Silicate mineralogy of the Middle Zone cumulates and associated gabbroic rocks from the Insch intrusion, NE Scotland

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Abstract

The Middle Zone (MZ) of the Insch intrusion lies in a geographically intermediate position between the Lower Zone (LZ) and Upper Zone (UZ) cumulate sequences, but is more complicated than either in comprising two intricately associated, but texturally distinct, components, the MZ cumulates and the fine-grained granular gabbros (FGG). In addition, there is a minor group of porphyritic granular gabbros (PGG), containing abundant plagioclase phenocrysts. A further variety of gabbroic rock, namely quartz-biotite norite (QBN) occupies a similarly intermediate position in the Boganclogh extension of the main Insch mass. These principal components (MZ cumulates, FGG, and QBN) show considerable mineralogical overlap with each other and with the lower part of the UZ succession (UZa). Unlike the UZ rocks, they are essentially olivine-free (apart from the most basic granular gabbros) and consist mainly of plagioclase, orthopyroxene, and Ca-rich clinopyroxene, with accessory Fe–Ti oxides and minor interstitial biotite and/or hornblende. Mineral compositions are in the range An_{70-55} (plagioclase), En_{71-44} (opx), and $Ca_{46}Mg_{42}Fe_{12}$ to $Ca_{45}Mg_{30}Fe_{25}$ (cpx), but in detail each rock group can be characterized mineralogically as well as texturally. It is concluded that the MZ cumulates and FGG (including PGG) are essentially complementary, formed in different locations, and under slightly different conditions, but in the same magma chamber. The complex relationships between them, and the apparently haphazard geographical variations in mineral compositions, may be the combined results of the magmatic events, possibly including the movement of large xenolithic fragments, and later block faulting. The substantial compositional overlap of the more evolved MZ cumulates by UZa is explained in terms of replenishment by magma of slightly more primitive (and potentially olivine-bearing) composition after the deposition of the MZ. The Boganclogh QBN is believed to represent a more hydrous fraction of the Insch MZ magma.

Introduction

THE Insch intrusion is the largest and petrologically most varied of the Caledonian Newer Gabbros in NE Scotland (Wadsworth, 1982). The ultramafic rocks (Lower Zone or LZ) at the eastern end of the intrusion and the olivine gabbros, syenogabbros and syenites (Upper Zone or UZ) in the more northern and western parts of the intrusion were interpreted by Clarke and Wadsworth (1970) as the early and late stages respectively of a layered cumulate succession. Following Read *et al.* (1961, 1965), Clarke and Wadsworth also recognized a group of essentially olivine-free hypersthene gabbros and norites, geographically intermediate between the other two principal components of the intrusion. These rocks are much more complex and problematical than the LZ and UZ cumulates, and are the principal subject of this account. They comprise two texturally distinct, but closely associated components, one of which is relatively coarse grained with cumulate textures, and was interpreted as representing the Middle Zone (MZ) of the Insch Layered Series, broadly equivalent to the olivine-free intermediate stages of the Skaergaard and Bushveld layered sequences. The other is finer grained, with a distinctive granular texture, and was interpreted as a later gabbroic intrusion. Minor variants of these granular gabbros include olivine-bearing and plagioclase-phyric types.

Preliminary investigations of mineral compositions by Clarke and Wadsworth (1970), based mainly on optical data, showed that the proposed MZ cumulates to some extent filled the mineralogical interval between the LZ and UZ

