Badcall

[NC 145 421]–[NC 157 413]

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Introduction

The Badcall GCR site, near Scourie, forms the southern part of the type locality for the Scourian component of the Central Region of the Lewisian Gneiss Complex (Peach *et al.,* 1907; Sutton and Watson, 1951). The well-preserved, late Archaean granulite-facies gneisses in this area led to the use of the term 'Badcallian' to describe the high-grade metamorphic event responsible for their generation from mainly plutonic igneous rocks (Park, 1970). The area is one of generally low Proterozoic strain and so preserves many early features, important for understanding the pre-granulite-facies evolution of the Lewisian Gneiss Complex. Palaeoproterozoic mafic dykes of the Scourie Dyke Suite cross-cut the gneisses, and Badcall is also part of the type area for defining the dyke suite.

In addition to being the prime example of granulite-facies gneisses in Great Britain, the Badcall GCR site is of international importance for several other reasons. The gneiss complex in the Scourie–Badcall area was mapped by W Gunn for the Geological Survey in 1887 and was one of the earliest to be fully described and understood in terms of its protoliths and general geological history (Peach *et al.,* 1907). Indeed, the maps produced by the early surveyors are still the basis for the published Geological Survey maps. It was also one of the first gneiss complexes to be studied extensively using various isotopic dating techniques (e.g. Holmes *et al.,* 1955; Giletti *et al.,* 1961; Moorbath *et al.,* 1969; Pidgeon and Bowes, 1972). More recently the area has been the subject of renewed isotopic investigations using ion-probe U-Pb techniques in an attempt to establish more accurately the chronology of the protoliths of the gneisses (Friend and Kinny, 1995; Kinny and Friend, 1997). This gneiss complex is one of the most strongly large-ion-lithophile (LIL) element-depleted pieces of lower crust currently known (e.g. Sheraton *et al.,* 1973; Tarney, 1976; Tarney and Weaver, 1987a) and so is a key area for research into the processes of granulite-facies metamorphism and/or the inheritance of chemical characteristics from a source region.

Description

The GCR site covers the south-west part of the large peninsula that culminates to the south in Farhead Point (Figure 3.2). It extends from the coast west of Cnoc an Fhir Bhreige (93 m) to south-east down to the lower rocky point of Rubh a' Bhad Choill. The exposures that best demonstrate relationships and rock types lie in a triangular-shaped, very low-strain area *c.* 1 km west of Upper Badcall, which stretches inland from the small inlet of Geodh' nan Sgadan [NC 146 417] (Figure 3.3). Here, the rocks are cleanly exposed on low crags that rise gently to the north-east to reach *c.* 55 m above OD.

The dominant gneisses are felsic with a tonalitic composition. Typically they are dark grey-brown when fresh, but bleached white where weathered, reflecting their dominant plagioclase feldspar content. On fresh surfaces it is difficult to make out any foliation, lineation or banding, but where weathered the internal structures and mineralogy are more easily discernible. The gneissic banding generally dips 25°–35° to the west and south-west, but around Rubh a' Bhad Choill dips are steeper and more variable. The gneisses preserve extensive orthopyroxene and are equigranular and coarse grained. These characters are very well displayed in the exposures at the car park [NC 154 416] at the end of the road from Upper Badcall.

Typically the felsic gneisses contain rafts and lenses of mafic and ultramafic rocks. One ultramafic body near Upper Badcall is of archaeological significance in that it has been used for the extraction of soapstone. Metasedimentary rocks are also present, typically associated with the rafts of mafic rocks, but form only a minor component of the gneisses. The disparate elements of this complex have all undergone polyphase deformation and high-grade metamorphism, during which cross-cutting leucotonalite ('trondhjemite') sheets were emplaced. Following these events the complex was intruded by numerous discordant mafic dykes of the Scourie Dyke Suite. Subsequent to dyke emplacement, relatively narrow, hydrous shear-zones developed locally, causing variable retrogression to amphibolite-facies assemblages and generation of new textures and fabrics. The shearing and retrogression are the result of the Laxfordian event, which only affected small parts of the high-grade gneisses in the Badcall area (Sutton and Watson, 1951).

Along the coast, tonalitic gneisses are inter-banded on a large scale with plagioclase-rich mafic rocks that show a mineralogical layering and are considered to have originated as layered gabbroic and leucogabbroic rocks. In detail the layering in the gabbroic rocks is cross-cut by the tonalitic gneisses, but within the gabbroic rocks there are distinct enclaves of felsic gneiss that have been interpreted as being representative of older material (Davies, 1975). The strongly foliated tonalitic gneisses also contain many small pods of ultramafic rock, mostly hornblendite and more rarely amphibolite, some of which include clinopyroxene. These pods are interpreted as relict mafic–ultramafic bodies originally intruded by sheets and veins of tonalitic gneiss. Their present form is a result of strain partitioning during the subsequent deformation.

