Caledonian Igneous Rocks of Great Britain

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Chapter 3

Mid-Ordovician intrusions of the North-east Grampian Highlands of Scotland

INTRODUCTION

W. J. Wadsworth and D. Stephenson

The Caledonian Orogeny in the Grampian Highlands reached a climax during the mid-Ordovician, with the formation of major folds and the peak of the Barrovian regional metamorphism (the Grampian Event). At this time the region formed the continental margin of Laurentia and the closure of the Iapetus Ocean was well underway. The precise reason for the timing of the orogenic climax is not clear; final closure of the ocean, with continent–continent collision and suturing on the southern margin of Laurentia, did not occur until the late Silurian, although Soper and Hutton (1984) suggested that westward subduction of Baltica beneath the eastern margin may have occured in the Ordovician. From evidence in Ireland, Dewey and Shackleton (1984) and Ryan and Dewey (1991) have suggested that the climax arises from the collision of the Laurentian margin with an island-arc complex related to a southward-dipping intra-ocean subduction zone. Given the evidence for the obduction of early Ordovician oceanic and island-arc material at Ballantrae, the Highland Border and Shetland (see Chapter 2), an extension of this model to include the Grampian Highlands seems plausible.

Large intrusions of tholeiitic basic and ultramafic rock in the NE Grampian Highlands are believed to have been emplaced into the Dalradian metasedimentary succession at about the same time as, or shortly after, the regional metamorphism reached its climax. Until recently this magmatism was believed to have occurred at around 490 Ma ago, but more precise U-Pb zircon age determinations now suggest 470 Ma (Rogers *et al.,* 1994). The basic intrusions are closely associated spatially with the Buchan-style (high temperature/low pressure) metamorphism and with migmatites and S-type granites in the NE Grampian area, also dated at around 470 Ma. The generation and upward migration of substantial volumes of basic magma clearly implies a regime of high heat flow. Whether the emplacement of large bodies of basic magma was directly responsible for the crustal melting that produced the granites and for the Buchan metamorphism, or whether these are all a general effect of the high heat flow, is still a matter of debate. However, the tholeiitic nature of the basic magmatism and the need to create space for its emplacement as large tabular intrusions, strongly suggests that all of this occurred in an extensional tectonic setting. This means that a period of crustal extension, triggering a major thermal perturbation, must have occurred immediately following the major crustal shortening. Although the effects of this extension were widespread in the NE Grampians, with voluminous magma generation, the event must have been short-lived, since the intrusions were affected by the subsequent D3 compressional deformation while they were still hot (see below). The tholeiitic magmatism and the implied short-lived crustal extension are unique to the NE of the Grampian Terrane; Caledonian tholeiitic intrusions occur nowhere else in the British or Irish sectors of the Laurentian continental margin.

The basic intrusions were divided by Read (1919) into 'Older' and 'Younger' groups, on the basis that the principal phase of folding and metamorphism intervened between the two magmatic events. This distinction has subsequently been shown to be too simple, and it is now clear that the 'Younger Basic' intrusions have been considerably modified by later Caledonian orogenic activity. This has involved large-scale folding and disruption of the original igneous bodies during the regional D3 deformation phase. Much of this disruption is associated with major shear zones (Ashcroft *et al.,* 1984; Fettes *et al.,* 1991) and considerable movement on these zones is indicated in places by contrasts in thermal history (Beddoe-Stephens, 1990), disruption of Dalradian stratigraphy and the removal of thermal aureoles from the margins of some basic intrusions. The shearing has resulted in substantial retrograde metamorphism, converting the peridotites and gabbros into serpentinites and amphibolites respectively (Mongkoltip and Ashworth, 1986). There has also been considerable deformation, resulting in the formation of schistose metagabbros and mylonites (see the Balmedie Quarry GCR site report). As a result, some of the 'Younger Basic' rocks have acquired characteristics previously regarded as hallmarks of the 'Older Basic' rocks. Careful reinvestigation of the apparently 'Older' mafic bodies has revealed that many of these have relict primary features linking them to the 'Younger Basic' intrusions. This is especially the case along the Portsoy Lineament (Figure 3.1), which effectively marks the western margin of the 'Younger Basic' province (Fettes *et al.,*

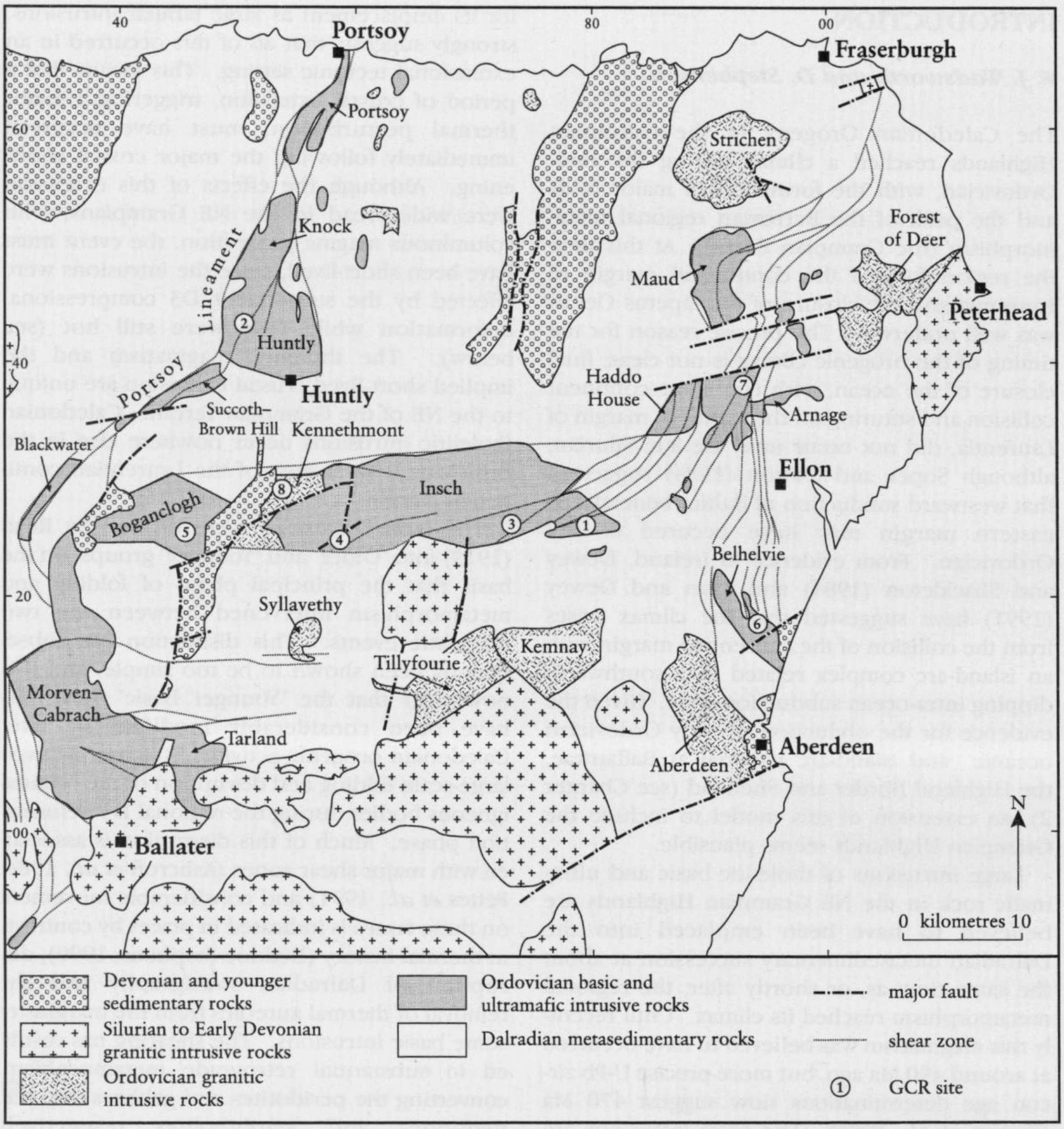

Figure 3.1 Location of basic intrusions and late Caledonian granitic intrusions in the NE Grampian Highlands, modified after Ashcroft *et al*. (1984) by Gould (1997). GCR sites: 1, Hill of Barra; 2, Bin Quarry; 3, Pitscurry and Legatesden quarries; 4, Hill of Johnston; 5, Hill of Craigdearg; 6, Balmedie Quarry; 7, Towie Wood; 8, Craig Hall.

1991). Here, for example, the Blackwater intrusion, which has been thoroughly deformed and metamorphosed, is now thought to be part of the 'Younger Basic' suite (Fettes and Munro, 1989). On the other hand, the nearby Succoth–Brown Hill mafic complex may well be a genuinely 'Older Basic' intrusion, and has more calc-alkaline, arc-like geochemical and mineralogical features (Gunn *et al*., 1996). Other evidence that Read's original distinction is still relevant, although based on different criteria now, is discussed elsewhere in this chapter (see the Hill of Creagdearg GCR site report).

The precise nature of the 'Younger Basic' intrusive event is not known, because of the subsequent tectonic modifications, but Read (1923) suggested the formation of a large sheet-like body initially, and this view has generally been

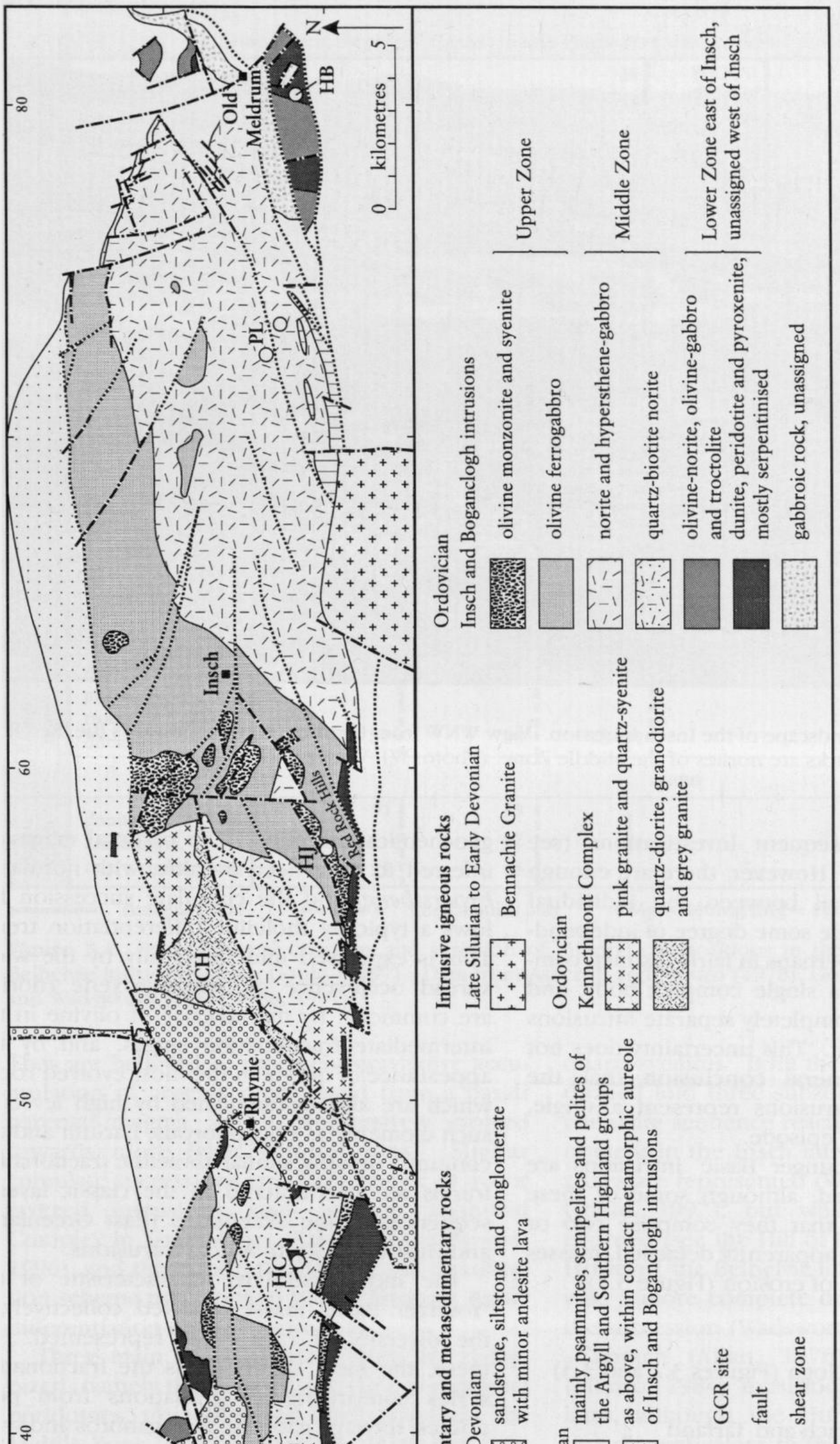

Figure 3.2 Map of the Insch, Boganclogh and Kennethmont intrusions, adapted from Gould (1997). GCR sites: CH Craig Hall; HB Hill of Barra; HC Hill of Craigdearg; HJ Hill of Johnston; PL Pitscurry and Legatesden quarries.