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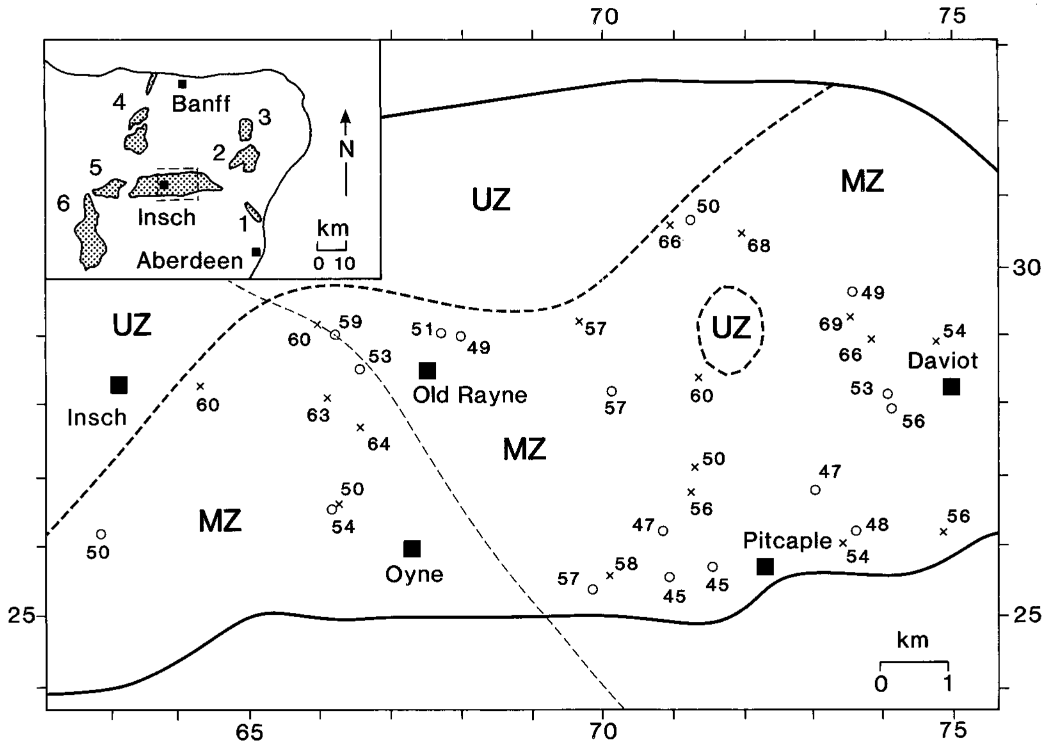

FIG. 1. Geological sketch map of the Middle Zone (MZ) area of the Insch intrusion, showing the approximate boundary (heavy dashed line) with the Upper Zone (UZ), and the position of the gas pipeline (fine dashed line) also referred to by Wadsworth (1986). *In situ* specimen localities are shown as open circles (MZ cumulates) or crosses (FGG), and the associated numbers refer to the En content of the orthopyroxenes. The grid references relate to National Grid Square NJ. The inset map shows the position of the Insch intrusion in relationship to the other Caledonian Newer Gabbros (1 Belhelvie; 2 Haddo-Arnage; 3 Maud; 4 Huntly; 5 Boganclogh; 6 Morven-Cabrach).

rocks, although there appeared to be significant gaps in the cryptic variation sequence (especially in the vicinity of the LZ/MZ boundary) and that there was no clear indication of stratigraphic sequence. The present study consists of a detailed mineralogical re-investigation of the Insch Middle Zone in order to establish the relationship of the proposed MZ cumulates to the LZ and UZ cumulates, and to the associated granular gabbros. In addition, the MZ rocks are compared with another group of broadly similar olivine-free gabbroic rocks from the Boganclogh intrusion (believed to be a westward extension of the Main Insch mass), where they occupy a geographically intermediate position between possible equivalents of the Insch LZ and UZ. These are generally referred to as quartz-biotite norites (Busrewil *et al.*, 1973), and similar rocks also occur in the Morven-Cabrach and Haddo House/Arnage intrusions (Wadsworth, 1982).

In the interests of brevity the following abbreviations are used. The term Middle Zone is applied to the association of coarse-grained and fine-grained (granular) gabbros and is equivalent to the 'hypersthene gabbros' of Read *et al.* (1965). The individual components are designated MZ cumulates* and FGG respectively (with the porphyritic varieties of granular gabbro separately identified as PGG). The quartz-biotite norites of Boganclogh are abbreviated to QBN.

