GARABAL HILL TO LOCHAN STRATH DUBH-UISGE

W. E. Stephens

OS Grid Reference: NN304177–NN282158

Introduction

The Garabal Hill–Glen Fyne igneous complex is well known worldwide from the pioneering study of Nockolds (1941). It is also celebrated for its wide and continuous range of rock types from peridotite to granite. The contribution of Nockolds, apart from publishing one of the first detailed geochemical studies of a plutonic complex, was to explain the whole sequence of rocks in terms of ‘crystallization differentiation' of a pyroxene-mica diorite parental magma. This process generated basic and ultrabasic cumulate rocks and more acid differentiates along a liquid line of descent, essentially the same process as that now known as ‘fractional crystallization'. This essentially closed system model for the petrogenesis of such complexes has been widely applied. Nockolds' paper influenced most studies of compositional diversity in granitic complexes worldwide for three subsequent decades and is still often cited as a classic study (e.g. Atherton, 1993).

The complex, which is a member of the South of Scotland Suite, was emplaced into Dalradian metasedimentary rocks of the Southern Highland Group at about 429 Ma. Compositional diversity is the most important feature of this complex, with four bodies of peridotite located within several varieties of diorite and gabbro. Peridotites are virtually absent from late Caledonian granitic complexes elsewhere and their presence is important in understanding the petrogenesis of the more basic members of such complexes. The main mass of granodiorite is porphyritic, although megacrysts are lacking in the east. Appinitic rocks are closely associated with the granodiorites, and large numbers of other appinitic bodies are known from this area (Anderson, 1935a; Anderson and Tyrell, 1937).

The first account of the complex was published by Dakyns and Teall (1892) who were struck by the petrological variety, which they attributed to the differentiation at depth of a single parental magma. This was a rather advanced view for its day. This was followed by the Geological Survey memoirs (Gunn *et al*., 1897; Hill, 1905), and a detailed study of the ultramafic and basic varieties of the complex (Wyllie and Scott, 1913). In the following eight decades or so, the only paper specifically to address the origin of this complex with new data was that of Nockolds (1941). Although Nockolds' model is often cited, it should be viewed with some caution in the light of modern studies. Most late Caledonian plutons that have been studied in any geochemical detail show evidence of significant open-system behaviour (e.g. Halliday *et al*., 1980) and a compilation of the available but rather meagre Sr isotopic data for Garabal Hill (Summerhayes, 1966; Harmon and Halliday, 1980) suggests that the granodiorite probably has a different origin to the rest of the complex.

Description

Garabal Hill is situated to the north of Loch Lomond and gives its name to the more petrologically variable part of the complex; the larger and more homogeneous mass of granodiorite occupies the high ground to the SE of Glen Fyne (Figure 8.28). The more basic rocks of the complex are separated from the main plutonic mass by the Garabal Fault, which in turn is truncated by the Glen Fyne Fault. The exposed area of the entire complex is 32 km^2.

