Chapter 3 Mid-Ordovician intrusions of the North-east Grampian Highlands of Scotland

Introduction

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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 Ballantrac, 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 orogcnic activity. This has involvcd 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.,* 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 evi dence 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 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 (Figure 3.2) and (Figure 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).

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 'stratigraphicar 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 12 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.

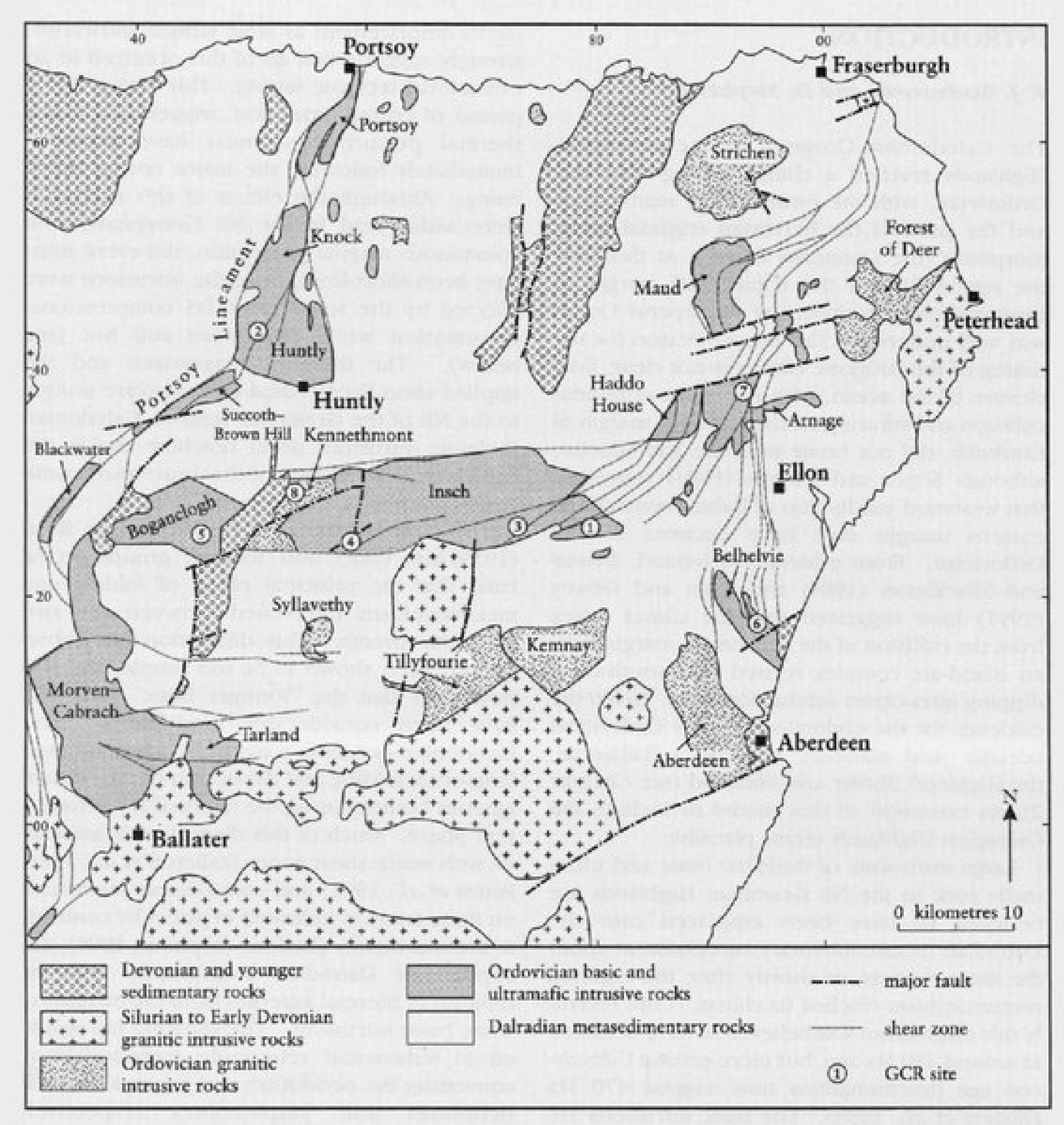
The relationships of the mafic igneous rocks (both 'Older' and 'Younger') of the area, to the more widespread and better-known Caledonian granites is by no means clear-cut. Read (1961), following Barrow (in Barrow and Cunningham Craig, 1912), recognized two principal periods of granite emplacement. His '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, inareas 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 preexisting 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.

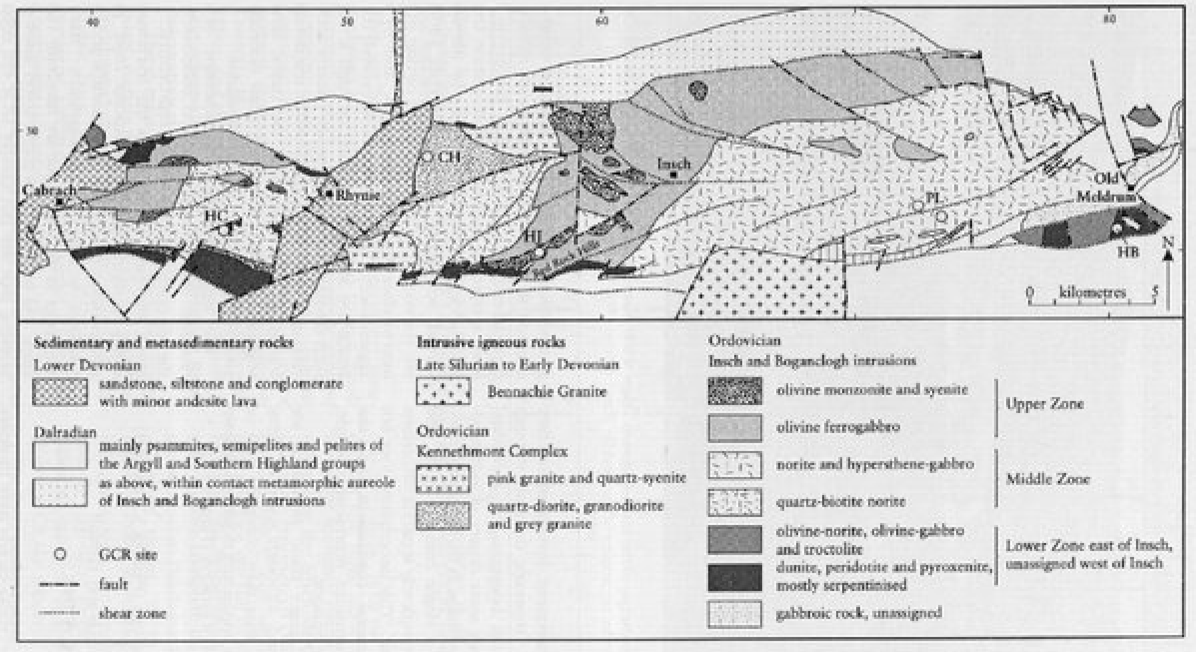
Most of the granites which are spatially associated with the 'Younger Basics' can be classified as late tectonic (Figure 3.1). Two suites are recognized. One consists of diorites, tonalites and granodiorites, with characteristics of a mantle or lower crustal igneous source (I-type); some are foliated 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.

References



(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.



(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.)

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

(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).