Field relations

MZ rocks occupy a NE-SW trending belt in the eastern half of the Insch intrusion (Fig. 1), between

* It should be emphasized here that the interpretation of these rocks as cumulates is largely based on their textural features, rather than the occurrence of small-scale lithological layering, which is rarely evident, but this interpretation is consistent with their overall distribution in relation to the texturally similar Insch LZ and UZ cumulates.

the ultramafic rocks (LZ) in the east (Ashcroft and Munro, 1978) and the central to north-westerly area of UZ rocks (Wadsworth, 1986). MZ exposures are generally scarce and the area has been affected by a number of major shear zones, especially along the southern margin of the intrusion (Ashcroft *et al.*, 1984). These have caused pronounced local amphibolization of the gabbros, and they may also have disrupted the original stratigraphic sequence of the MZ cumulates and obscured the primary relationships between the various gabbro components of the MZ. Such disruption has certainly affected the LZ rocks at the extreme eastern end of Insch (Ashcroft and Munro, 1978), where the effect of the shear zones has been compounded by later N–S and NW–SE faults. However, it must be emphasized that the essential coherence of the MZ, with respect to both the LZ and MZ, has been maintained despite these tectonic disturbances. The only departure from a clear-cut distribution of LZ, MZ, and UZ rock types is the occurrence of a small area of UZ rocks, forming relatively high ground WNW of Daviot (Fig. 1), and this can be regarded as simple outlier of UZ if it is assumed that the attitude of the layered succession is close to horizontal in this part of the intrusion.

Although the MZ as a whole forms a well-defined unit between the LZ and UZ parts of the intrusion, the distribution and inter-relationships of the various components within the MZ is poorly known. It is impossible to separate the MZ cumulates from the granular gabbros by conventional mapping because of poor exposure, and the intimate association of the two main rock types. In general it is unusual to find cumulates and granular gabbros in the same outcrop, but in Pitscurry Quarry just north of Pitcaple (Grid Ref. NJ 728 267), the main working face in the northern part of the quarry exposes cumulates at its western end, FGG in the centre and PGG to the east. These units appear to be near-vertical in attitude, but there is no direct evidence of relative ages. The change from one textural type to another appears to be gradational over a few centimetres, and there is no sign of veining of one rock type by another. The situation is further obscured by prominent jointing and shearing, and also by amphibolization associated with the intrusion of later granite pegmatite sheets. Rather similar gradations are seen in the nearby Legatesden Quarry (NJ 737 262). Elsewhere there are local variations of grain size and texture, resulting in fine granular areas within generally coarse-grained gabbros (and vice versa).

However, the exposures on Candle Hill (NJ 662 265), 1 km WNW of Oyne, are more informative. Here the MZ cumulates display unusually well-developed layering, dipping northwards at angles between 30° and 50°. This comprises not only centimetre-scale variations in modal proportions of felsic and mafic constituents, but also a layer (5–7 m thick) which contains abundant xenoliths. These tend to be distinctly tabular in shape, rarely more than 15 cm in length, and exhibit a strongly preferred orientation parallel to the modal layering. They are generally much more feldspathic than their immediate matrix, and are characterized by a fine-grained granular texture, very similar to normal FGG. The matrix, which forms a very small proportion of the xenolithic layer, is texturally and mineralogically similar to the more mafic component of the nearby cumulate layers.

Elsewhere, small-scale layering within the MZ cumulates is rarely seen *in situ*, although it is sometimes present in the abundant and widely-scattered boulders of coarse-grained hypersthene gabbro. *In situ* examples are entirely restricted to the southeastern part of the MZ area, and the dips are generally 25–50° towards the WNW, NW or N. This evidence is consistent with the general north-westward stratigraphic progression from LZ to UZ rocks, and it was used by Clarke and Wadsworth (1970) as the basis for estimating the thickness of the MZ (approximately 2 km).