These banded and foliated rocks are cross-cut by distinct sheets of white to pale-grey leucotonalite ('trondhjemite') (e.g. Rollinson and Windley, 1980; Cartwright, 1988), that show mineral assemblages indicative of both granulite- and amphibolite-facies. However, the amphibolite-facies sheets commonly contain blue quartz, suggesting that originally they may have been at granulite facies. In the Badcall area there appear to be two types of leucotonalite: the first forms sharply defined, cross-cutting sheets; the second forms nebulous patches and areas which are clearly derived from the host gneisses as they contain relict, disrupted structures essentially continuous with those in the enclosing rocks. These structures include dismembered fold noses and relict gneissose layering. Cross-cutting relationships suggest that the sharply defined sheets normally postdate the nebulous patches.

Several generations of folds and foliations can be identified within the site. The gneissose enclaves in the gabbroic rocks appear to have an early banded structure (Davies, 1975) and the gabbros themselves appear to have been foliated prior to invasion by the dominant tonalitic rocks (e.g. Cartwright, 1988). These host tonalites then acquired a foliation which was subsequently deformed by tight to isoclinal structures upon which are superimposed the nebulous partial-melting textures. These structures are deformed by open, NW-verging asymmetrical folds, well displayed on a low bluff immediately east of Geodh' nan Sgadan. Because the rocks are essentially not retrogressed, it is probable that all of these fabrics and structures were formed either before, or synchronous with, the granulite-facies metamorphism.

The gneisses at Badcall Bay are cut by numerous, essentially undeformed but variably amphibolitized, mafic to ultramafic dykes, which form part of the Scourie Dyke Suite. The dykes within the GCR site can be divided into four different types: (i) the dominant NW-trending gabbroic to doleritic dykes with prominent sub-ophitic textures; (ii) thin ultramafic veins and veinlets; (iii) narrow E–W-trending dark-green amphibolite dykes; (iv) quartz-bearing, hypersthene dolerites. Within the site crosscutting relationships between the dykes are limited to one instance of a NW-trending dolerite cutting a hypersthene dolerite. The NW-trending doleritic to gabbroic dykes are typified by the thick dyke (in excess of 30 m) on Cnoc an Fhir Bhreige [NC 146 417], in which many internal textural features can be seen.

Amphibolite shear-zones affect the margins of most of the dykes. Progressive development of a shear fabric from an essentially homogeneous starting material is well demonstrated in these shear zones. Within the dykes, the amount of amphibolitization of the mafic minerals decreases progressively away from the shears until, in places, relics of the original igneous pyroxenes are found. Beach (1978) described a Scourie dyke on the coast at [NC 145 415], the northern part of which is undeformed and has a planar contact with the host gneisses. The southern margin, by contrast, has an irregular contact and a strong fabric, defined by orientated hornblende crystals.

At the summit of the small hill [NC 153 413] above Badcall Bay, a Laxfordian shear-zone that runs from Farhead Point to Badcall Point can be seen (Beach, 1978). Close to the summit a Scourie dyke enters the shear zone from the north-west and is deflected along the zone as far as the coast at [NC 157 413]. Within the shear zone, the gneissose banding is roughly vertical and strongly attenuated, and the gneisses have been recrystallized under amphibolite-facies conditions. The continuation of the shear zone can be seen on the south side of Farhead Point at [NC 149 410]. On the northern side of this point, the tonalitic gneisses are deformed into a series of folds with NW-trending axial planes that are in turn deformed by the main shear-zone.

Interpretation

Because of the low post-dyke strain and generally slight subsequent hydrous, retrogressive metamorphism, the Badcall Bay-Scourie area represents one of the best areas in which to study the protoliths and the mutual relationships of some of the components of the Lewisian Gneiss Complex. The Badcall GCR site also provides an opportunity to address the possible effects of granulite-facies metamorphism upon the different gneiss types. Later cross-cutting dykes and minor amphibolite-facies metamorphism complete the geological history.

The old debates regarding the origin of the grey gneisses have been resolved, in that it is now accepted that they represent plutonic, calc-alkaline igneous rocks (e.g. Tarney, 1976) rather than partially to totally melted sedimentary rocks (e.g. Sutton and Watson, 1951) or felsic volcanic rocks (e.g. Pidgeon and Bowes, 1972). Undoubted metasedimentary rocks are present, but they are quite distinct from the orthogneisses and represent only a very minor component of the gneiss complex. Partial melting has occurred in some parts of the tonalitic gneisses and was probably related to dehydration reactions leading to granulite-facies assemblages.