Figure 3.3 Typical landscape of the Insch intrusion. View WNW from Candle Hill, Oyne towards the 'Red Rock Hills'. Foreground rocks are norites of the Middle Zone. (Photo: W.J. Wadsworth.)

reinforced by subsequent investigations (see Wadsworth, 1982). However, there are enough differences in detail between the individual intrusions to indicate some degree of independent development, perhaps in fairly distinct 'compartments' within a single complex body, and the possibility of completely separate intrusions cannot be ruled out. This uncertainty does not invalidate the general conclusion that the 'Younger Basic' intrusions represent a single, coherent magmatic episode.

Six principal 'Younger Basic' intrusions are generally recognized, although some of these are composite, in that they comprise two or three adjacent, but apparently detached, masses at the present level of erosion (Figure 3.1):

1. Belhelvie
2. Insch–Boganclogh (Figures 3.2 and 3.3)
3. Huntly–Knock
4. Morven–Cabrach and Tarland
5. Haddo House–Arnage
6. Maud

The 'Younger Basic' rocks clearly have tholeiitic geochemical affinities. The parental magma is inferred to have been basaltic, with normative *hypersthene*, and the cumulate succession follows a typically tholeiitic differentiation trend. This is expressed mineralogically by the widespread occurrence of orthopyroxene (norites are common), by the absence of olivine in the intermediate fractionation stages, and by the appearance of quartz in the most evolved rocks, which are also distinguished by high levels of such elements as phosphorous, barium and zirconium. Broadly similar tholeiitic fractionation trends are encountered in the classic layered sequences of the Skaergaard (East Greenland) and Bushveld (South Africa) intrusions.

The most distinctive characteristic of the 'Younger Basic' masses, viewed collectively, is the diversity of rock types represented. Of these, the most significant is the fractionation series comprising all gradations from peridotites, through gabbros, ferrogabbros and syenodiorites, to extreme quartz-syenites. Many of the rocks in this sequence are texturally cumulates, and in some cases they exhibit small-scale layering (see the Bin Quarry GCR site report).

Zone		Rock type	%Fo Olivine	%En Orthopyroxene	#Mg Clinopyroxene	%An Plagioclase	Or/Ab/Cn Alkali feldspar	#Mg Amphibole	#Mg Biotite	Estimated thickness of unit (m)
Upper Zone	c	syenite			6 30	28 31 41	80/20/0 81/18/1 79/19/3	19	8	50
Upper Zone	b	olivine monzonite	6 13	20 24 29	40	49	76/19/5 63/24/13	17	18	50
Upper Zone	a	olivine-ferrogabbro	18 47	34 IP {47, 52} 58	46 54 63	52 50–56		31 53	31 58	200
Middle Zone		norite, granular gabbro, quartz-biotite norite		IP {44, 53} 71	55 78	47–52 69–74		43 60	42 70	2000+
			hiatus							
Lower Zone		olivine-norite, troctolite, dunite	77 87	79 87	82 88	70–76 78–84				1800+
			hiatus							
Bogan-clogh		dunite, harzburgite, rare wehrlite	89 92	91 95	89 92 95					unknown

—— cumulus phase   - - - - - intercumulus only   #Mg = 100Mg/(Mg + Fe)   IP = inverted pigeonite

Figure 3.4 Petrographical divisions and variation of mineral compositions in the Insch, Boganclogh and Belhelvie intrusions, from Gould (1997). Data from Ashcroft and Munro (1978), Gould (1997), Styles (1994) and Wadsworth (1986, 1988, 1991).

They are believed to represent gravitative accumulation of crystals precipitated from a basalt parental magma, which progressively evolved towards more felsic compositions. Similar cumulate successions are characteristic of major layered intrusions such as the Bushveld Complex in South Africa (Eales and Cawthorne, 1996), and these form the basis of the classification scheme now applied to the 'Younger Basic' differentiation series (Figure 3.4).

Three main 'stratigraphical' units are recognized, namely the Lower Zone (LZ), comprising peridotites, troctolites and olivine-gabbros; the Middle Zone (MZ), comprising olivine-free two-pyroxene gabbros; and the Upper Zone (UZ) comprising olivine-ferrogabbros, syenodiorites (see the Hill of Johnston GCR site report) and quartz-syenites. Both the LZ and UZ are further divided into three subzones (a, b and c). The cumulate sequence reaches its maximum development in the Insch intrusion, where all three zones are represented (Wadsworth, 1986, 1988; Gould, 1997), but where the LZ is poorly exposed (see the Hill of Barra GCR site report). However, the Belhelvie intrusion appears to provide a more complete duplicate of this part of the succession (Wadsworth, 1991). The Morven–Cabrach (Allan, 1970) and Huntly–Knock (Munro, 1984) intrusions both contain cumulates, although the Huntly rocks, which are broadly equivalent to the LZ elsewhere, are significantly different in some details (see the Bin Quarry GCR site report).

The intermediate stage of the main fractionation series (MZ) which is only fully represented in the Insch intrusion (see the Pitcaple GCR site report), consists essentially of olivine-free two-pyroxene gabbros ('hypersthene-gabbros' of Read *et al.*, 1965). These were originally interpreted as a separate intrusion, unrelated to the neighbouring LZ and UZ rocks at Insch, but are now regarded as an integral part of the succession (Wadsworth, 1988). However, not all the MZ rocks are normal cumulates. There is an intricate association of cumulates and fine-grained granular gabbros, some of which are porphyritic, containing prominent plagioclase phenocrysts. These granular rocks have been variously explained as thermally metamorphosed gabbros (Whittle, 1936), as the products of late-stage basic magma injections into the MZ cumulates (Clarke and Wadsworth, 1970) and, most recently, as an integral component of the MZ, but possibly representing a gabbroic 'roof facies', parts of which foundered periodically into the cumulate pile (Wadsworth, 1988). Rather similar granular gabbros also occur in the Huntly intrusion (Fletcher and Rice, 1989).

Another variety of olivine-free rock of broadly gabbroic composition is found in many of the 'Younger Basic' intrusions. This is generally described as quartz-biotite norite and appears to form distinct bodies of homogeneous basic rocks, without obvious cumulate textures. These are particularly important in the Insch–Boganclogh intrusion (especially in the Boganclogh area) and the Morven–Cabrach intrusion, and also occur at Huntly, Haddo House–Arnage and Maud. They are usually taken to represent 'Younger Basic' magma which has crystallized *in situ* under relatively hydrous conditions.

Further diversity among the 'Younger Basic' intrusions is associated with their margins, where these represent igneous rather than tectonic contacts, and especially in what was probably the roof region of the original bodies. The characteristic assemblage of these occurrences is predominantly xenolithic, with a wide variety of hornfels fragments in a cordierite norite (grading to tonalite) matrix (see the Towie Wood site report). The fragments are generally interpreted as the refractory residues (restites) resulting from partial melting of Dalradian country rock, that was heated by the 'Younger Basic' magma. They fall into three categories, namely quartz-rich, silica-deficient (aluminous), and (rarer) calc-silicate, which were derived from psammitic, pelitic and calcareous metasedimentary rocks respectively. The matrix material probably represents the partial melt component, which may have mixed locally with the basic magma. These marginal xenolithic complexes are most prominent in the Haddo House–Arnage intrusion (Read, 1923, 1935; Gribble, 1968), but are also an important component of the Huntly–Knock intrusion (Dalrymple, 1995), and occur locally at Insch (Read, 1966). Contact metamorphism of the Dalradian country rock without partial melting is also well-documented by Droop and Charnley (1985). From a study of hornfelsed pelites adjacent to the basic intrusions, they have estimated temperatures of 700–850°C and pressures of 4–5 kbar, implying an emplacement depth of 15–18.5 km.

The relationships of the mafic igneous rocks (both 'Older' and 'Younger') of the area, to the more widespread and better-known Caledonian granites is by no means clear-cut. Read (1961), following Barrow (in Barrow and Cunningham Craig, 1912), recognized two principal periods of granite emplacement. His 'Older Granites' (often migmatitic) were believed to be younger than the 'Older Basic' bodies and the main episodes of Caledonian folding, and probably coeval with the Buchan regional metamorphism. He described the 'Younger Basic' intrusions as representing a 'basic interlude' between the 'Older Granites' and the main late Caledonian granites, which he termed 'Newer Granites', and which included a distinct sub-group termed the 'Last Granites'. Subsequently, the 'Newer Granites' were divided into three groups, based mainly upon radiometric ages by Pankhurst and Sutherland (1982), the youngest of which was broadly equivalent to Read's 'Last Granites'. Many of the radiometric ages used in this grouping are now considered to be unreliable and the 'Newer Granites' are now more simply classified as either late tectonic or post-tectonic, depending more on their relationships to the tectonic history of the surrounding rocks or, where this is not known, by their petrological and geochemical affinities (Stephenson and Gould, 1995; see Chapter 8).

Syntectonic granites (equivalent to Read's 'Older Granites') in the Scottish Highlands probably originated during many different events over a long time-span, ranging from about 800 Ma to the peak of Caledonian regional metamorphism and deformation at 470 Ma. In the NE Grampian Highlands they are represented, in areas of middle amphibolite facies metamorphism and above, by migmatitic segregations and elsewhere by small, sheet-like masses of deformed muscovite-biotite granite, most notably those at Portsoy, Windyhills, Keith and Muldearie. There are no published modern age determinations (only a Rb-Sr isochron age of 655 ± 17 Ma for the Portsoy granite; Pankhurst, 1974). Most are highly sheared, with a strong augen texture, but their sheet-like form suggests that their emplacement was controlled by pre-existing shear zones. They could be similar in age to the Ben Vuirich Granite of Perthshire (590 Ma), but equally they could be coeval with the 'Newer Basics' and not much older than the D3 shearing. No sites have yet been selected for the GCR to represent the syntectonic granites.

Most of the granites which are spatially associated with the 'Younger Basics' can be classified as late tectonic (Figure 3.1). Two suites are recognized. One consists of diorites, tonalites and granodiorites, with characteristics of a mantle or lower crustal igneous source (I-type); some are foliated and many are highly xenolithic. They include the Kennethmont granite–diorite complex, which is located at the western end of the Insch 'Younger Basic' mass (Figure 3.2), but which is regarded as a result of a slightly younger separate magmatic event (see the Craig Hall GCR site report). It also includes the Syllavethy, Corrennie and Tillyfourie intrusions (Harrison, 1987b; Gould, 1997), which all lie within the area of an extensive tonalite–granodiorite vein complex to the south of Insch. The other late tectonic suite consists of biotite-muscovite granites, which are commonly foliated and garnet-bearing. Contacts with country rock are gradational and compositions are compatible with an S-type origin by partial melting of mid- to upper- crustal metasedimentary rocks. They post-date the D3 folding, the regional migmatization and the basic intrusions, but their most likely age of intrusion, based on U-Pb monazite determinations is comparable to these events at around 470 Ma. They include large bodies such as the granites of Strichen, Forest of Deer, Kemnay (Gould, 1997) and Aberdeen (Munro, 1986; Kneller and Aftalion, 1987), and many smaller bodies. Many of the minor granite and pegmatite sheets that cut the 'Younger Basic' masses may be coeval with this suite. No sites have yet been selected for the GCR to represent this suite.

The remaining NE Grampian granites (Figure 3.1), including those of the East Grampian Batholith (which can be taken as marking the southern limit of the area) and large bodies west of Aberdeen (e.g. Bennachie, Hill of Fare, Crathes, Cromar) and to the north (Peterhead) are all post-tectonic I-type or transitional to alkaline (A-type) granites. They have emplacement ages in the range 420 to 395 Ma and, like the late Caledonian granitic intrusions as a whole (see Chapter 8: Introduction), can be related to late-orogenic uplift.

HILL OF BARRA (NJ 803 257)

W. J. Wadsworth

Introduction

Olivine-rich ultramafic rocks believed to represent the Lower Zone of the 'Younger Basic'

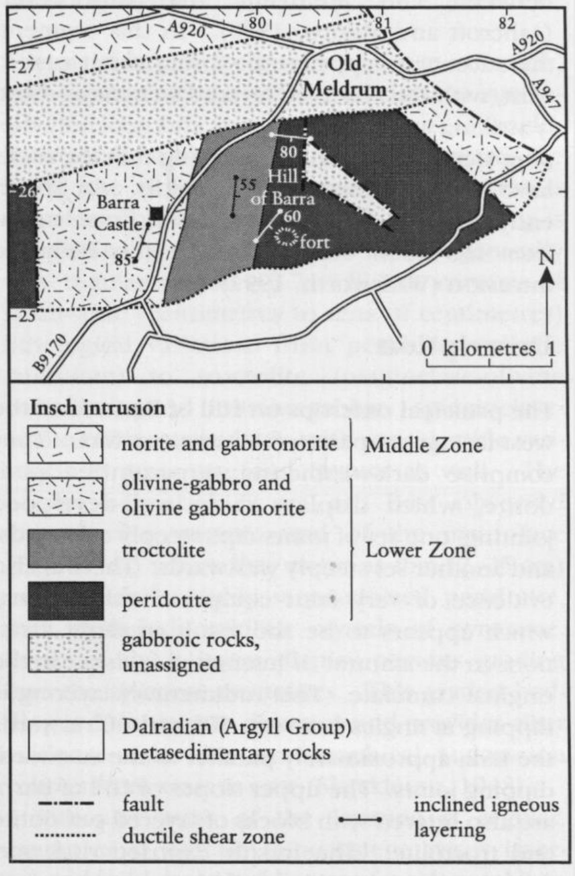

Figure 3.5 Geological map of the area around the Hill of Barra GCR site, Insch intrusion, from Ashcroft and Munro (1978) and BGS 1:10 000 sheets NJ72NE (1989) and NJ82NW (1989).

layered sequence can be recognized in both the Belhelvie and Insch intrusions, but natural exposures are generally very poor because the rocks are heavily serpentinized. However, Hill of Barra, at the eastern end of the Insch intrusion, is exceptional in forming a positive topographic feature and in providing relatively good exposures, despite the degree of serpentinization (Gould, 1997) (Figure 3.5).