Petrology

The various components of the Insch MZ are mineralogically similar, comprising essential plagioclase, two pyroxenes (Ca-rich cpx and Ca-poor opx), and Fe–Ti oxide, with minor hornblende and/or biotite. In addition, olivine occurs in the most basic FGG, and in PGG, while quartz is generally present in QBN. However, the textural differences are always clear-cut.

The MZ cumulates are characterized by their relatively coarse grain size (generally > 1 mm) and the euhedral to subhedral shape of the plagioclase, pyroxenes, and opaque oxides. Plagioclase typically constitutes about 50% by volume, with orthopyroxene more abundant than clinopyroxene, but more feldspathic variants (tending towards anorthosite) are encountered locally, especially where small-scale layering is apparent. Minor interstitial biotite is usually present, sometimes accompanied by amphibole. Although the textures are entirely consistent with the interpretation of these rocks as cumulates, they do not often develop a preferred orientation of tabular plagioclase or prismatic pyroxene crystals. The cumulus grains rarely display marginal zoning, suggesting that these rocks are adcumulates, and the ubiquitous interstitial biotite is never abundant enough to warrant the term mesocumulate, as

Table 1 Summary of Insch Middle Zone (MZ) mineralogy

Sample	Locality (Grid Ref.)	Olivine Fo	Orthopyroxene En	Clinopyroxene Ca	Mg	Fe	(Mg#)	Plagioclase Mean An	(range)	Amphibole Mg#	Biotite Mg#
	MZ cumulates										
CM1	(701 254)[1]	-	44.2[2]	44.9	30.5	24.5	(55.4)	55.5	(53.7 - 58.4)	-	41.8
254	(715 257)	-	45.7[2]	44.8	31.7	23.5	(57.5)	56.6	(54.7 - 58.5)	43.0	43.6
PY1	(729 267)	-	46.5[2]	45.2	32.0	22.8	(58.3)		n.a.	-	48.9
152	(735 295)	-	49.2[2]	45.2	32.8	21.9	(59.9)	58.0	(55.0 - 60.2)	-	57.0
HD3	(741 280)	-	52.5[2]	45.3	34.1	20.6	(62.3)	59.3	(57.4 - 61.7)	-	n.a.
HD2	(740 279)	-	55.7	45.5	35.6	18.9	(65.3)	60.5	(58.8 - 63.2)	-	n.a.
M39	(661 290)	-	59.1	45.7	37.3	17.0	(68.7)	62.4	(60.7 - 63.7)	59.7	60.0
CC2	(758 268)[1]	-	71.3	45.6	42.5	11.9	(78.1)	70.7	(69.0 - 74.4)	-	69.8
	FGG (including PGG*)										
FB3	(712 270)	-	50.3[2]	45.6	33.6	20.8	(61.7)	62.0	(59.2 - 66.5)	-	n.a.
19	(747 289)	-	54.2	45.9	35.3	18.8	(65.3)	63.5	(59.8 - 66.1)	56.0	48.1
R	(701 259)	-	58.1	45.3	37.0	17.7	(67.7)	64.5	(62.5 - 66.2)	n.a.	n.a.
75	(643 282)	-	60.4	44.6	38.2	17.2	(68.9)		n.a.	57.2	58.4
1023	(660 280)	-	63.3	45.0	38.8	16.2	(70.5)	65.5	(63.5 - 66.9)	n.a.	n.a.
S	(665 275)	-	64.4	44.9	39.6	15.5	(72.0)		n.a.	-	-
CN1*	(708 306)	57.2	66.2	45.4	39.5	15.1	(72.3)	70.3	(67.0 - 72.4)[3]	60.4	n.a.
V	(719 304)	61.6	68.4	46.1	39.9	14.0	(74.0)	66.1	(64.1 - 67.1)	64.0	72.0
PY3*	(730 267)	62.6	-	45.9	39.8	14.3	(73.6)	69.3	(66.1 - 72.9)[3]	n.a.	n.a.
PY2	(729 267)	62.8	-	45.8	40.5	13.7	(74.7)		n.a.	n.a.	-
SS1	(735 293)	63.9	69.4	46.4	40.2	13.4	(75.1)	66.4	(65.3 - 67.6)	65.6	-
	QBN (Boganclogh)										
BG43	(445 278)	-	51.2	44.9	35.0	20.2	(63.4)	Zoned An 68.1 → 47.9		-	50.9
BG29	(416 257)	-	52.6	44.8	35.5	19.7	(64.4)		n.a.	54.4	51.4
BG11	(418 255)	-	53.0	45.2	36.3	18.5	(66.3)	Zoned An 69.6 → 49.6		57.9	52.0
BG14	(452 252)	-	55.9	45.0	37.1	17.9	(67.4)		n.a.	61.2	55.2
BG4	(424 262)	-	57.0	44.6	37.8	17.6	(68.2)	Zoned An 72.2 → 52.2		-	58.4