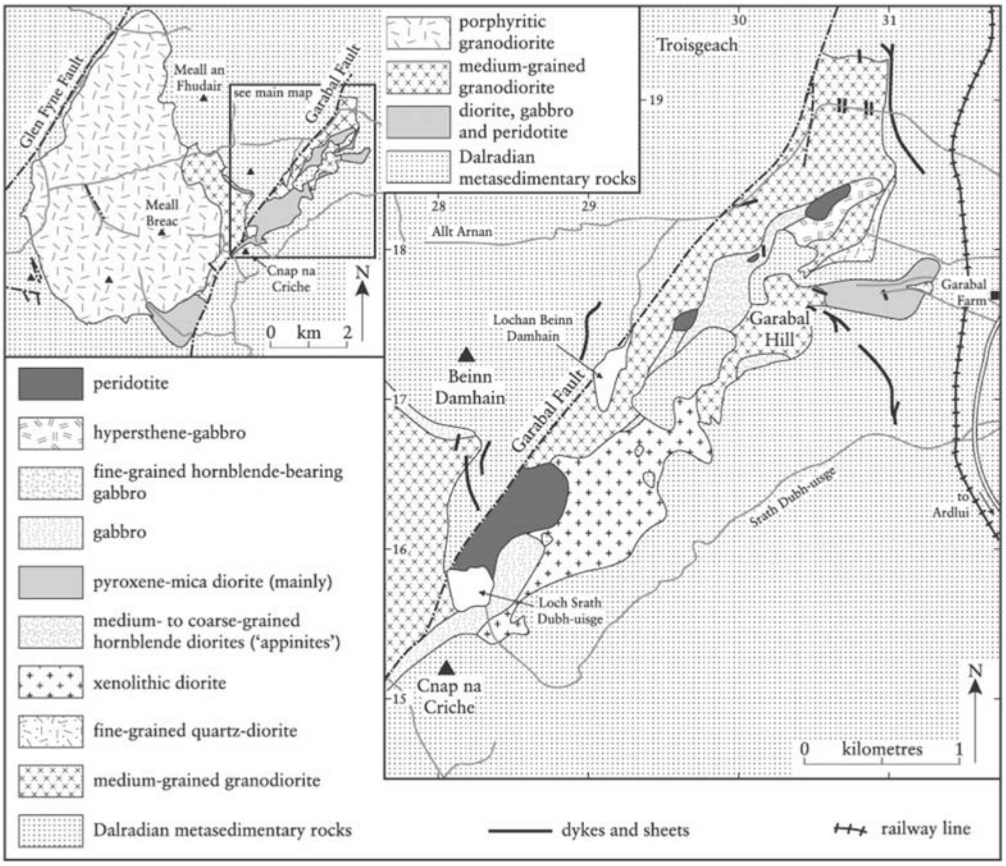

Figure 8.28: Map of the Garabal Hill–Glen Fyne igneous complex (after Nockolds, 1941).

The wide range of petrology has been adequately described in the papers cited above, but a summary is necessary here to convey the key feature of extreme petrological variation. The descriptions are based on Nockolds (1941) supplemented with modal and electron microprobe data from Mahmood (1986).

Ultramafic rocks crop out as discrete bodies, 100 m to 1 km across (Figure8.28), and include peridotites, pyroxenites and hornblendites. The fresh ultramafic rock is typically a black peridotite (wehrlite) with approximately equal amounts of olivine (about Fo_{80}) and clinopyroxene (augite–diopside), although the content of clinopyroxene can drop to about one-third. The peridotite is often at least partly serpentinized (Figure8.29). Other types of peridotite, including dunite, lherzolite and plagioclase-bearing varieties are also present, usually showing internal contacts with the main peridotite. In the pyroxenites, olivine is typically absent and orthopyroxene becomes more important, although clinopyroxene is still the principal mineral. Clinopyroxene is commonly replaced by brown amphibole, and in extreme cases the rock has been described as a hornblendite by Nockolds.

Figure 8.29: Serpentinized peridotites (wehrlite) at Lochan Strath Dubh-uisge, Garabal Hill–Glen Fyne igneous complex. (Photo: W.E. Stephens.)

Gabbroic rocks are especially important as they are the most basic component of the pluton with clear evidence of non-cumulate magmatic textures, and are thus potential candidates for a parental magma. The largest outcrop of gabbro stretches for about 1.4 km around Lochan Srath Dubh-uisge and, after being cut out for about a kilometre by granodiorite, also forms quite a large mass at the southern end of the complex (Figure8.28). The typical gabbro has abundant clinopyroxene, partly or largely replaced by actinolitic amphibole or brown hornblende. Hypersthene-bearing varieties are known; biotite is present in the gabbros close to late veins of granodiorite.

Diorites were the favoured parental magma of Nockolds, specifically the pyroxene-mica diorite. This latter rock, found in the east of the complex (Figure8.28), contains more clinopyroxene (about 17%) than orthopyroxene (7%), biotite (about 17%), and pseudomorphs after olivine. About half of the rock is plagioclase of about An_{41} composition. As is typical in this complex, clinopyroxene is commonly replaced by amphibole. Hornblende-rich diorites are also present in the eastern part of the complex, and show marked variations in grain size which Nockolds described as coarse appinitic diorite (coarse-grained), to medium appinitic diorite (medium grained) to fine-grained quartz diorite. There is some debate as to whether the amphibole is primary or secondary in these rocks; although many amphibole crystals are idiomorphic in form and would appear to be primary, others clearly show evidence of replacement. Some diorites are also remarkably rich in xenoliths (Nockolds' xenolithic diorite) which appear to be dominantly of basic igneous rocks.