In terms of the original layered sequence, the Hill of Barra peridotites are referred to the basal subdivision of the Lower Zone (LZa) as defined by Wadsworth (1982) and are classified as olivine cumulates. Although the eastern end of the Insch intrusion is structurally complicated, geophysical evidence (mainly magnetic anomalies) and borehole sampling have shown that there is a relatively continuous sequence from LZa peridotites (olivine cumulates), to LZb troctolites (plagioclase-olivine cumulates) and LZc norites (plagioclase-orthopyroxene-olivine cumulates) along the southern edge of the intrusion, between Old Meldrum and Cuttlecraigs (Ashcroft and Munro, 1978). In this segment, the succession appears to 'young' from east to west, with the observed layered structures mostly striking approximately N–S and generally dipping steeply eastwards, indicating that the rocks have been overturned (Figure 3.5). An apparently identical sequence of Lower Zone cumulates has been described from the Belhelvie intrusion (Wadsworth, 1991).

Description

The principal outcrops on Hill of Barra form the west-facing ramparts of an ancient fort. They comprise dark-weathering serpentinized peridotite, which displays fairly well-developed jointing; one set of joints dips steeply eastwards, and another set steeply westwards. There is also evidence of very faint compositional layering, which appears to be the result of slight variations in the amount of interstitial feldspar in the original cumulate. This rudimentary layering is dipping at angles between 50° and 60° towards the ESE, approximately parallel to the eastward-dipping joints. The upper slopes of Hill of Barra are also littered with blocks of layered peridotite and troctolite. The freshly exposed rock surfaces are dominated by dull-black serpentinized olivine, but scattered poikilitic crystals of intercumulus pyroxene can be discerned, and at least a trace of interstitial plagioclase (now substantially altered to secondary minerals), can be seen on weathered surfaces, since it is slightly more resistant to weathering than the serpentine. The plagioclase content may approach 10% by volume in the relatively feldspathic layers. Westwards from Hill of Barra, towards Barra Castle, plagioclase gradually increases in abundance, and eventually occurs as cumulus grains, giving rise to the troctolitic (plagioclase-olivine) cumulates of LZb.

Although the ultramafic rocks of LZa are heavily serpentinized, remnants of fresh olivine occur locally and have compositions in the range of Fo_{87-86} (Wadsworth, 1991). The serpentine forms a distinctive mesh-structure, and is associated with granular aggregates and stringers of magnetite. The intercumulus pyroxene generally occurs as large poikilitic crystals, and although augite is the most obvious variety of pyroxene, because it is relatively unaltered, orthopyroxene has also been recorded. The original intercumulus plagioclase has been almost entirely replaced by turbid, isotropic material, possibly hydrogrossular, but rare patches with relict multiple twinning can be distinguished. The plagioclase composition is rather variable, but is generally in the bytownite–labradorite range. Corona structures are sometimes developed at the contact between original olivine and plagioclase, and these consist typically of a zone of granular orthopyroxene, immediately adjacent to the olivine, surrounded by a zone of fibrous amphibole in symplectic intergrowth with turbid isotropic material (probably altered feldspar). These coronas are believed to be the result of reaction between olivine and plagioclase under metamorphic conditions (Mongkoltip and Ashworth, 1983).

Interpretation

The significance of the ultramafic rocks at the eastern end of the Insch intrusion as the most primitive members of an extreme fractionation series (culminating in the 'syenitic' rock compositions found farther west; see the Hill of Johnston GCR site report), was first recognized by Read, Sadashivaiah and Haq (1961). They interpreted the layered peridotites and troctolites as basal cumulates, formed by gravitative differentiation of gabbroic magma, and recognized that the original sub-horizontal layering has been thoroughly disturbed by subsequent tectonic events. The cumulate theme was developed and refined by Clarke and Wadsworth (1970), who recognized that the Hill of Barra peridotites are olivine cumulates, and that cumulus plagioclase and pyroxenes (both clinopyroxene and orthopyroxene) only appear higher in the succession (i.e. farther west) to give rise to cumulate troctolites and gabbros. A more detailed structural study of the eastern end of the Insch intrusion by Ashcroft and Munro (1978) identified a number of separate fault blocks of LZ cumulates, with the Hill of Barra rocks forming part of a steeply dipping cumulate sequence, younging from east to west, and locally overturned. It is on this basis that the Hill of Barra rocks are referred to LZa of the complete layered sequence (Wadsworth, 1982, 1991). It is now thought that these ultramafic cumulates are not the same as, or even closely related to, the serpentinized peridotites found along the southern margin of the Insch–Boganclogh intrusion (see the Creag Dearg GCR site report).

Conclusions

The rocks of the Hill of Barra GCR site are typical of the layered ultramafic unit found in the 'Younger Basic' masses (Insch and Belhelvie), and believed to represent the early-formed olivine-rich cumulates. The original peridotite has been highly serpentinized, but there is some evidence of rudimentary layering, dipping steeply eastwards and indicating considerable post-depositional tectonic disturbance. Exposures of these ultramafic rocks are generally very poor; this highlights the significance of the western slopes of Hill of Barra, which provide relatively good outcrops.

BIN QUARRY (NJ 498 431)

W. J. Wadsworth

Introduction

Although the 'Younger Basic' igneous bodies are generally interpreted as layered intrusions, because of their large-scale compositional variations, they rarely display convincing small-scale layered structures. However, the Bin Quarry, which is located near the western margin of the Huntly–Knock intrusion (Figure 3.6), is exceptional in this respect, and exposes a sequence of spectacularly layered cumulates.

The Bin Quarry rocks are broadly troctolitic (plagioclase-olivine cumulates) to gabbroic (plagioclase-olivine-augite cumulates) in composition, but there are considerable modal variations from layer to layer (generally on a scale of centimetres or tens of centimetres), producing mafic (olivine-rich) and felsic (plagioclase-rich) lithologies locally. These layered rocks have moderately steep dips towards the west, but since they are believed to represent the lower part (LZ) of the Huntly–Knock cumulate sequence, which generally 'youngs' from west to east in this area, (Munro 1984), they must have been overturned tectonically in the vicinity of the Bin Quarry. This view is supported by the evidence of small-scale 'sedimentological' features such as graded bedding which are clearly displayed in the quarry (Shackleton, 1948), and by progressive variations in the mineral compositions in this part of the Huntly intrusion.

Description

The main face of the quarry is 130 m in length, and exposes an apparently continuous succession of layered cumulates dipping at angles between 40° and 60° (averaging 50°) towards the WNW; the exposed stratigraphical thickness is therefore approximately 100 m. The layering is exceptionally well-developed and is generally very regular (Figures 3.7, 3.8). It consists of small-scale (centimetres to tens of centimetres) lithological variations from peridotite (olivine cumulate) to troctolite (plagioclase-olivine cumulate) and olivine-gabbro (plagioclase-augite-olivine cumulate), with considerable variations in grain size and texture as well. The olivine cumulate layers are best observed towards the western end of the main face (Figure 3.7) where they occur as thin (2–25 cm) units of dark, highly serpentinized peridotite, with scattered poikilitic crystals of pyroxene. Some of these layers display obvious grading into the adjacent troctolites. This graded bedding is consistent in direction and provides clear evidence that the stratigraphical succession youngs from west to east (Shackleton, 1948).

Although most of the layering is regular, examples of laterally impersistent, wispy layering and local cross-bedding are found, notably in the large loose blocks at the foot of the main face towards the western end of the quarry. These have probably fallen from the exceptionally well-

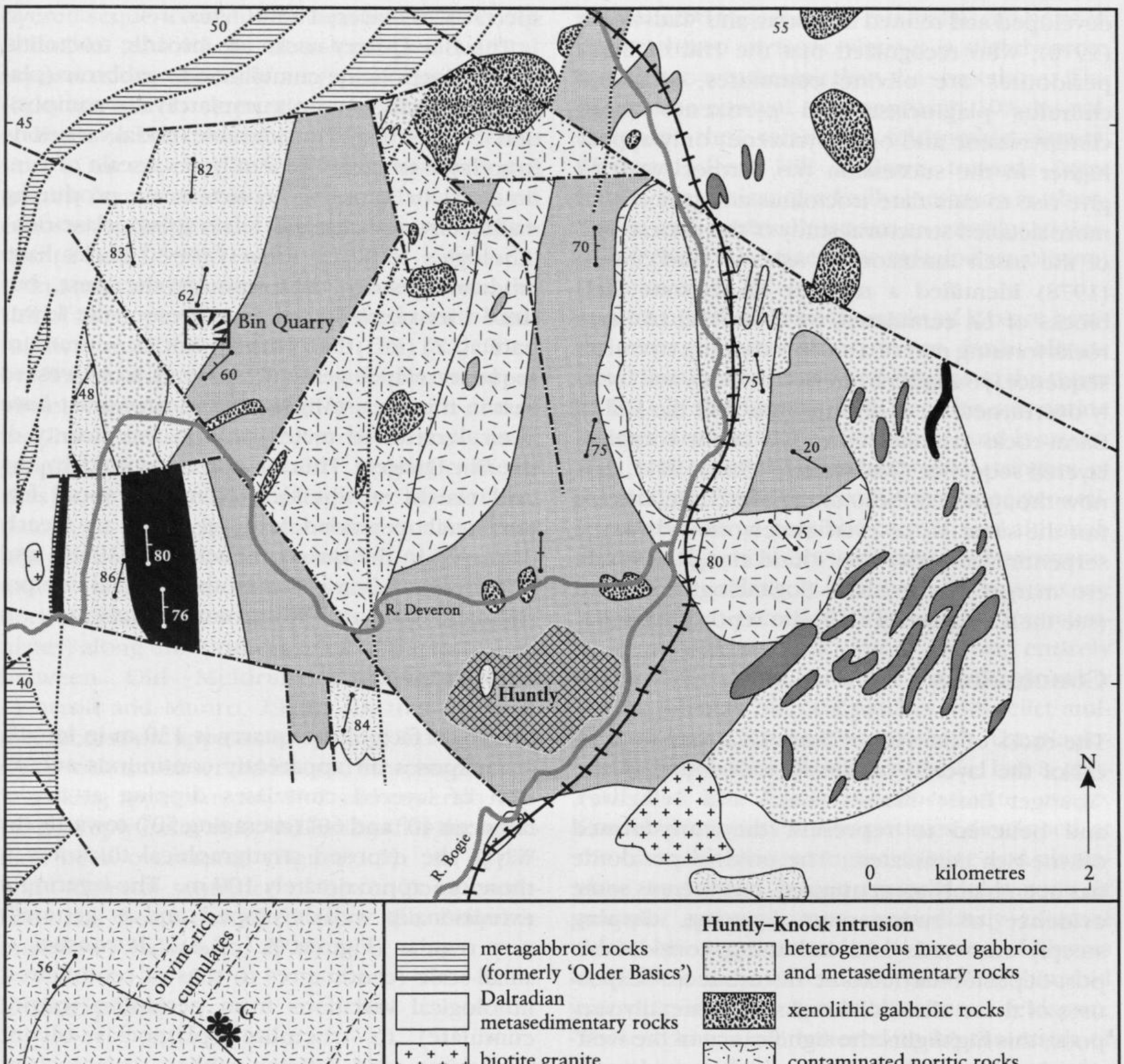

Figure 3.6 Map of the southern part of the Huntly–Knock intrusion, from BGS 1:50 000 Sheet 86W (in press), with details of the Bin Quarry GCR site, from Gunn and Shaw (1992).