n.a. = not analysed

Mg# = 100 x Mg/(Mg+Fe)

The grid references relate to National Grid Square NJ

1 not *in situ*

2 inverted pigeonite

3 groundmass plagioclase (phenocrysts An_{79-80})

defined by Irvine (1982). In general, the MZ cumulates are texturally similar to the UZ cumulates (Wadsworth, 1986), but unlike the latter they never contain olivine or apatite.

The granular gabbros are distinguished from the cumulates by their much smaller grain size (generally < 0.5 mm) and their distinctive texture. In terms of grain size these rocks could be described as dolerites, but they never display the characteristic interlocking doleritic texture, and in view of their close affinities to genuinely gabbroic rocks, the term gabbro is preferred in this context. In detail, their textures vary from almost granoblastic, with rounded or 'blebby' grains, to a more typical granular mosaic of subhedral polygonal crystals. In some rocks this granular texture grades locally into areas in which more elongate subhedral crystals of plagioclase and pyroxene tend to lie in subparallel orientation. The modal proportions are fairly constant, with approximately equal proportions of plagioclase to pyroxene, and orthopyroxene to clinopyroxene. Fe–Ti oxides are always present (up to 5% by volume) and minor amphibole, sometimes accompanied by biotite, often occurs interstitially. The rocks of the PGG sub-group can be matched almost exactly in terms of their groundmass mineralogy and texture with members of the FGG suite, and are only distinguished by their large plagioclase phenocrysts, which often comprise between 50 and 70% modally, so that in the field these rocks are easily confused with coarse-grained gabbros. The plagioclase phenocrysts, which tend to be subhedral, are typically between 5 and 10 mm in cross-section, and show no sign of a preferred orientation. The other principal minerals in the PGG (orthopyroxene, clinopyroxene, and olivine) are restricted to the groundmass.

The quartz–biotite norites, which form most of

Table 2 Representative analyses of orthopyroxenes (MZ cumulates)

	CC2	M39	HD2	HD3	152	PY1	254	CM1
SiO_2	53.15	51.53	50.89	50.75	50.70	50.49	50.53	49.88
TiO_2	-	0.30	0.30	0.24	0.29	0.23	-	-
Al_2O_3	0.94	1.32	1.13	1.23	0.89	0.96	1.01	1.00
FeO+	18.59	24.73	26.36	28.20	30.39	31.22	31.95	32.08
MnO	0.49	0.58	0.64	0.58	0.62	0.55	0.65	0.71
MgO	25.86	20.06	18.61	17.48	16.53	15.24	15.08	14.26
CaO	0.80	1.10	1.44	1.58	1.26	1.15	0.93	1.34
Total	99.83	99.62	99.37	100.06	100.68	99.84	100.15	99.27
Cations to 6 oxygens								
Si	1.952	1.956	1.956	1.954	1.958	1.973	1.974	1.973
Ti	0.000	0.009	0.009	0.007	0.008	0.007	0.000	0.000
Al	0.041	0.059	0.051	0.056	0.041	0.044	0.046	0.046
Fe	0.571	0.785	0.847	0.908	0.982	1.020	1.044	1.062
Mn	0.015	0.019	0.021	0.019	0.020	0.018	0.021	0.024
Mg	1.416	1.135	1.066	1.003	0.952	0.888	0.878	0.841
Ca	0.031	0.045	0.059	0.065	0.052	0.048	0.039	0.057
Ca	1.5	2.3	3.0	3.3	2.6	2.5	2.0	2.9
Mg	70.2	57.8	54.1	50.8	47.9	45.4	44.8	42.9
Fe	28.3	39.9	42.9	45.9	49.5	52.1	53.2	54.2
En	71.3	59.1	55.7	52.5	49.2	46.5	45.7	44.2