The first direct dating of the tonalitic gneiss protoliths in the Badcall area, using U-Pb single zircon methods, has given an age of *c.* 2960 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997). Previously, the best estimate of the age of the grey gneisses was that of Whitehouse (1989) who used Sm-Nd whole-rock methods to obtain model Nd ages of *c.* 2930 Ma. Earlier age estimates of *c.* 2950 Ma (e.g. Hamilton *et al.,* 1979) were not based upon cogenetic suites of rocks and have now been discounted.

The timing of the granulite-facies metamorphic event is still rather enigmatic. Bulk zircons from rocks at the Badcall road end suggested a U-Pb age of 2660–2700 Ma (Pidgeon and Bowes, 1972) and whole-rock U-Pb isotopic data supported this, giving a *c.* 2700 Ma age (e.g. Chapman and Moorbath, 1977). Most recently, Corfu *et al.* (1994), using modern U-Pb geochronological techniques, have also recognized a high-grade metamorphic event at 2710 Ma or older. However, information from single zircon U-Pb systems from unretrogressed granulite-facies samples has indicated another major event at *c.* 2500 Ma (Corfu *et al.,* 1994; Friend and Kinny, 1995). This proposed metamorphic event correlates well with a similar age obtained by a combined mineral and whole-rock Sm-Nd study of granulite-facies rocks a short distance to the north at Scourie (Humphries and Cliff, 1982). This raises the problem that there appear to have been two or more granulite-facies metamorphic events. The younger event apparently occurred at a time hitherto considered to represent the start of the Inverian event, yet it seems responsible for formation of the granulite-facies assemblages at Badcall, the type area for the Badcallian event. Recently, Kinny *et al.* (2005) reclassified the Badcallian as a *c.* 2490 Ma granulite-facies event that is found only in the Central Region.

There has also been debate over the age and origin of the mafic-ultramafic rocks in the Badcall area, and those to the north on Scourie Mor. Plausibly, they could have two possible origins: either representing dismembered layered bodies (e.g. Sills *et al.,* 1982); or as relict fragments of the mafic source material from which the tonalitic protoliths were derived. Given the preserved cross-cutting relationships it would seem that, in common with other parts of the North Atlantic craton, the mafic-ultramafic rocks are an older component into which the gneiss protoliths were emplaced.

Geochemically the Badcall gneisses represent one of the most LIL-element-depleted gneiss complexes known, and it is important to understand how this came about. The main debate centres on whether the depletion was the result of granulite-facies metamorphism, or whether it reflects a chemical control exerted by the source regions of the different lithologies. Further debate concerns the origin of the leucotonalite sheets; they may have formed by in-situ anatexis of the gneisses under granulite-facies conditions (e.g. Cartwright, 1988), or their emplacement may have largely pre-dated the granulite-facies event (Rollinson and Windley, 1980). One possible explanation, which could link the two different debates, is that the depletion in the tonalitic gneisses resulted from the removal of small amounts of melt during granulite-facies metamorphism (e.g. Pride and Muecke, 1980, 1982; Cartwright, 1988). Alternatively, Rollinson (1994) used new geochemical data to suggest that the leucotonalite sheets are the result of partial melting of lower crustal mafic material. Close examination of the field relationships could be interpreted to indicate that the nebulous leucotonalite patches are the products of in-situ anatexis, whereas the sharply defined sheets represent aggregated and migrated melt of external origin.