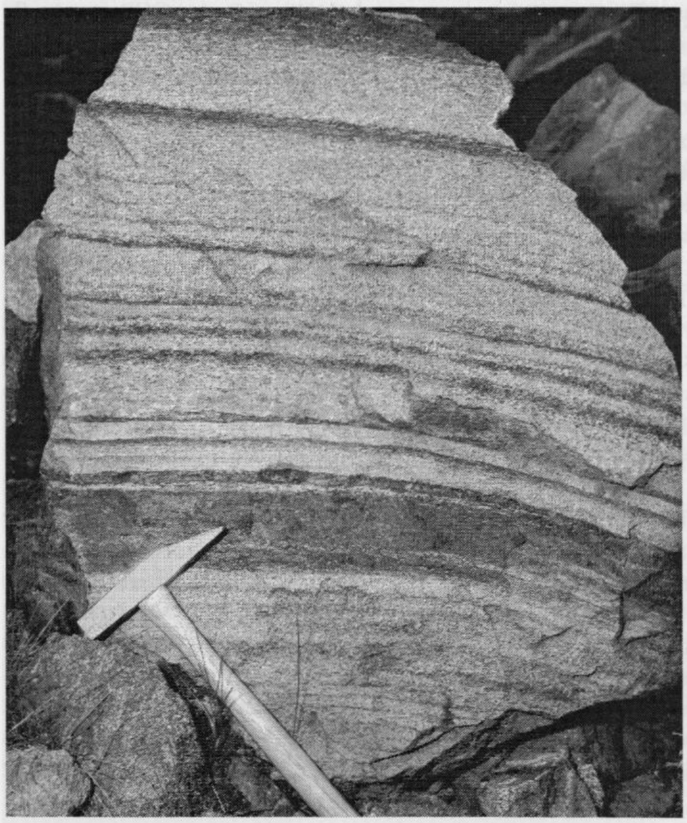

Figure 3.7 Layered olivine-gabbro cumulates of the Huntly intrusion Lower Zone in the Bin Quarry. Layering dips at 50° to the NW, but modal layering, 'sedimentary' structures and variations in mineral composition show that the sequence 'youngs' to the SE and hence is inverted. (Photo: BGS no. D4122.)

Figure 3.8 Block of layered olivine-gabbro cumulate of the Huntly intrusion Lower Zone in the Bin Quarry. The layering, which is inverted in this photograph, reflects both modal and mineral compositional variation, ranging from peridotite, through mafic gabbro and troctolite to anorthosite. (Photo: BGS no. D4121.)

layered material which can be seen near the top of the face in this area. There is considerable variation in grain size between layers, and there are also lenses of very coarse-grained pegmatitic gabbro which are associated with significant sulphide mineralization (Fletcher, 1989; Gunn and Shaw, 1992). Two areas of gossan seen in the main quarry face (Figure 3.6) mark the location of irregular pegmatitic pyroxenite sheets. The troctolites and gabbros are well jointed, with the principal joint surfaces dipping at moderate angles (20–25°) towards the east. They are mostly well spaced, but are closer together (and slightly steeper) in the central part of the main quarry face.

The troctolitic and gabbroic cumulates are distinctively speckled black and white rocks, with variable proportions of cumulus plagioclase to cumulus olivine, and typically displaying a preferred orientation of the tabular plagioclase crystals parallel to the lithological layering (a feature normally referred to as 'igneous lamination'). The olivines sometimes display corona structures consisting of granular orthopyroxene and fibrous amphibole and presumably of metamorphic origin. Serpentinization of the olivines has resulted in the development of distinctive expansion cracks, radiating from the altered olivines out into the surrounding feldspars. The troctolites usually contain scattered crystals of intercumulus augite, and they are interlayered with more obviously gabbroic cumulates, in which the augite is of cumulus habit. Orthopyroxene is not present as a primary mineral (either cumulus or intercumulus) in these rocks. Cumulus mineral compositions in the troctolites and gabbros have been determined as follows: plagioclase (An_{74}), olivine (Fo_{80}) and augite ($Ca_{48}Mg_{44}Fe_8$) (Munro, 1984). There is also evidence of a slight but progressive change in olivine composition from west to east within the quarry (Fo_{81} to Fo_{78}), and this fits well with the graded layering structures in indicating eastward 'younging' of the succession despite the westward dips.

Thin sheets of pegmatitic gabbro, consisting of quartz, feldspar and biotite, occur in the eastern part of the main face. They are generally sub-horizontal in attitude, but have some steeper offshoots. They appear to have caused extensive amphibolitization of the mafic minerals in the immediately adjacent cumulates. Some vein-like areas of alteration contain radiating needles of xonotlite and botryoidal prehnite (Gillen, 1987).

Interpretation

The recognition that the Bin Quarry provides a classic example of cumulate rocks formed at a relatively early stage of gabbroic magma crystallization is based on a combination of lithological features. These include: a) the small-scale layering itself, which is predominantly the result of frequent changes in the cumulus mineral assemblage, but also involves textural features, such as the development of well-laminated plagioclase-rich layers; b) the occurrence of distinctive textures comprising both cumulus and intercumulus components; c) the cumulus mineral compositions (relatively magnesian olivine and augite, relatively calcic plagioclase) and their slight but systematic variation with stratigraphical position. The recognition of specifically sedimentational aspects (especially graded bedding, and its use as a 'way-up' criterion) was first applied to the 'Younger Basics' by Shackleton (1948), as the results of observations at the Bin Quarry, and this approach has been substantiated by most other studies in the area (e.g. Stewart and Johnson, 1960; Read, 1961).

In general terms, the predominantly troctolitic cumulates of the Huntly–Knock area are regarded as equivalent to Lower Zone rocks at Belhelvie and Insch, but from higher levels than LZa (as seen at the Hill of Barra GCR site in the Insch mass, or on the western edge of the Belhelvie mass). They are therefore referred to LZb/LZc, since they contain cumulus plagioclase and augite (Wadsworth, 1982; Munro, 1984; Fletcher, 1989). However, there is now considerable evidence that the lower part (LZ) of the Huntly–Knock succession is not identical to the Insch and Belhelvie equivalents. For example, there is no evidence of a distinct ultramafic (LZa) unit in the Huntly–Knock mass, although olivine-rich cumulate layers occur locally, as in the Bin Quarry sequence. Shallow drilling of the poorly exposed western margin (Munro, 1984) suggests that troctolitic and gabbroic rocks persist from the quarry area as far as the contact with Dalradian country rocks. In addition, there is the scarcity of orthopyroxene in the Huntly–Knock LZ cumulates, and the compositions of the co-existing cumulus minerals (olivine, plagioclase and augite) show small but significant differences between Huntly–Knock and Belhelvie–Insch (Munro, 1984; Wadsworth, 1991). These features lend support to the view that the regionally available 'Younger Basic' gabbro magma underwent progressive fractional crystallization in at least two separate magma chambers (or distinct compartments of a single complex chamber) with resultant slight differences in the respective crystallization sequences, as advocated by Weedon (1970), Ashcroft and Munro (1978) and Munro (1984). This is in contrast to the proposal by Wadsworth (1970, 1982) that the 'Younger Basics' represent a single-layered intrusion, subsequently disrupted by tectonic events.

Conclusions

The troctolitic and gabbroic cumulates of the Bin Quarry GCR site, with their magnesian olivines and pyroxenes, and calcic feldspars, are excellent examples of a relatively early stage of fractionation in the Lower Zone (LZb/LZc) of the 'Younger Basic' layered sequence, although they are not quite as primitive as the ultramafic (LZa) cumulates at the Hill of Barra GCR site. Various features of the rocks are of particular significance in the context of the 'Younger Basic' intrusions. Most prominent is the small-scale layering, with its associated 'sedimentary' structures, providing convincing evidence of gravity accumulation of crystals. The steep dips indicate post-depositional tectonic disturbance, and the graded (olivine-rich to plagioclase-rich) layers show that the sequence has been overturned, at least in the quarry area.

PITSCURRY AND LEGATESDEN QUARRIES (NJ 728 267 AND 737 263)

W. J. Wadsworth

Introduction

The intermediate fractionation stages of the 'Younger Basic' magmatic event, which are collectively termed the Middle Zone (MZ), are best represented in the Insch intrusion, especially in the area around Pitcaple. The Insch MZ rocks are mainly olivine-free, two-pyroxene gabbros, with mineral compositions broadly intermediate between those of the Lower Zone (LZ) and Upper Zone (UZ) cumulates respectively, but displaying much greater textural diversity and structural complexity than either. Two principal

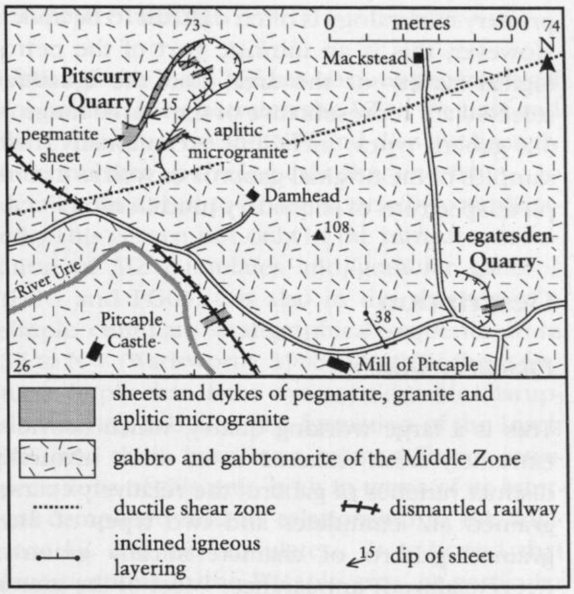

Figure 3.9 Map of the area around Legatesden and Pitscurry quarries, Insch intrusion, from BGS 1:10 000 Sheet NJ72NW (1989).

textural variants are found throughout the Insch MZ, associated in approximately equal abundance, namely gabbroic cumulates and relatively fine-grained granular gabbros (FGG). However, their precise distribution and relationships are difficult to define, partly because of generally poor natural exposures, and partly because this area of the Insch intrusion lies within a major shear-belt (Read, 1956; Ashcroft *et al*., 1984; Kneller and Leslie, 1984) so that the original rocks have been substantially modified. The Insch MZ rocks were originally described as a separate intrusion of hypersthene-gabbro, apparently unrelated to the main differentiation series (Read *et al*., 1965) but Clarke and Wadsworth (1970) recognized a distinct cumulate element that partly bridges the gap between LZ and UZ, and all the MZ gabbros are now interpreted as integral components of the Insch sequence (Wadsworth, 1988; Gould, 1997).

The most important exposures of the Insch MZ gabbros are found in quarries, especially in the Pitcaple area (Figure 3.9). Two separate, but neighbouring quarries (Pitscurry and Legatesden) provide complementary information about the different MZ components and their relationships. Because both quarries lie within one of the main shear-belts affecting the Insch intrusion, much of the gabbroic material has been deformed and amphibolized, so that the primary mineralogy is often difficult to decipher. However, this is an intrinsic part of the petrological variety of the area, and the localities selected are representative of the whole range of MZ gabbro types, including exceptionally fresh samples of the original gabbros as well as a complete spectrum of secondary modifications.

Description

Pitscurry Quarry

This is a large working quarry, which provides extremely fresh material from three texturally distinct varieties of gabbro; the relatively coarse-grained MZ cumulates and two types of fine-grained gabbro of characteristically granular (?recrystallized) appearance. Most of the granular gabbros are aphyric (fine-grained granular gabbro or FGG), but some contain abundant plagioclase phenocrysts (porphyritic granular gabbros or PGG). Despite the continuous exposure, the field relationships between these different gabbro components are difficult to decipher, largely because the face is too steep to be readily accessible, but partly because of the combination of prominent jointing and local deuteric alteration along the joint planes.

In general terms, the relatively coarse-grained gabbros, assumed to be MZ cumulates, are found at the western end of the working face. They consist of cumulus orthopyroxene (En_{47}), augite ($Ca_{45}Mg_{32}Fe_{23}$) and plagioclase (An_{60}), and appear to be unlayered.

The rest of the working face comprises members of the fine-grained granular gabbro suite. In the central part of the face the rocks are olivine-bearing, which is unusual, but their textural features are typical of the more commonly encountered olivine-free types of FGG. These gabbros consist of olivine (Fo_{63}), augite ($Ca_{45}Mg_{41}Fe_{14}$) and plagioclase (An_{65}) and are also exceptionally fresh. Farther east they pass into PGG with an abundance of large plagioclase phenocrysts (An_{80} zoned to An_{65}) in a groundmass virtually identical to the olivine-bearing FGG described above.

These varieties of granular gabbro (normal FGG, olivine-bearing FGG and PGG) are also encountered in the same relative positions in the newly-developed quarry area above the main working face, close to Pitscurry Wood, but even here there is as yet no direct evidence of their age relationship, only negative features in the sense that there are no obvious chilled margins, intrusive veins, or xenoliths of one rock type in another.