The final intrusive phases consist of granodiorites. The medium-grained granodiorite is earlier than the porphyritic granodiorite, occurring both on the eastern margin of the main Glen Fyne intrusion and as a separate strip SE of the Garabal Fault. This facies contains hornblende and biotite with quartz, K-feldspar and plagioclase. A major feature is the abundance of xenocrysts of plagioclase, augite and amphibole, making it a very heterogeneous rock. Nockolds interpreted these xenocrysts as ‘earlier igneous material' which he believed to have had a significantly modifying effect on the overall composition. The main porphyritic ‘granodiorite' is a rather more homogeneous biotite granite, with a porphyritic character imparted by megacrysts of alkali feldspar.

Interpretation

Age relationships within the complex have been established by cross-cutting internal contacts, veins of late granodiorite, and xenolithic inclusions. It is clear on these criteria that the ultramafic rocks are early and are cut by the gabbros, which in turn provide xenoliths for the diorites, which are intruded by the granodiorites. Thus the age sequence appears closely to match the order of increasing acidity. The age of emplacement is also well constrained. Rogers and Dunning (1991) found the U-Pb age on an appinitic diorite to be 429 ± 2 Ma (zircon) and 422 ± 3 Ma (titanite). Combining these data with the Rb-Sr biotite-whole rock age of 406 ± 4 Ma (Summerhayes, 1966), it may be concluded that emplacement took place at about 429 Ma, followed by cooling through 600°C at 422 Ma, down to about 300°C at 406 Ma.

The geochemical study of the complex by Nockolds revealed a gradual change in composition from the peridotites (as low as 42% SiO_2) to the granites at 68% SiO_2, which led to his classic interpretation of closed system differentiation. Nockolds reasoned that rocks more basic than his proposed parental pyroxene-mica diorite magma must be the products of mineral accumulation, as evidenced by the abundant mafic minerals in the appinitic diorites, the gabbros and especially in the peridotites. The differentiated magmas went on to evolve into the granodiorites. Mahmood (1986) tested this hypothesis with numerical models of the compositions and found a gabbro parental magma to provide a better model for the observed compositions, although no simple closed-system fractionation model tested was capable of generating the granodiorite compositions. Mahmood also provided new trace element data that contrasted with the major oxides in not describing single smooth linear trends. The trace element data are therefore difficult to reconcile with a simple liquid line of descent, although they do provide evidence of cumulate processes (exceptional Ni- and Cr-enrichments in the peridotites). This evidence is not completely unambiguous, but it is likely that the granodiorites evolved quite separately from the main gabbro–diorite series. The data also suggest that the gabbros and diorites represent quite distinct magma series.

One of the very early applications of the Rb-Sr isotope technique to the study of granite plutons was performed on Garabal Hill (Summerhayes, 1966). By modern standards the precision of the age and initial ratio calculations is rather poor. Nevertheless the range of initial ratios measured is so large as to be significant in terms of the petrogenesis. Summerhayes found that the ($^{87}Sr/^{86}Sr$) initial values of all the uncontaminated components of the complex are the same within error, around 0.705. He noted, however, that several samples of the medium-grained granodiorite have higher values of this ratio (about 0.710) and concluded that these had the same parental magma as the main complex but were contaminated by local Dalradian metasedimentary rocks. This is consistent with the abundance of included xenoliths, as noted by Nockolds (1941). These are important petrogenetic conclusions but must be viewed in the context of modern Sr isotope studies in which variations of an order of magnitude smaller are taken to have petrogenetic significance. A higher precision isotopic study of a single sample from the medium-grained granodiorite, the area of contaminated granodiorites studied by Summerhayes, gave a ($^{87}Sr/^{86}Sr$)initial value of 0.7074 and $\delta^{18}O$ of 10.4 ‰ (Harmon and Halliday, 1980).

Isotope ratios are now used routinely to test whether complexes such as Garabal Hill evolved in a closed system (i.e. no addition of exotic material to the parental magma) or in an open system, in which case the contaminant is usually evident in changes to the isotope ratios. Whereas the old data of Summerhayes do not permit a rigorous test, the newer Sr and O isotope data are strong indicators of a significant involvement of evolved crustal material in the genesis of the granodiorite magmas, while the remainder of the complex appears to have the relatively primitive signature of young basic crust and/or mantle sources.