+ Total Fe as FeO

the central area of the Boganclogh extension of the Insch intrusion (Busrewil *et al.*, 1973) are broadly similar in grain size to the MZ cumulates, but are characterized mineralogically by the relative abundance of biotite and the occurrence of interstitial quartz (associated with minor apatite and zircon). Texturally they do not appear to be cumulates, being dominated by randomly orientated and strongly zoned plagioclase crystals, interlocked with subhedral pyroxenes and poikilitic biotite, amphibole, and Fe–Ti oxides.

Mineralogy

A preliminary microprobe study of orthopyroxenes from most of the Insch MZ exposures (Fig. 1), and from a selection of loose blocks, revealed a wide range of compositions, with considerable overlap between the various MZ components, and between the MZ and UZ cumulates (Wadsworth, 1986). From this reconnaissance, a range of samples for more detailed mineralogical investigation of each component (cumulates, FGG, PGG, and QBN) was selected. In general, only material collected *in situ* was used, except in the case of the MZ cumulates where the two extremes of composition are represented by loose blocks. Only the crystal cores or apparent cores were analysed, except in a few samples where marginal zoning was obviously significant and at least 5 spots were analysed for each mineral (between 10 and 20 for plagioclase). The results are summarized in Table 1 and the analytical conditions described in an appendix. (The QBN specimen localities are shown in Busrewil *et al.*, 1973, Fig. 1, but without their BG prefix.)

Pyroxenes. The pyroxene analyses are presented in Tables 2 and 3 (MZ cumulates), Tables 4 and 5 (FGG and PGG), and Table 6 (QBN), and the compositional trends within each rock group are plotted in Figs. 2 and 3, and compared with pyroxenes from UZa (Wadsworth, 1986). The most significant features are the distinct pyroxene trends for MZ cumulates, UZa cumulates and QBN respectively, despite considerable overlap in terms of Mg/Fe ratio, and the apparently single trend defined by the combination of MZ cumulates and granular gabbros (Fig. 3). In the latter case the

Table 3 Representative analyses of clinopyroxenes (MZ cumulates)

	CC2	M39	HD2	HD3	152	PY1	254	CM1
SiO_2	51.40	51.29	51.98	51.22	51.54	50.55	51.45	51.10
TiO_2	0.66	0.53	0.45	0.55	-	0.37	0.28	0.49
Al_2O_3	2.55	2.04	1.97	2.19	1.54	1.70	1.66	1.91
FeO+	7.45	10.38	11.58	12.66	13.46	13.87	14.48	14.92
MnO	-	0.30	0.47	0.34	0.52	0.46	-	0.25
MgO	14.85	12.82	12.26	11.72	11.30	10.92	10.99	10.42
CaO	22.20	21.86	21.76	21.63	21.67	21.44	21.57	21.39
Total	99.42^{o}	99.22	100.47	100.31	100.03	99.31	100.43	100.48
Cations to 6 oxygens								
Si	1.918	1.942	1.952	1.937	1.963	1.946	1.955	1.947
Ti	0.019	0.015	0.013	0.016	0.000	0.011	0.008	0.014
Al	0.112	0.091	0.087	0.097	0.069	0.077	0.075	0.086
Fe	0.232	0.329	0.364	0.400	0.429	0.447	0.460	0.476
Mn	0.000	0.010	0.015	0.011	0.017	0.015	0.000	0.008
Mg	0.826	0.723	0.686	0.661	0.642	0.626	0.622	0.592
Ca	0.887	0.887	0.876	0.877	0.884	0.884	0.878	0.873
Ca	45.6	45.7	45.5	45.3	45.2	45.2	44.8	44.9
Mg	42.5	37.3	35.6	34.1	32.8	32.0	31.7	30.5
Fe	11.9	17.0	18.9	20.6	21.9	22.8	23.5	24.5
Mg#	78.1	68.7	65.3	62.3	59.9	58.3	57.5	55.4