The more southerly part of the quarry area consists mostly of coarse-grained gabbroic rocks, with textural features similar to the MZ cumulates elsewhere, but they have been thoroughly

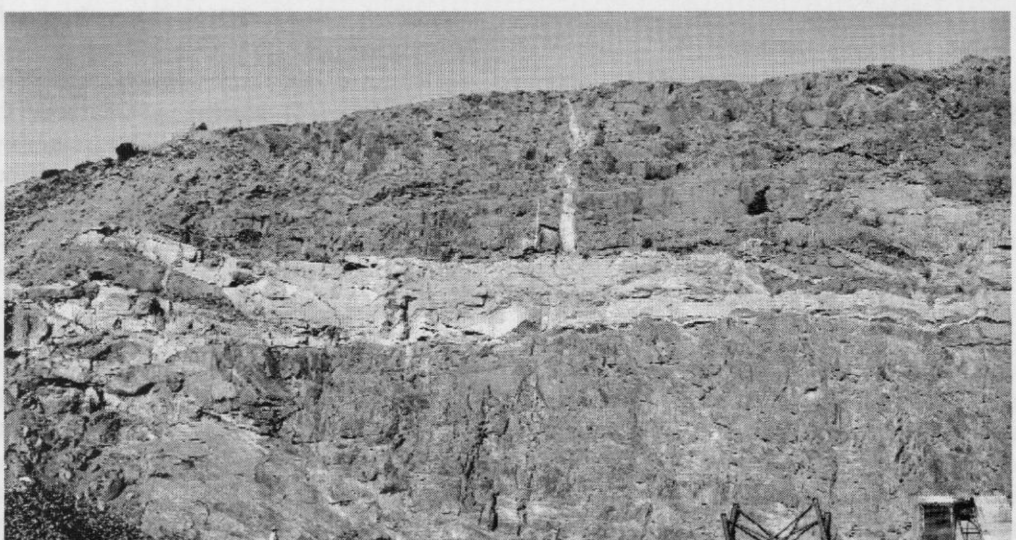

Figure 3.10 Norite of the Middle Zone, Insch intrusion, intruded by a 10 m-thick sheet of pegmatitic granite with narrow veins branching off the main sheet, Pitscurry Quarry, Pitcaple. (Photo: BGS no. D4332.)

amphibolitized. Pitscurry Quarry also contains examples of the later pegmatitic granite sheets. These are best seen in the western face, where they form a 10 m-thick, approximately horizontal sheet, with minor offshoots (Figure 3.10). Smaller inclined or vertical sheets are seen in the northern face. In addition to feldspar, quartz and micas, these pegmatites contain garnet, black tourmaline (schorl) and rare beryl (Leslie, 1987).

Legatesden Quarry

This small quarry (no longer worked) is entirely within MZ cumulates, but displays gradations from fresh material at the NW end of the exposure into moderately deformed and amphibolitized rocks elsewhere. The fresh gabbros consist of cumulus plagioclase (An_{60}) and orthopyroxene (En_{55}), together with scattered subhedral grains of opaque oxide, and a small amount of interstitial augite and biotite.

Just to the SE of the central part of the main quarry face, close to a 2 m-wide sheet of pegmatitic granite, the cumulates exhibit well-developed layering, consisting of an alternation of felsic and mafic units on a relatively small scale (centimetres to tens of centimetres). Some of the mafic layers are rather wispy and laterally impersistent, and there is also an indication of upward grading from the principal mafic layer in this outcrop. The base of this layer is also remarkably uneven in a way that is reminiscent of loading structures in sediments and clearly implies a considerable degree of post-cumulus instability. Unfortunately these layered cumulates have been thoroughly altered in proximity to the pegmatite sheet, and now consist predominantly of chlorite, moderately sodic plagioclase, which is rather strained and locally recrystallized, and epidote. As well as this local modification of the cumulates, there is also a more general increase in degree of shearing and alteration from NW to SE in the quarry. The earlier stages appear to involve plagioclase deformation and the replacement of the original pyroxene by colourless amphibole. More advanced alteration results in the recrystallization of plagioclase (and formation of epidote) and the development of chlorite at the expense of the secondary amphibole. Detailed discussion of the textural and mineralogical modification to gabbros involved in shear zones is given by Kneller and Leslie (1984).

Interpretation

Although the Insch MZ has obvious geographical coherence, lying between the LZ to the east and the UZ to the west and NW, and displays broadly intermediate petrological characteristics, in detail it turns out to be unexpectedly complicated. This is seen not only in the intricate association of MZ cumulates and granular gabbros (FGG and PGG), but also in the absence of a simple cumulate stratigraphical sequence from SE to NW (Wadsworth, 1988). Both of these features imply that there was considerable disruption during and after the formation of the Insch MZ, and there have been many different interpretations of this unit, both in terms of its internal complexity and its relationship to the adjacent LZ and UZ cumulates. It is hoped that investigations in the Pitcaple area, in particular in the large working quarry at Pitscurry, will eventually resolve the situation.

Whittle (1936) was the first to investigate the Insch (MZ) hypersthene-gabbros and, on textural grounds, concluded that the granular gabbros are older than the coarse-grained gabbros (now regarded as cumulates) and have been thermally metamorphosed by them. Read *et al.* (1965) were more concerned with the significance of the hypersthene-gabbro unit as a whole, rather than with the internal textural features, and decided that it represents a distinct intrusion, invading the Insch cumulates (LZ and UZ) and not directly related to them. To Read and his colleagues, the main significance of the hypersthene-gabbros lies in their lack of olivine (and relative abundance of orthopyroxene), which they took to indicate large-scale contamination of the regionally available 'Younger Basic' magma by argillaceous sedimentary material.

Clarke and Wadsworth (1970) re-interpreted the coarse-grained hypersthene-gabbros as an integral part of the Insch cumulate succession, thus defining the MZ stage of differentiation. However, they believed the associated granular gabbros to be slightly younger than the cumulates, and to represent invasion by pulses of the parental 'Younger Basic' magma. Wadsworth (1988) was persuaded by the mineralogical evidence that the MZ cumulates and the granular gabbros are both part of a coherent, intermediate fractionation stage. He suggested that the FGG and PGG represent material which crystallized near the intrusion margins (probably the roof) and subsequently foundered into the contemporary cumulate pile from time to time as large 'rafts' of essentially solid material. Such a mechanism would not only explain the intimate association of MZ cumulates and FGG/PGG, but might also account for some of the structural complexity of the cumulate succession. One important line of evidence is the occurrence of abundant small FGG xenoliths in a MZ cumulate matrix at Candle Hill (662 265), between Pitcaple and Insch (Wadsworth, 1988).

However, it must be emphasized that although Pitscurry quarry provides excellent exposures of the various MZ components, their precise relationships are not immediately evident, and await a more thorough investigation.

Conclusions

Pitscurry and Legatesden quarries are representative of the Middle Zone (MZ) of the 'Younger Basic' layered sequence. Between them they provide access to the great variety of Insch MZ rocks, both primary and secondary (shear-belt modification), as well as later pegmatitic granite sheets. Pitscurry is particularly important in terms of the close association of unusually fresh MZ cumulates and granular gabbros, whereas Legatesden is significant in displaying small-scale layering in MZ cumulates (rarely seen elsewhere), with evidence of post-cumulus instability.

HILL OF JOHNSTON (NJ 575 250)

W. J. Wadsworth

Introduction

One of the most distinctive features of the 'Younger Basics' is the development of a pronounced fractionation trend towards iron-rich, felsic residual material, which appears to be represented by the final stages of the Insch cumulate succession from Lower Zone (LZ), Middle Zone (MZ) and eventually through to Upper Zone (UZ) stages. Read *et al*. (1961) were the first to describe these late-stage differentiates, which they recognized as forming a series of small hills (referred to as the 'Red Rock Hills', because of the reddish 'syenitic' rocks found at their summits), trending from SW to NE, to the west of Insch town (Figure 3.11). Clarke and Wadsworth (1970) formally grouped all the olivine-bearing rocks (and closely related felsic material) lying to the west and NW of the predominantly olivine-free MZ gabbros (hypersthene-gabbros of Read *et al*., 1965) as comprising the Insch UZ, which they subdivided into three sub-zones (UZa, b and c) according to their detailed mineralogy. This classification was further refined by Wadsworth (1986). The UZa rocks are widespread throughout this part of the Insch intrusion, and are ferrogabbros (Fe-rich olivine-plagioclase-pyroxene cumulates). The ferrogabbros are overlain locally (in the 'Red Rock Hills') by UZb, which consists of ferromonzodiorites (monzonites locally) (similar to UZa, but with cumulus alkali feldspar), and then by UZc, which is always heavily altered but is approximately quartz-syenitic in composition.

This type of sequence is represented to varying degrees on all the 'Red Rock Hills', but exposures are generally very poor (Figure 3.12). The most complete sequence (both in terms of exposure and variety of rock types) is found at Hill of Johnston, the most south-westerly of the 'Red Rock Hills', where UZb has been quarried for roadstone and where UZc is at least seen ***in situ***, although by no means well exposed.

Description

Although UZa rocks are not exposed in the immediate vicinity of Hill of Johnston, excellent examples of very fresh material from this sub-zone occur elsewhere in the north-western part of the Insch intrusion, e.g. at Brankston (589 308), and clearly represent the immediate precursors to the more extreme differentiates at this locality. They are essentially gabbroic cumulates, comprising Fe-rich olivine, two pyroxenes (Fe-rich orthopyroxene and ferroaugite) and plagioclase (approximately An_{50}).

The 'stratigraphically' lowest rocks of the sequence at Hill of Johnston are exposed in the roadside quarry at the SW foot of the hill, and in another small quarry at Mill of Johnston, 200 m to the SE.

The rocks from the lower part of the main quarry (no longer worked) are cumulates, although there is no small-scale layering visible at this locality. They are mineralogically complex, consisting mainly of cumulus plagioclase (An_{45}), alkali feldspar, olivine (Fo_9) and ferroaugite ($Ca_{42}Mg_{21}Fe_{37}$), with relatively abundant apatite and zircon, both of which may be cumulus phases, and intercumulus hornblende

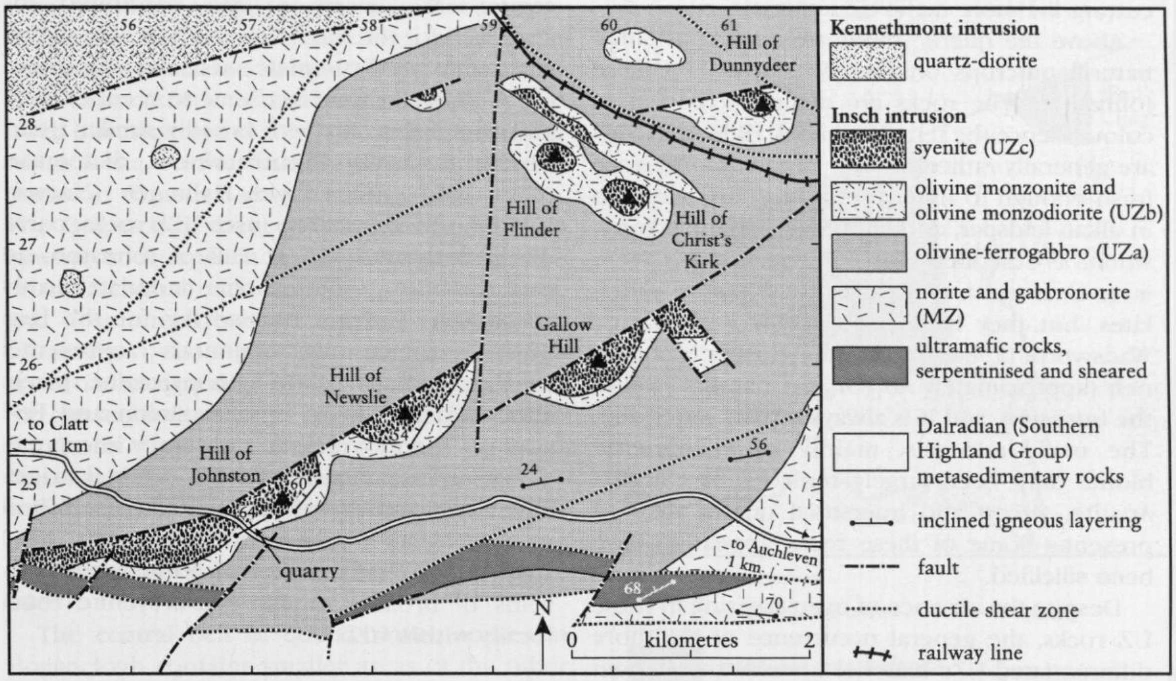

Figure 3.11 Map showing the location of the principal 'Red Rock Hills' (UZb and UZc of the Insch intrusion), west of Insch, from BGS 1:50 000 Sheet 76W (1993).

and biotite. Orthopyroxene (En_{24}) occurs in some rocks and interstitial quartz is generally present. The cumulus alkali feldspar, which is microperthitic orthoclase, is notable for its high Ba content ($Ab_{19}Or_{71}Cn_{10}$). These rocks were termed syenogabbros by Read *et al.* (1961) but are probably more accurately described as olivine ferromonzodiorites (or ferromonzonites) and have been interpreted as representing UZb (Wadsworth, 1986). They are well jointed, and tend to weather spheroidally.