The trace element and limited isotopic data currently available do suggest therefore that

Nockolds' model is inappropriate for this complex. However, there are other plutons (e.g. the Boggy Plain pluton of SE Australia, Wyborn *et al.*, 1987) where melts can be clearly shown to undergo crystal–liquid fractionation in the manner envisaged in 1941 for Garabal Hill–Glen Fyne, so that the wider conclusions of Nockolds' study remain valid to the present day.

In a further study, Garabal Hill was chosen as a good example in which to investigate the disappearance of Ca-poor pyroxenes from crystallizing calc-alkaline magmas (Cawthorn, 1976). Cawthorn concluded from petrographical evidence that the replacement of the assemblage calcic pyroxene–calcium-poor pyroxene–plagioclase by amphibole–plagioclase in the more evolved rocks is explicable in terms of increasing fugacity of water, during differentiation of a basic magma.

Conclusions

The Garabal Hill–Glen Fyne complex shows the greatest variety of 'granitic' rocks in any one complex in the Caledonian of the British Isles. An orderly sequence of intrusion from basic to acid magmas can be demonstrated and the complex is an important site for the testing and developing of modern ideas on the origins of granitic rocks.

A model in which a single dioritic parental magma underwent differentiation by the removal of crystals as they formed, causing the residual magma to change composition along a 'liquid line of descent' was proposed by Nockolds in 1941. This very detailed study was widely acclaimed and the ideas were applied to other plutons worldwide. The influence of the study has undoubtedly been seminal, but critical examination of new geochemical and isotopic data from the Garabal Hill–Glen Fyne complex suggests that the model is oversimplified and that here, more than one different magma and modification by crustal contamination may have been involved. However, the original concept, which subsequently became known as 'fractional crystallization', has been shown to be valid for other plutons elsewhere in the world.

Reference list

Anderson, J. G. C. (1935a) The Arrochar intrusive complex. *Geological Magazine*, **72**, 263–83.
Anderson, J. G. C. and Tyrell, G. W. (1937) Xenolithic minor intrusions in the Loch Lomond District. *Transactions of the Geological Society of Glasgow*, **19**, 373–84.
Atherton, M. P. (1993) Granite magmatism. *Journal of the Geological Society of London*, **150**, 1009–23.
Cawthorn, R. G. (1976) Calcium-poor pyroxene reaction relations in calc-alkaline magmas. *American Mineralogist*, **61**, 907–12.
Dakyns, I. and Teall, J. J. H. (1892) On plutonic rocks of Garabal Hill and Meall Breac. *Quarterly Journal of the Geological Society of London*, **48**, 104–21.
Gunn, W., Clough, C. T. and Hill, J. B. (1897) The geology of Cowal. *Memoir of the Geological Survey of Great Britain*, Sheet 29 (Scotland).
Halliday, A. N., Stephens, W. E. and Harmon, R. S. (1980) Rb-Sr and O isotopic relationships in 3 zoned Caledonian granitic plutons, Southern Uplands, Scotland: evidence for varied sources and hybridisation of magmas. *Journal of the Geological Society of London*, **137**, 329–48.
Harmon, R. S. and Halliday, A. N. (1980) Oxygen and strontium isotope relationships in the British late Caledonian granites. *Nature*, **283**, 21–5.
Hill, J. B. (1905) The geology of Mid-Argyll. *Memoir of the Geological Survey of Great Britain*, Sheet 37 (Scotland).
Mahmood, L. A. (1986) Mineralogy, petrology and geochemistry of some zoned dioritic complexes in Scotland. Unpublished PhD thesis, University of St Andrews.
Nockolds, S. R. (1941) The Garabal Hill–Glen Fyne Igneous Complex. *Quarterly Journal of the Geological Society of London*, **96**, 451–511.
Rogers, G. and Dunning, G. R. (1991) Geochronology of appinitic and related granitic magmatism in the W Highlands of Scotland: constraints on the timing of transcurrent fault movement. *Journal of the Geological Society of London*, **148**, 17–27.
Summerhayes, C. P. (1966) A geochronological and strontium isotope study of the Garabal Hill–Glen Fyne igneous complex, Scotland. *Geological Magazine*, **103**, 153–65.
Wyborn, D., Turner, B. S. and Chappell, B. W. (1987) The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt.

Australian Journal of Earth Sciences, **34**, 21–43.
Wyllie, B. K. N. and Scott, A. (1913) The plutonic rocks of Garabal Hill.*Geological Magazine*, **50**, 499–508, 536–45.