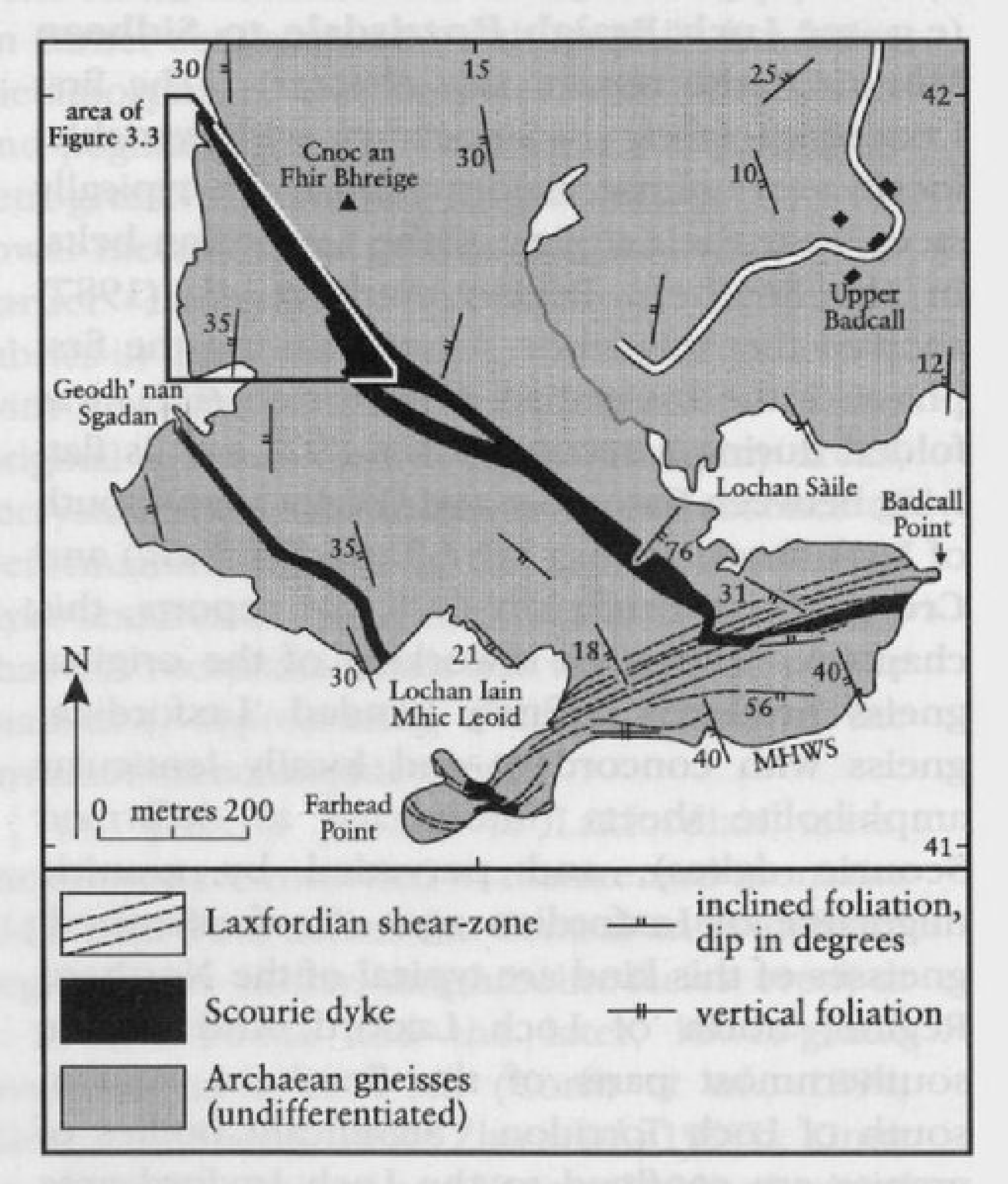
Following the *c.* 2500 Ma granulite-facies event, Scourie dykes were intruded at Badcall at around 2400 Ma and possibly also in a further event at about 2000 Ma (Heaman and Tarney, 1989). The shear zones that affect the dykes are presumed to be of Laxfordian age; feldspar and muscovite from pegmatites that cut the dykes and shears have yielded Rb-Sr mineral ages of 1600–1500 Ma (Giletti *et al.,* 1961).