At higher levels in the quarry the rocks are slightly less mafic, and also contain more alkali feldspar ($Ab_{19}Or_{76}Cn_5$) relative to plagioclase (An_{37}). The ferromagnesian minerals tend to be more altered, with olivine (Fo_6) almost completely serpentinized, and ferroaugite ($Ca_{42}Mg_{14}Fe_{44}$) occurring as relict cores in amphibole. Zircon and apatite are still abundant, and are accompanied by interstitial biotite and quartz. These relatively felsic rocks also occur as near-vertical veins, up to 5 cm across,

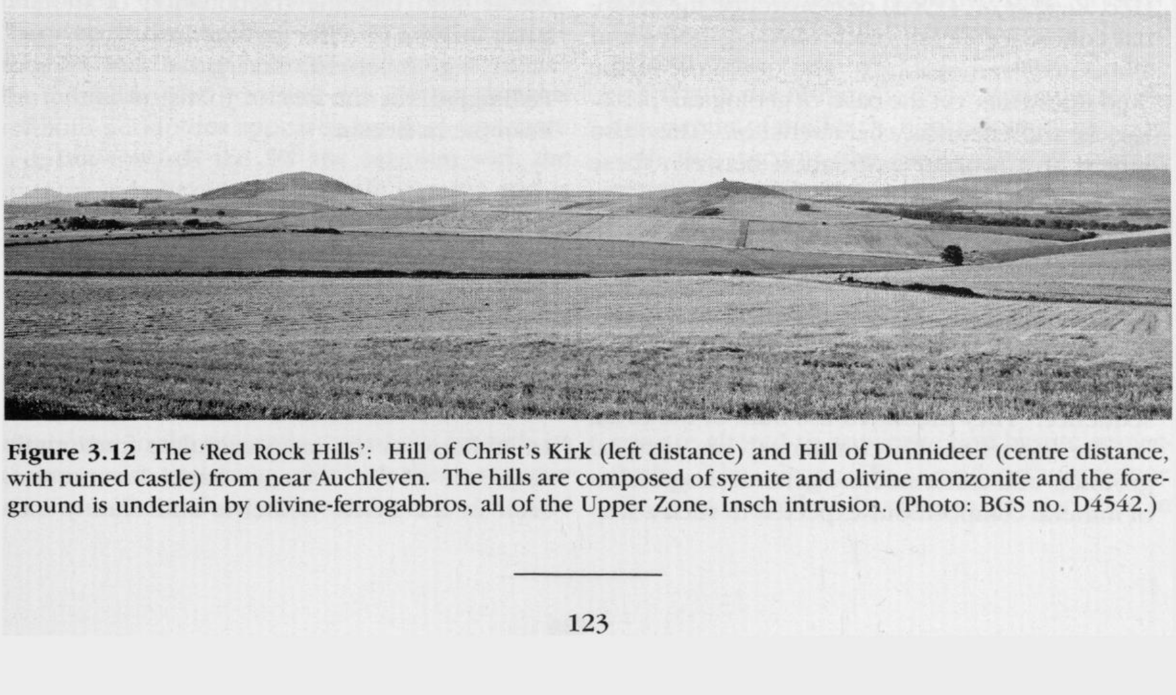

Figure 3.12 The 'Red Rock Hills': Hill of Christ's Kirk (left distance) and Hill of Dunnideer (centre distance, with ruined castle) from near Auchleven. The hills are composed of syenite and olivine monzonite and the foreground is underlain by olivine-ferrogabbros, all of the Upper Zone, Insch intrusion. (Photo: BGS no. D4542.)

cutting the more mafic UZ material.

Above the quarry, there are numerous small natural outcrops on the SW slopes of Hill of Johnston. The rocks are distinctly reddish in colour, hence the term 'Red Rock Hills', and they are generally rather altered. Some examples are fresh enough to indicate that they are very rich in alkali feldspar, and approach syenitic compositions as described by Read *et al.* (1961). There is no clear textural evidence that they are cumulates, but they have been referred to UZc by Wadsworth (1986). The alkali feldspar is not Ba-rich (approximately $Ab_{18}Or_{81}Cn_1$) at this level in the intrusion, and it is always heavily sericitized. The mafic minerals, mainly amphibole and biotite have been largely replaced by chlorite. Apatite, zircon and interstitial quartz are also present. Some of these rocks appear to have been silicified.

Despite the absence of overt layering in these UZ rocks, the general occurrence of the more differentiated UZc material towards the summit of Hill of Johnston suggests that the cumulate succession is approximately horizontal in this area of the Insch intrusion. Elsewhere in the 'Red Rock Hills' sub-horizontal layering occurs at Hill of Dunideer and Hill of Christ's Kirk, but dips of 50° to the NNW have been recorded at Hill of Newleslie (Gould, 1997).

Interpretation

The Hill of Johnston outcrops provide the clearest evidence available that the parental magma of the 'Younger Basics' was capable of evolving towards extremely felsic and iron-rich compositions, as represented by the rocks of UZb and UZc. Read *et al.* (1961) demonstrated the essential coherence of the Insch olivine-gabbros and associated 'syenogabbros' and 'syenites' of the 'Red Rock Hills' on the basis of geological, petrological and chemical characteristics. They also hinted at a broader association between these rocks (now referred to the Insch UZ) and the peridotites and troctolites at the eastern end of the Insch intrusion (now referred to the LZ).

Clarke and Wadsworth (1970) developed this theme, and extended it to include the hypersthene-gabbros, as representing the intermediate stage (MZ) of the complete fractionation sequence. They identified the bulk of the rocks in the intrusion as cumulates, on textural grounds, and confirmed the general progression of mineral compositions expected in such a situation. Wadsworth (1986) continued this approach for the Insch UZ, and was able to construct a detailed cumulate succession, emphasizing the trend towards extreme iron enrichment, and comparing this with broadly similar trends in the Bushveld (South Africa), Skaergaard (Greenland) and Fongen–Hyllingen (Norway) layered intrusions. The Insch UZb rocks, particularly well displayed at Hill of Johnston, are probably the uppermost true cumulates in the succession, and are noteworthy for the large number of cumulus minerals represented (olivine, orthopyroxene, clinopyroxene, plagioclase, alkali feldspar, apatite, zircon and Fe-Ti oxide). The UZc rocks are generally interpreted as having crystallized from the residual magma after significant crystal settling had ceased (Read *et al.*, 1961; Clarke and Wadsworth, 1970; Wadsworth, 1986). This is also indicated by the veins of broadly similar quartz-syenite found locally within UZb.

Conclusions

The Hill of Johnston GCR site is particularly important in providing information about the later stages (UZ) of crystallization in the 'Younger Basics' in general, and the Insch intrusion in particular. In this way, it is complementary to the LZ (Hill of Barra and Bin Quarry) and MZ (Pitscurry and Legatesden) GCR sites. The most significant geochemical aspects of the Hill of Johnston rocks are their pronounced iron, barium and zirconium enrichment, as indicated by the olivine and pyroxenes (UZb and c), alkali feldspar (UZb) and cumulus zircon (UZb), respectively. Similar features are known to result from extreme fractionation of tholeiitic basic magma in other layered intrusions worldwide, e.g. Bushveld, Skaergaard and Fongen–Hyllingen, but the Hill of Johnston is the only example in Britain.

HILL OF CREAGDEARG (NJ 453 259)

W. J. Wadsworth

Introduction

In addition to the main cumulate fractionation sequence of the 'Younger Basic' intrusions, as seen in the Insch, Belhelvie and Huntly intrusions, there are other igneous rocks that are spatially associated with the cumulates and may be genetically related to them. These are particularly characteristic of the western end of the Insch intrusion and of the Boganclogh intrusion, which is the westward continuation of the Insch intrusion (Busrewil *et al.*, 1973; Gould, 1997). The Boganclogh area contains three principal igneous rock types: a northern strip of ferrodiorites, a central region of quartz-biotite norites, and a southern belt of heavily serpentinized ultramafic rocks (Figure 3.2). The ferrodiorites are broadly equivalent to the Insch Upper Zone; the quartz-biotite norites are also represented in the Insch mass, but are very poorly exposed there; serpentinites occur sporadically along the western part of the southern margin of the Insch mass (Read, 1956), but reach their maximum development in the Boganclogh area (Blyth, 1969).

The central belt of quartz-biotite norites at Boganclogh contains smaller areas of the other components. Two such areas occur at Hill of Creagdearg and at nearby Red Craig (Figure 3.13). In each case, well-exposed ultramafic rocks (peridotites) with an unusually high proportion of fresh olivine, are surrounded by typical quartz-biotite norites. The names of the two hills are derived from the characteristic reddish-brown colour of the weathered surfaces of the peridotite (Figure 3.14) which stand out in marked contrast to the grey-weathering norites.

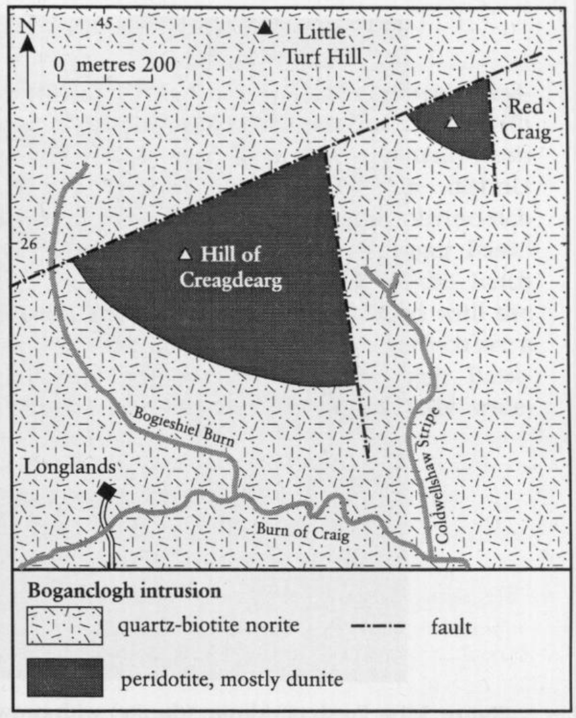

Figure 3.13 Map of the Hill of Creagdearg and Red Craig area, Boganclogh intrusion, from BGS 1:10 000 sheets NJ42NW (1991) and NJ42NE (1991).

Description

The two areas of peridotite (Hill of Creagdearg and Red Craig) can be clearly delineated, because of the excellent exposure and the obvious colour contrast between the main rock types in the field. The northern and eastern margins of both peridotites appear to be steep and faulted, but towards the SW the junction with the norites is believed to be gently dipping and is probably an original igneous contact (Gould, 1997). Despite this, there is no unambiguous evidence of relative age. The peridotites appear to be totally unaffected in proximity to the norites, and there is no evidence of inclusions or veining of one rock type by the other. The only hint of age relationships is a slight reduction of grain size in the quartz-biotite norite towards its contact with peridotite, although this is not very pronounced and may be unrelated to marginal chilling, since the norite shows considerable variations in grain size throughout its outcrop.

The peridotites appear to be essentially massive and structureless in the field, with no evidence of small-scale layering such as is seen in the Insch Lower Zone cumulates at the Hill of Barra GCR site. They consist of a high proportion (80 to 95%) of olivine, together with minor spinel and scattered orthopyroxene crystals. The degree of serpentinization is variable, but in general these rocks are remarkably fresh compared with the ultramafic rocks along the southern margin of the Insch–Boganclogh mass.

In thin section, the olivine crystals average approximately 2 mm in length, with polygonal boundaries showing 120° angles at triple junctions. The spinel is chromite, with translucent red-brown margins, and occurs both within and between the olivine crystals. The orthopyroxene occurs as sparse grains, similar in size and shape to the olivines, and in places displaying exsolution lamellae of augite. Olivine and orthopyroxene are altered to antigorite and bastite respectively. The olivine (Fo_{91}) and orthopyroxene (En_{91}) are significantly more magnesian than in

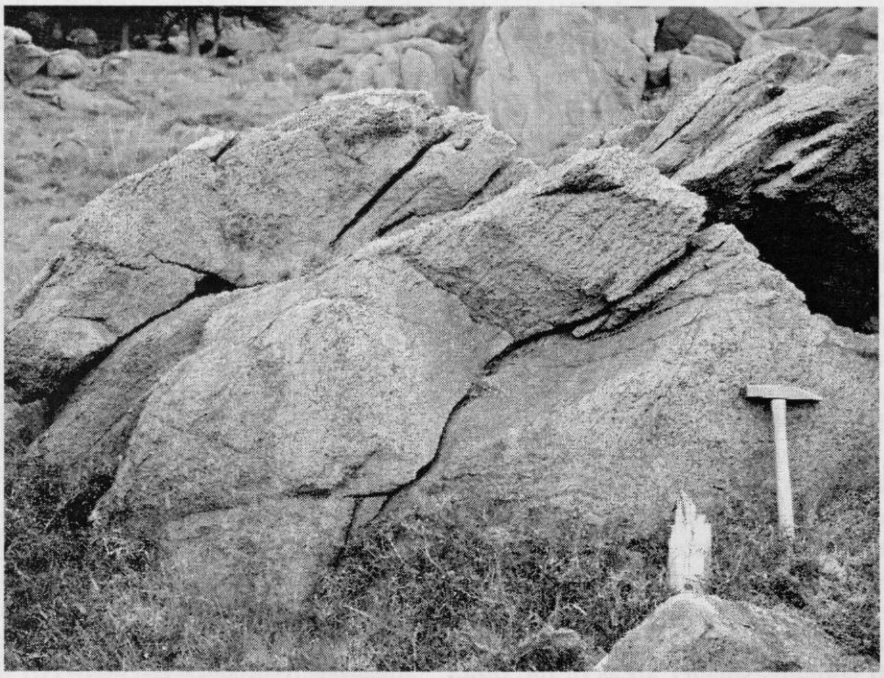

Figure 3.14 Fresh peridotite (dunite) with brown-weathering crust, Red Craig, Boganclogh intrusion. (Photo: BGS no. D4532.)

the LZa cumulates at Insch or Belhelvie, where olivine is typically Fo_{87-86}.

