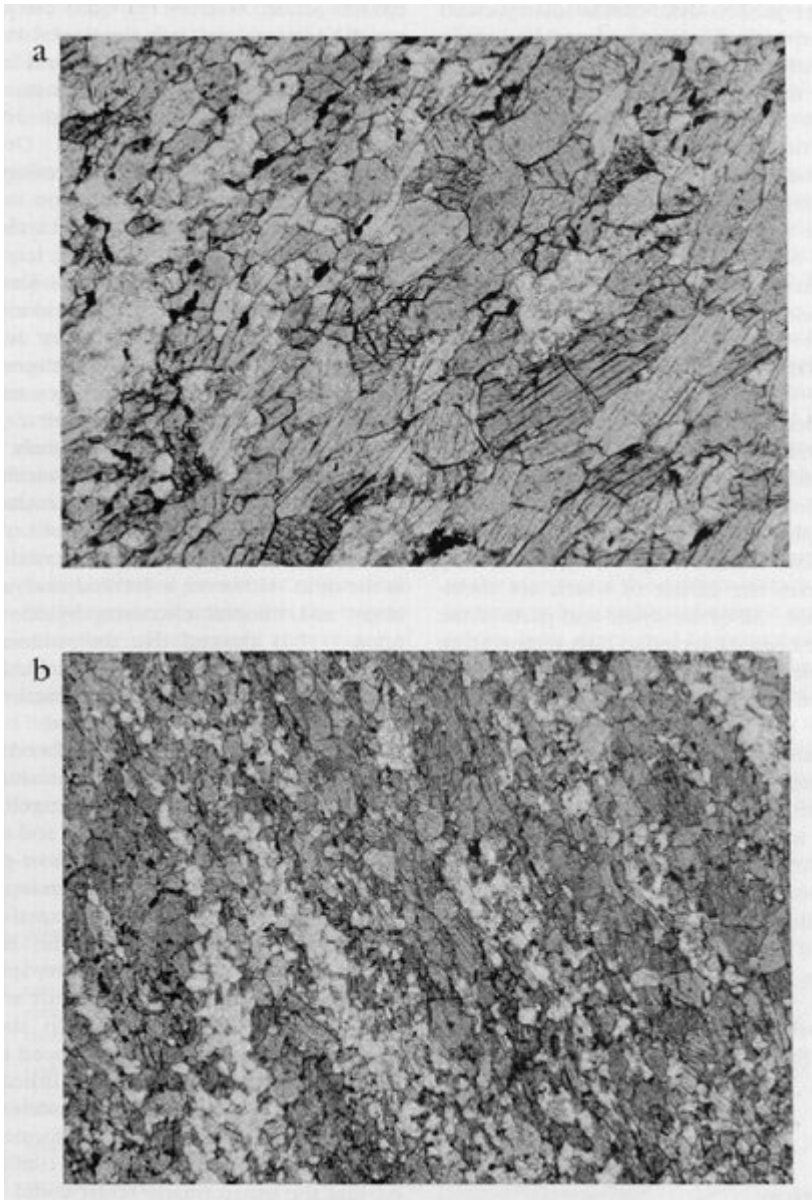
Geological relationships preserved at Millenderdale are unique within the Ballantrae Complex and influence its interpretation as an ophiolite assemblage. It therefore forms an important complement to the GCR sites elsewhere in the Ballantrae district which illustrate other ophiolitic aspects. Unusual igneous and metamorphic features are also seen. The gabbro–dyke relationships require a protracted period of intrusion commencing while the gabbro was still in a relatively hot and plastic state. Development of foliations between phases of intrusion implies that the site of intrusion was tectonically active. The textural evidence indicates that much of the hornblende in the 'beerbachites' has replaced granoblastic pyroxene developed in original doleritic and gabbroic lithologies. This requires a post-magmatic metamorphism at about 900 to 1000°C (Jelínek *et al.*, 1980). Cooling from this event is probably recorded by the K-Ar age of  $487 \pm 8$  Ma obtained from the flaser gabbro by Bluck *et al.* (1980) which is within error of most other indicators of the age of formation of the Ballantrae Complex. Geochemical data presented by Jelínek *et al.* (1980) for the gabbro and beerbachite dykes was interpreted in terms of a genetically related, ocean-floor tholeiite suite with the more evolved gabbros originating as the upper differentiates of a layered assemblage. In this context, although not representing a true sheeted-dyke complex, the Millenderdale gabbro–dyke association uniquely represents an important component of ophiolite 'stratigraphy'. However, data from the gabbro alone was thought by Stone and Smellie (1990) to be more indicative of within-plate, ocean-island magmatism and so the nature of the original intrusive setting remains controversial.

Quite apart from uncertainties over the geo-tectonic setting of intrusion there has also been debate over the circumstances and mechanics of incorporation of the metamafic rocks into the ultramafic belt. Various possibilities have been considered ranging from intrusion into a mass of hot peridotite with subsequent disruption and metamorphism as xenoliths, to metamorphism resulting from repeated intrusion in the same area with the gabbro–dyke blocks incorporated into the serpentinite during its cold, diapiric rise. Currently the most satisfactory explanation is probably the faulted spreading ridge model proposed by Jelínek *et al.* (1980). They envisaged a part of the ridge displaced by transform-fault movement such that spreading and fault movement in opposing directions combined to keep a ridge segment adjacent to the high heat-flow zone. Such an environment would allow both polyphase intrusion and high-temperature metamorphism in a tectonically active region.

## Conclusions

The Millenderdale GCR site contains one of the more enigmatic components of the Ballantrae Complex, the interpretation of which has an important bearing on models for development of the complex as an ophiolite. A banded and foliated gabbro has been repeatedly intruded by doleritic dykes the earlier of which are themselves foliated. All of the dykes and parts of the gabbro have been subjected to high-temperature metamorphic recrystallization and are now granular-textured metamafic rocks ('beerbachites' *sensu lato*) rich in pyroxene and amphibole. The explanation of these phenomena may lie in the development of the gabbro–dyke assemblage at or near an oceanic spreading centre; faulting is invoked to maintain the assemblage in the high heat-flow environment and allow thermal metamorphism. If such an interpretation is correct the Millenderdale rocks uniquely illustrate an aspect of ophiolite lithology not seen elsewhere in the Ballantrae Complex.

## References



(Figure 2.31) Photomicrographs illustrating textures seen in 'beerbachite' dykes near Millenderdale: (a) Polygonal, granoblastic texture developed between feldspar and brown amphibole. Plane polarized light, x40. (Photo: BGS no. PMS469); (b) Development of mafic and leucocratic domains. Plane polarized light, x20. (Photo: BGS no. PMS470.)