Conclusions

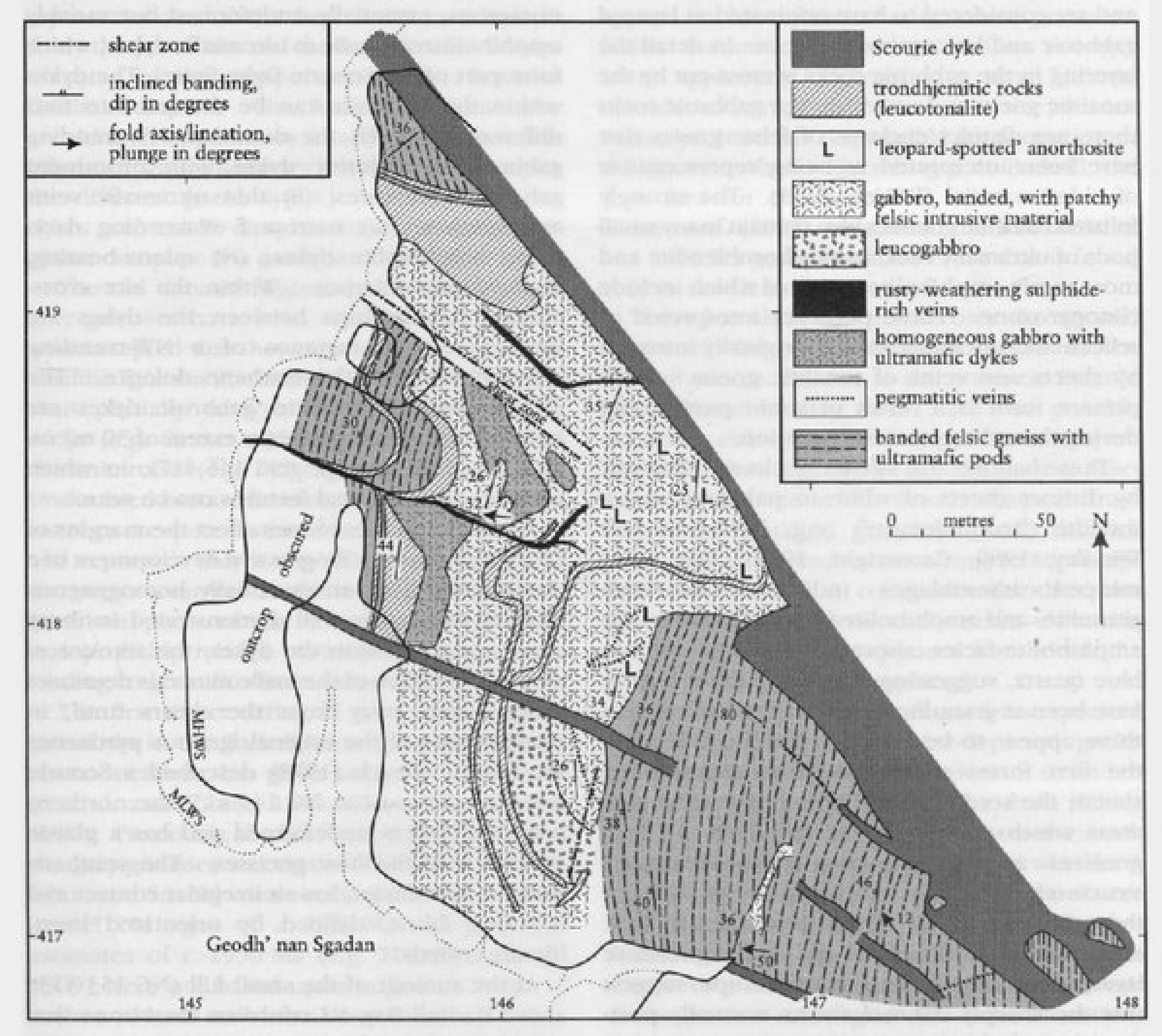
The Badcall GCR site demonstrates some of the best-preserved granulite-facies rocks on the mainland of Britain. The area has been little affected by subsequent hydrous retrogressive metamorphism and has escaped most of the later Proterozoic Laxfordian deformation. Thus, it affords one of the best locations for examination of the early stages of evolution of the Lewisian Gneiss Complex. Several different episodes of pre- or syn-granulite-facies deformation, resulting in the formation of different foliations and folds, can be recognized. Because of the low-strain, textures associated with granulite-facies metamorphism are preserved, including patchy areas of partial melting in the host gneisses.

There are particularly well-displayed relationships between the rock units, which allow the relative ages of different events to be established. The oldest rocks are enclaves of felsic gneiss contained within layered gabbroic material. The gabbros were intruded by the main tonalitic phase around 2960 Ma. This igneous complex was then subjected to granulite-facies metamorphism, possibly in two separate events at around 2700 Ma and 2500 Ma. Post-granulite-facies mafic dykes, part of the Scourie Dyke Suite, cross-cut the structures in the gneisses. Four different lithological types of dyke can be recognized, the most common of which are metadolerites. Subsequent to the intrusion of these dykes there is evidence of restricted amphibolite-facies metamorphism and the progressive development of hydrous shear-zones and associated fabrics within the dykes. The site is of international significance as it not only exposes the earliest features of the Lewisian Gneiss Complex, but is also historically important for lithological, geochemical and geochronological investigations of basement gneiss complexes.

References



(Figure 3.2) Sketch map of the Badcall area, Scourie, showing the major Scourie dykes and later shear-zones. Based on the Geological Survey 1:10 560 Sheet Sutherland 39 (1912), and Beach (1978).



(Figure 3.3) Map of the coastal area immediately north of Geodh' nan Sgadan, showing the distribution of the different types of gneisses and the position of some of the later cross-cutting leucotonalite (trondhjemitic) sheets and Scourie dykes. After Rollinson and Windley (1980).