The adjacent quartz-biotite norites are easily distinguished from the ultramafic rocks, not only by the grey colour of their weathered surfaces, but by the prominent sub-horizontal jointing, giving rise to distinctive 'slabby', tor-like outcrops. The norites consist of plagioclase (An_{60}), augite ($Ca_{45}Mg_{37}Fe_{18}$), orthopyroxene (En_{55}), poikilitic biotite (up to 20% by volume), hornblende, and interstitial quartz (2 to 3% by volume). Ilmenite and magnetite are typically present and are sometimes accompanied by traces of pyrrhotite.

Interpretation

Although the quartz-biotite norite is clearly part of the 'Younger Basic' magmatic spectrum, being represented in many of the individual intrusions, the status of the ultramafic rocks at Boganclogh is more contentious. From the detailed investigations of Blyth (1969), it is clear that the peridotites at Hill of Creagdearg and Red Craig are essentially part of the main ultramafic belt which lies along the southern margin of the Boganclogh intrusion, and extends eastwards as a series of discontinuous lenses along the southern edge of the Insch intrusion (Read, 1956). It is also clear that these ultramafic rocks are associated with major shear zones, and that the southern boundary of the Insch–Boganclogh mass is tectonic. This accounts for the highly serpentinized nature of these rocks generally, but inevitably tends to obscure evidence of their primary origin. For this reason, the relatively unserpentinized peridotites from Hill of Creagdearg and Red Craig are particularly significant.

Hinxman and Wilson (1890) suggested a possible correlation between the serpentinites of the southern marginal belt, and the broadly similar rocks at the eastern end of the Insch intrusion (now referred to as LZa cumulates). Both Read (1956) and Blyth (1969) discounted this correlation, emphasizing certain differences between the two ultramafic associations. Blyth, in particular, stressed the absence of any gradations to more gabbroic lithologies in the Boganclogh peridotites and serpentinites. However, neither Read nor Blyth speculated further about the source of the strongly tectonized serpentinites, except to imply that they came 'from depth'.

Busrewil *et al.* (1973), on the other hand, believed that the mineralogical and textural evidence, especially from the Hill of Creagdearg peridotites, supports the link between the LZ cumulates and the marginal serpentinites. The olivine compositions, in particular, appear to show overlap between the two occurrences. However, more recent investigations have shown that the Hill of Creagdearg peridotites contain distinctly more magnesian olivines (Fo_{91}) than in the LZa cumulates (Fo_{87-86}). This, together with the lack of feldspar, and the absence of convincing cumulate textures, now re-inforce Blyth's view that the Boganclogh ultramafic rocks are not related to the cumulate succession. Further, the olivine (and orthopyroxene) compositions suggest a close connection with mantle peridotites, either in the form of tectonically emplaced mantle fragments, or as the early crystallization products of very primitive, mantle-derived, magma, which have subsequently been involved in major tectonic disturbance.

In this connection, it is of interest to note the occurrence of similar, highly magnesian olivines in the Succoth–Brown Hill intrusion (S–BH), to the NW of Boganclogh (Gunn *et al.*, 1996), although the crystallization sequence olivine–clinopyroxene–plagioclase at S–BH is in marked contrast to the early appearance of orthopyroxene in the Boganclogh peridotites, suggesting a fundamentally different, possibly more calc-alkaline magma (Styles, 1994). Like the southern margin of the Insch–Boganclogh mass, the S–BH intrusion is also associated with a major shear zone (within the Portsoy Lineament) and the latter is believed to indicate a significant magmatic event earlier than the 'Younger Basic' intrusions. On this basis the S–BH intrusion, and possibly the Boganclogh ultramafic rocks, provide support for Read's original (1919) idea that two main episodes ('Older' and 'Younger') of basic magmatism are represented in NE Scotland.

The quartz-biotite norites are certainly part of the 'Younger Basic' activity, and therefore are probably significantly younger than the peridotites at Hill of Creagdearg, although the age relationships are not convincingly displayed in the field. The quartz-biotite norites are generally interpreted as samples of basic magma similar to the parental magma of the cumulate succession, but which crystallized under relatively hydrous conditions (Wadsworth, 1988). They probably represent in-situ crystallization without significant crystal settling.

Conclusions

The Hill of Creagdearg GCR site provides evidence of primitive mafic magma associated with a 'Younger Basic' intrusion. The unusually fresh peridotites are believed to be quite distinct from, and possibly older than, the olivine-rich Lower Zone cumulates of the 'Younger Basic' suite, found at the eastern end of the Insch intrusion and at Belhelvie. Associated with the peridotites are quartz-biotite norites which are a significant component of the 'Younger Basic' activity in general, but are particularly widespread at Boganclogh.

BALMEDIE QUARRY (NJ 944 182)

W. J. Wadsworth

Introduction

In addition to the wide range of igneous components found in the 'Younger Basic' intrusions, other variations have been imposed by later tectonic events. Late Caledonian (D3) folding was responsible for the variable, and often steep, dips in the layered cumulates, and may have caused some disruption of the original igneous complex into smaller bodies. Another aspect of the post-intrusion structural disturbance was the development of major shear zones, which may have played an important part in the final emplacement and configuration of the 'Younger Basic' masses (Ashcroft *et al.*, 1984). These shear zones are associated particularly with the present margins of the intrusions, notably the Insch–Boganclogh mass (Figure 3.2), but they also produced significant modifications internally. These modifications may be dominantly mineralogical, involving the progressive amphibolitization of the gabbros, or textural, involving the formation of gabbro mylonites, or a combination of both effects.

One of the most prominent shear zones runs approximately N–S from near Fraserburgh southwards towards Aberdeen and, near its southern end, it intersects the Belhelvie intrusion (Figure 3.15). Although enough of the intrusion is unaffected for it to be possible to establish a detailed cumulate stratigraphy (Munro, 1986; Wadsworth, 1991), substantial areas have been thoroughly amphibolitized (Stewart, 1946) and, locally at least, show evidence of pronounced textural changes with the production of schistose (or flaser) gabbros and mylonites. Excellent examples of both types of modification associated with the shear zones are seen in Balmedie Quarry, just north of Belhelvie village, and have been fully documented. (Boyd and Munro, 1978; Munro, 1986).

Description

Balmedie Quarry is situated in the centre of an approximately 1 km-wide shear-zone stretching northwards from Belhelvie village to the eastern margin of the Belhelvie intrusion (Figure 3.15). The original cumulates are believed to represent the upper part (LZc) of the Belhelvie succession (Wadsworth, 1991) and consist of cumulus olivine (Fo_{77}), orthopyroxene (En_{79}), augite ($Ca_{45}Mg_{45}Fe_{10}$) and plagioclase (An_{75}). Primary layering in the least-deformed examples shows a wide variety of modal variations, with all graduations between mafic (peridotite) and felsic (anorthosite) layers, although most of the these cumulates are gabbroic or noritic.

Deformation affects the whole area of the quarry, but the intensity varies considerably, even over a scale of a few centimetres. No systematic pattern of variation is recognizable within the area studied. In the initial stages of modification the original mineralogy is retained, but the texture is modified to the extent of producing localized strain effects in individual crystals, as well as some degree of marginal granulation and minor recrystallization. Where the deformation was more intense, the textural changes are accompanied by the development of aggregates of secondary amphibole crystals in place of the original pyroxene. With increasing degree of deformation the original igneous textures are obliterated, and the resultant rock consists of lensoid clusters of amphibole, biotite and opaque minerals (representing the original ferromagnesian minerals) and irregular plagioclase porphyroclasts, in a fine-grained aggregate of mafic material.

The most intense deformation is restricted to

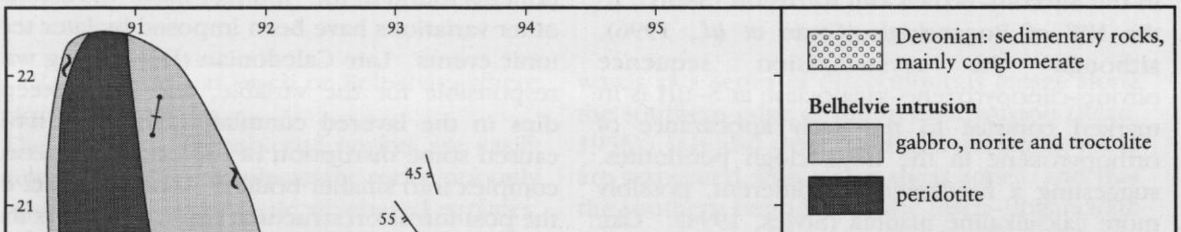

Figure 3.15 Map of the northern part of the Belhelvie intrusion, showing the position of the Balmedie Quarry GCR site in relation to a major shear zone, after Boyd and Munro (1978).

Figure 3.16 Balmeddie Quarry; block of deformed mafic rock, cut by narrow zones of mylonite that in part conform with and in part transgress an earlier foliation. Scale in centimetres. (Photo: from Boyd and Munro, 1978, plate 1a.)

narrow zones (generally less than 1 cm wide), which cut the more typically foliated gabbros in sinuous fashion (Figure 3.16). The rocks in these zones are essentially mylonites, and consist of porphyroclasts of frayed plagioclase (and more rarely amphibole or pyroxene) in a groundmass of amphibole, biotite, opaque minerals and plagioclase. The larger feldspar fragments typically retain their original composition (An_{80-75}) in their cores, but have strongly zoned margins (An_{45-40}). Large crystals of quartz occur locally, and there is considerable evidence that there has been an episode of late-stage silicification. Although the detailed attitude of both the general foliation, and the intensely mylonitized zones, is extremely variable, there is an overall tendency for these structures to strike approximately N–S, and to display steep dips. Some of the more sinuous mylonite zones form minor folds with steeply plunging axes.

In addition to the deformed gabbroic rocks, there is a small strip of hornfelsed and mylonitized metasedimentary rocks (10–15 m wide) in the eastern part of the quarry, and there are also some granitic minor intrusions, which are generally medium grained, but include tourmaline-bearing pegmatitic types. Most of these granites are undeformed, and appear to post-date the foliation in the mafic rocks but some of them have been affected by shearing, at least locally.

Interpretation

In general, the shear zones appear to represent localized regions of strong mechanical distortion and dislocation, accompanied by low pressure (2–3 kbar), amphibolite facies (600°C) metamorphism, which occurred soon after the intrusion and crystallization of the 'Younger Basic' igneous bodies approximately 470 Ma ago (Ashcroft *et al.*, 1984). In Balmedie Quarry, the shear zone is itself cut by granitic minor intrusions, one of which has been radiometrically dated at 462 ± 5 Ma (Pankhurst, 1982). Most of these granitic intrusions are undeformed, but some of them show evidence of marginal crushing and shearing (Munro, 1986). This suggests that there may have been more than one episode of granite veining, or that deformation continued, at least on a reduced scale, after the 'Younger Basic' igneous activity had ceased.

The textural features of the modified gabbros in Balmedie Quarry suggest that a pervasive foliation was developed at an early stage in the deformation history, resulting in relatively limited shearing, granulation and recrystallization. This then seems to have been followed by an episode of more intense deformation, restricted to the narrow mylonite zones. The broadly similar structural trends of the foliation and the mylonite zones suggests that the two types of deformation were related, and represent a continuum of structural disturbance rather than discrete events. From the mineralogical evidence, the initial stages of deformation appear to have been simply cataclastic, but the later stages were characterized by recrystallization in the presence of volatile components, resulting in the formation of amphibole, biotite and relatively sodic plagioclase at the expense of the original pyroxenes and calcic plagioclase (Kneller and Leslie, 1984). It is also evident that additional silica was added during this stage (Boyd and Munro, 1978).

Conclusions

Balmedie Quarry is important for the remarkably clear evidence that it exhibits of the effects of post-magmatic tectonic events on the original layered gabbros and norites of the 'Younger Basic' intrusions. These effects are partly mechanical, resulting in locally intense shearing and crushing, to give rise to flaser gabbros and mylonites. Mineralogical changes are also represented; these involve metamorphism of the original high-temperature igneous assemblage (olivine, pyroxenes, calcic plagioclase) to a lower grade (amphibolite facies) assemblage of amphibole, biotite and sodic plagioclase, together with additional silica. The main period of deformation was followed by intrusion of minor granite sheets, some of which are pegmatitic.