+ Total Fe as FeO Mg# = 100 x Mg/(Mg+Fe) ^{o} includes 0.31% Cr_2O_3 (0.009 cation per formula unit)

Table 4 Representative analyses of orthopyroxenes (FGG and PGG*)

	SS1	V	CN1*	S	1023	75	R	19	FB3
SiO_2	53.22	52.62	53.18	52.69	52.27	51.85	52.08	51.49	50.56
TiO_2	-	0.26	0.43	0.25	0.32	0.29	0.27	-	0.24
Al_2O_3	1.81	1.62	1.37	1.55	1.32	1.20	1.12	1.08	1.06
FeO+	19.11	19.51	20.97	22.26	22.51	24.00	25.50	27.30	29.80
MnO	0.37	0.35	0.46	0.33	0.50	0.53	0.54	0.52	0.72
MgO	24.35	23.70	23.02	22.64	21.77	20.51	19.88	18.11	16.89
CaO	0.95	1.42	1.11	1.02	1.07	1.28	0.99	0.96	1.12
Total	99.81	99.48	100.54	100.74	99.76	99.66	100.38	99.46	100.39
Cations to 6 oxygens									
Si	1.956	1.949	1.959	1.949	1.958	1.960	1.965	1.978	1.954
Ti	0.000	0.007	0.012	0.007	0.009	0.008	0.008	0.000	0.007
Al	0.078	0.071	0.060	0.068	0.058	0.053	0.050	0.049	0.048
Fe	0.587	0.604	0.646	0.689	0.705	0.759	0.805	0.877	0.963
Mn	0.011	0.011	0.014	0.010	0.016	0.017	0.017	0.017	0.024
Mg	1.334	1.309	1.264	1.248	1.216	1.156	1.118	1.037	0.973
Ca	0.037	0.056	0.044	0.041	0.043	0.052	0.040	0.039	0.046
Ca	1.9	2.8	2.2	2.1	2.2	2.6	2.0	2.0	2.3
Mg	68.1	66.5	64.7	63.1	61.9	58.8	57.0	53.1	49.1
Fe	30.0	30.7	33.1	34.8	35.9	38.6	41.0	44.9	48.6
En	69.4	68.4	66.2	64.4	63.3	60.4	58.1	54.2	50.3

Table 5 Representative analyses of clinopyroxenes (FGG and PGG*)