TOWIE WOOD (NJ 933 383)

POTENTIAL GCR SITE

W. J. Wadsworth

Introduction

One of the most distinctive aspects of the 'Younger Basic' intrusions is the local occurrence of a marginal facies of cordierite norites rich in xenolithic material derived from the Dalradian country rock. These are known from both the Insch and Huntly intrusions, but reach their maximum development in the Haddo House–Arnage intrusion (Read, 1923, 1935; Read and Farquhar, 1952; Gribble, 1968), notably in the classic, but poorly exposed, areas of Craigmuir Wood and Wood of Schivas, in the Ythan Valley. Here the least modified component of the 'Younger Basic' intrusions is quartz-norite, although olivine-norite occurs locally. The xenolithic complexes comprise abundant small fragments of hornfels in a matrix of igneous aspect texturally, but with a distinctive mineralogy involving various proportions of plagioclase, cordierite, biotite, orthopyroxene and quartz, sometimes accompanied by garnet and alkali feldspar. These rocks are generally referred to as cordierite norites although some of them are quartz-rich and would be more accurately described as tonalites. The xenoliths represent a wide range of compositions, but fall into two principal categories, namely silica-deficient, aluminous types and silica-rich types. These are believed to represent argillaceous and quartz-rich Dalradian metasedimentary rocks, respectively. Local concentrations of calc-silicate hornfels xenoliths (e.g. from Craigmuir Wood, near Haddo House) were presumably derived from calcareous layers in the Dalradian (Read, 1935). The cordierite norites and associated xenoliths have generally been taken to represent some form of interaction between 'Younger Basic' magmas and the adjacent country rock, especially in the roof region of the original intrusions, but there has been considerable disagreement about the precise nature of this interaction.

Description

The Towie Wood site lies towards the northern extremity of the eastern or Arnage area of the Haddo House–Arnage intrusion (Figure 3.17). Most of the exposures are found on, or close to, the former railway line and in the adjacent Ebrie Burn. At Towie Wood, the old railway cutting provides exposures of quartz-norite, while a small, but compact and well-exposed area of xenolithic material occurs just to the south, on the eastern side of the railway trackbed, where it forms a distinct knoll (Munro and Leslie, 1987).

The quartz-norite, which is essentially homogenous and xenolith-free, consists of plagioclase (An_{60-50}), orthopyroxene (En_{68-55}), clinopyroxene, hornblende, biotite and quartz. It is of medium- to coarse-grain size, with conspicuous biotite crystals (Munro and Leslie, 1987).

The xenolithic complex has an igneous-textured matrix of rather variable grain size and modal proportions, in which the principal minerals are plagioclase, cordierite, biotite, orthopyroxene, garnet and quartz. This cordierite norite is intimately associated with xenolithic material, although the relationship between the two components is by no means constant. Locally the xenoliths are dominant, and appear to represent relatively undisturbed country rock invaded by veins and stringers of norite. This arrangement was taken by Read (1923) to indicate proximity to the roof of the intrusion. Elsewhere, xenoliths and matrix are approximately equal in abundance, with an apparently chaotic mixture of xenolith types in random orientation. This type of assemblage grades into more homogeneous cordierite norites, with fewer relict xenoliths.

Two principal types of xenolith are present. One type is quartz-rich, presumably representing more psammitic Dalradian material. These tend to be angular in shape, and show all size gradations from centimetres to tens of centimetres across; some display relict bedding structures. In thin section they are seen to be plagioclase-quartz-biotite hornfelses, with sporadic garnet, cordierite or orthopyroxene. The other type comprises compact, homogeneous blue-grey hornfelses derived from pelitic Dalradian metasediments. They tend to be smaller (generally less than 5 cm across) and more rounded than the siliceous xenoliths. Mineralogically, they are silica deficient, consisting of variable proportions of cordierite, plagioclase, spinel, sillimanite and garnet, accompanied by corundum, orthopyroxene or biotite. Some of the argillaceous xenoliths are composed entirely of cordierite. In addition to the xenoliths and cordierite norite matrix, quartz-rich veins and stringers are quite widespread.

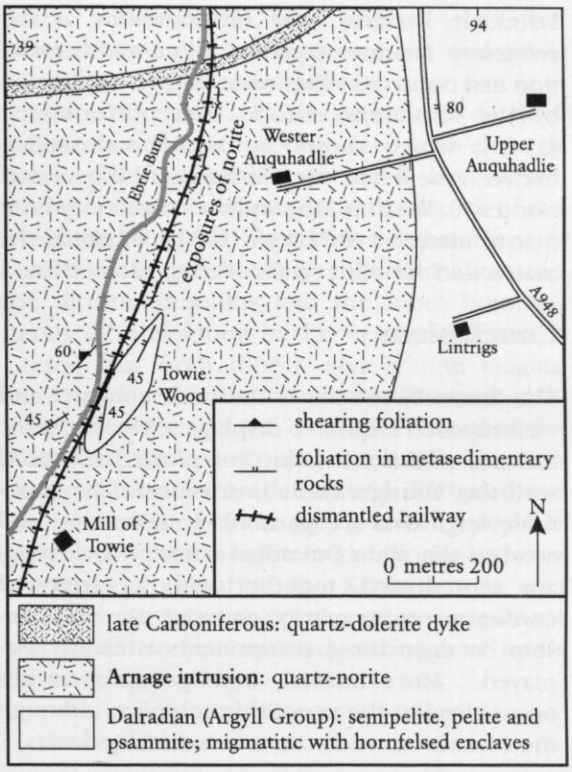

Figure 3.17 Map of the area around the Towie Wood GCR site, Arnage–Haddo intrusion, from BGS 1:10 000 Sheet NJ93NW (1986) by W. Ashcroft and M. Munro, Aberdeen University.

Interpretation

Although there has been broad agreement that the cordierite norites and associated xenolithic assemblages are genetically related, and were developed as part of the 'Younger Basic' magmatic event, various explanations of their precise relationship and significance have been presented.

Read (1923) considered the cordierite norites to represent basic magma which had been contaminated by assimilation of country rock. He suggested that Si, Ca, Na and K had been selectively extracted from Dalradian pelites by the magma, leaving a residue of silica-deficient, aluminous xenoliths. He also regarded the more homogeneous quartz-norites of the Haddo House–Arnage area, as mildly contaminated intermediates between the cordierite norites and the olivine-gabbros more typical of the 'Younger Basic' activity in general. Read subsequently re-interpreted these xenolithic rocks as parts of an older migmatite complex implying that the associated 'Younger Basic' norites were not actively involved in their formation (Read and Farquhar, 1952). However, he continued to invoke large-scale regional contamination of 'Younger Basic' magma with Dalradian pelitic material to explain the apparently anomalous hypersthene-gabbro unit (now interpreted as Middle Zone cumulates) in the Insch intrusion (Read *et al.*, 1965), and appeared to accept a contamination origin for xenolithic cordierite norites occurring locally at the margin of this intrusion.

Gribble (1968) re-investigated the xenolithic complexes at Haddo House–Arnage, and concluded that the 'Younger Basic' intrusions had played a vital part in their formation by raising temperatures in the adjacent country rocks, so that they began to melt. The cordierite norites were believed to represent partial melts of the

Dalradian material, and the xenoliths as the refractory residues (restites) after melt extraction had occurred. This conclusion is supported by the strontium isotope data of Pankhurst (1969), which shows no significant overlap between the initial $^{86}Sr/^{87}Sr$ ratios for the normal norites (0.706 to 0.715) and the cordierite norite matrix material (0.720 to 0.731), whereas the matrix and xenolith ratios overlap each other.

Conclusions

The Towie Wood site is the most compact and well-exposed locality to display the characteristic features of the xenolithic complexes associated with the 'Younger Basic' intrusions. The xenolithic fragments are particularly abundant, and most of the main Dalradian country rock types are represented, together with a variety of cordierite norite matrix material; the relationship between these components is clearly displayed. More normal, homogeneous norites occur close to the xenolithic complex, although the contact between the two is not exposed.

CRAIG HALL (NJ 530 292)

W. J. Wadsworth

Introduction

Forming the western margin of the main Insch intrusion, the Kennethmont granite–diorite complex comprises homogeneous granites (both pink and grey varieties) and diorites, together with a group of xenolithic rocks consisting of dioritic fragments in a granitic matrix (Gould, 1997). The complex as a whole is poorly exposed, but the principal components were mapped and described by Sadashivaiah (1954), who suggested that they are essentially unrelated to the 'Younger Basic' magmatic event. He concluded that they represent a later invasion of granitic magma which interacted locally with already consolidated basic rocks, similar to hypersthene-gabbros of the Insch mass, to produce hybrid xenolithic diorites. Read and Haq (1965) provided geochemical data to support these conclusions. Busrewil *et al.* (1975) re-investigated the Kennethmont granite–diorite complex, and recognized that the situation is more complicated than indicated by Sadashivaiah. They showed that two distinct magmas (granitic and dioritic) were responsible for the formation of the xenolithic rocks, and that the 'Younger Basic' rocks were not involved at all. They also realized that the pink granite member of the complex is unrelated to the other rock types, although it is probably of similar age. It has been dated at 453 ± 4 Ma (Pankhurst, 1982), and is probably one of the late tectonic granites.

Because of the poor exposure, and the way in which the principal components of the complex are distributed, it is impossible to identify a compact site in which they are all present. However, the Craig Hall area (Figure 3.18) is important in that the xenolithic assemblages, with diorite fragments in various stages of assimilation in a grey granitic matrix, are well represented. Although exposures are scarce, there is abundant loose material that is believed to be of very local derivation.

Description

All gradations occur between rocks consisting of relatively coherent dioritic xenoliths in apparently unmodified grey granite matrix, to more granodioritic material containing small (millimetre to centimetre) mafic inclusions, with rounded or irregular shapes; these are believed to represent residual, partly digested, xenoliths. The grey granite comprises quartz, microcline, oligoclase and biotite (with minor titanite and apatite), and appears to show all gradations to granodioritic compositions, as plagioclase becomes the dominant feldspar. The dioritic xenoliths are relatively mafic, with pyroxene (mostly clinopyroxene, but some orthopyroxene) hornblende, biotite and titanite all present, although biotite is usually the dominant mineral. Plagioclase (An_{35}) is the principal felsic constituent, although small amounts of quartz occur in some samples. The mafic inclusions in the granodiorite consist of biotite and hornblende. The inclusions are typically finer grained than the acid matrix, and they show gradations from an igneous texture, with a few relict phenocrysts of plagioclase, to a distinctly granular metamorphic texture. Chemical data (Busrewil *et al.*, 1975) show gradational relationships from the xenolithic basic material, through 'contaminated' rocks, with partly digested xenoliths, to the grey granitic matrix.

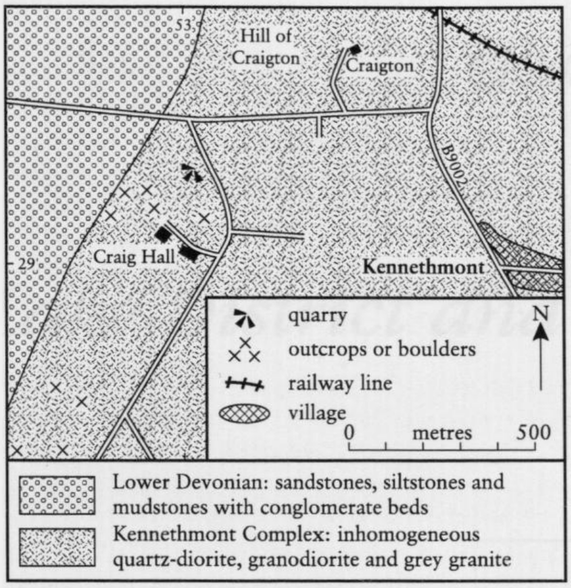

Figure 3.18 Map of the area around the Craig Hall GCR site, Kennethmont, from unpublished BGS maps.

Interpretation

The xenolith-bearing granitic rocks of the Kennethmont granite–diorite complex clearly imply interaction between acid magma and a solidified basic component, but the origin of the latter, and the extent to which hybridization was capable of producing relatively homogeneous intermediate rock types (diorites), has been a controversial issue. Sadashivaiah (1954), followed by Read and Haq (1965) identified the 'Younger Basic' intrusions as the most likely source of the mafic xenoliths, since a variety of suitable compositions was locally available in the Insch intrusion. Of these the hypersthene-gabbros were regarded as the most appropriate protolith. Further, it was implied that the Kennethmont diorites represent the end-products of the hybridization process.

Busrewil *et al.* (1975) presented detailed chemical evidence (especially rare-earth element data) which effectively excluded any of the 'Younger Basic' components as the source of the xenoliths. Instead, they showed that there is considerable geochemical coherence between the dioritic xenoliths and the more homogeneous diorites found in the vicinity. They concluded that both diorite and granite magma were emplaced at about the same time, approximately 465 Ma ago (i.e. perhaps 5 Ma after the 'Younger Basic' event), and that locally the diorite crystallized first, to be invaded, disrupted and partly assimilated by the grey granite. A possible genetic connection between the diorite and grey granite component of the Kennethmont area was envisaged, but the pink granite component was shown to be unrelated, although of much the same age.

Conclusions

The Craig Hall area is of interest in that it provides evidence of a slightly younger magmatic event (the Kennethmont granite–diorite complex), spatially associated with the Insch intrusion, but apparently otherwise unrelated to it. In particular, it is of significance in the occurrence of xenolithic material, superficially resembling the 'Younger Basic' xenolithic complexes (see the Towie Wood site report), but of quite different origin (and age). The xenolithic assemblage of the Kennethmont complex essentially involved the interaction of two magmas (dioritic and granitic), whereas the typical 'Younger Basic' xenolithic association represents local partial melting of adjacent country rock.