	SS1	PY2	V	PY3*	CN1*	S	1023	75	R	19	FB3
SiO_2	51.75	51.42	51.82	50.95	51.02	51.76	51.47	52.03	51.71	51.72	50.93
TiO_2	0.69	0.92	0.87	0.70	1.04	0.77	0.53	0.59	0.43	0.54	0.64
Al_2O_3	3.02	3.22	2.85	3.24	3.36	2.36	2.63	2.35	1.85	1.88	2.05
FeO+	8.26	8.34	8.64	8.71	9.21	9.57	9.98	10.79	11.01	11.64	12.73
MnO	0.27	0.27	0.31	-	-	-	-	-	0.31	0.30	0.30
MgO	13.95	13.86	13.83	13.62	13.53	13.78	13.36	13.39	12.94	12.31	11.50
CaO	22.36	21.77	22.20	21.85	21.68	21.67	21.60	21.74	22.05	22.23	21.74
Total	100.30	99.80	100.52	99.57°	99.84	99.91	99.57	100.89	100.30	100.62	99.89
Cations to 6 oxygens											
Si	1.919	1.915	1.921	1.907	1.906	1.933	1.933	1.934	1.943	1.943	1.937
Ti	0.019	0.026	0.024	0.020	0.029	0.022	0.015	0.017	0.012	0.015	0.018
Al	0.132	0.141	0.125	0.143	0.148	0.104	0.116	0.103	0.082	0.083	0.092
Fe	0.256	0.260	0.268	0.273	2.888	0.299	0.313	0.335	0.346	0.366	0.405
Mn	0.009	0.008	0.010	0.000	0.000	0.000	0.000	0.000	0.010	0.009	0.010
Mg	0.771	0.769	0.764	0.760	0.753	0.767	0.748	0.742	0.724	0.689	0.652
Ca	0.889	0.869	0.881	0.876	0.867	0.868	0.869	0.866	0.888	0.895	0.886
Ca	46.4	45.8	46.1	45.9	45.4	44.9	45.0	44.6	45.3	45.9	45.6
Mg	40.2	40.5	39.9	39.8	39.5	39.6	38.8	38.2	37.0	35.3	33.6
Fe	13.4	13.7	14.0	14.3	15.1	15.5	16.2	17.2	17.7	18.8	20.8
Mg#	75.1	74.7	74.0	73.6	72.3	72.0	70.5	68.9	67.7	65.3	61.7

+ Total Fe as FeO Mg# 100 x Mg/(Mg+Fe) °includes 0.50% Cr_2O_3 (0.015 cations per formula unit)

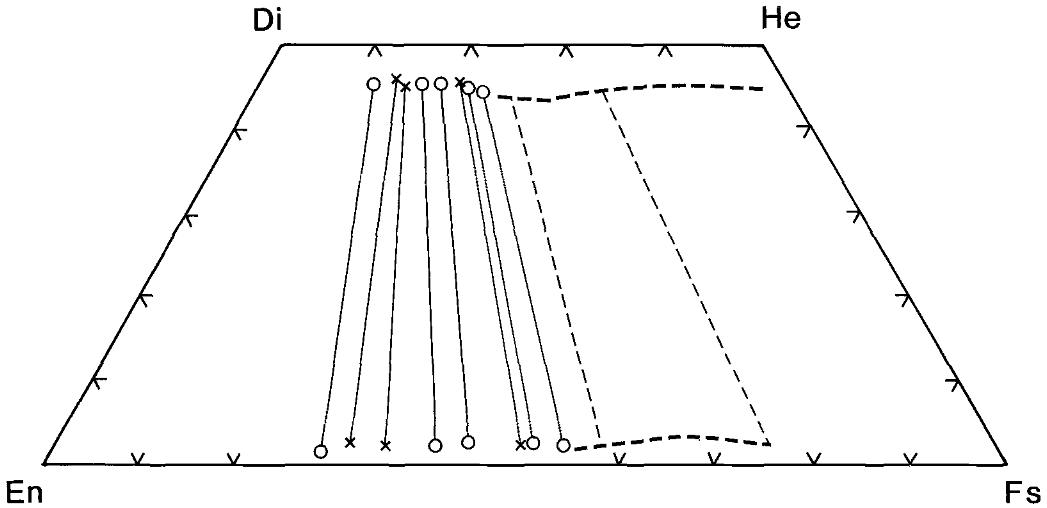

FIG. 2. Plot of selected examples of coexisting Ca-rich and Ca-poor pyroxenes from the Insch MZ rocks (same symbols as in Fig. 1). The firm dashed lines indicate the UZ pyroxene trends, which also overlap the MZ compositions to some extent, and the fine dashed lines are tie lines relating to selected UZ pyroxene pairs.

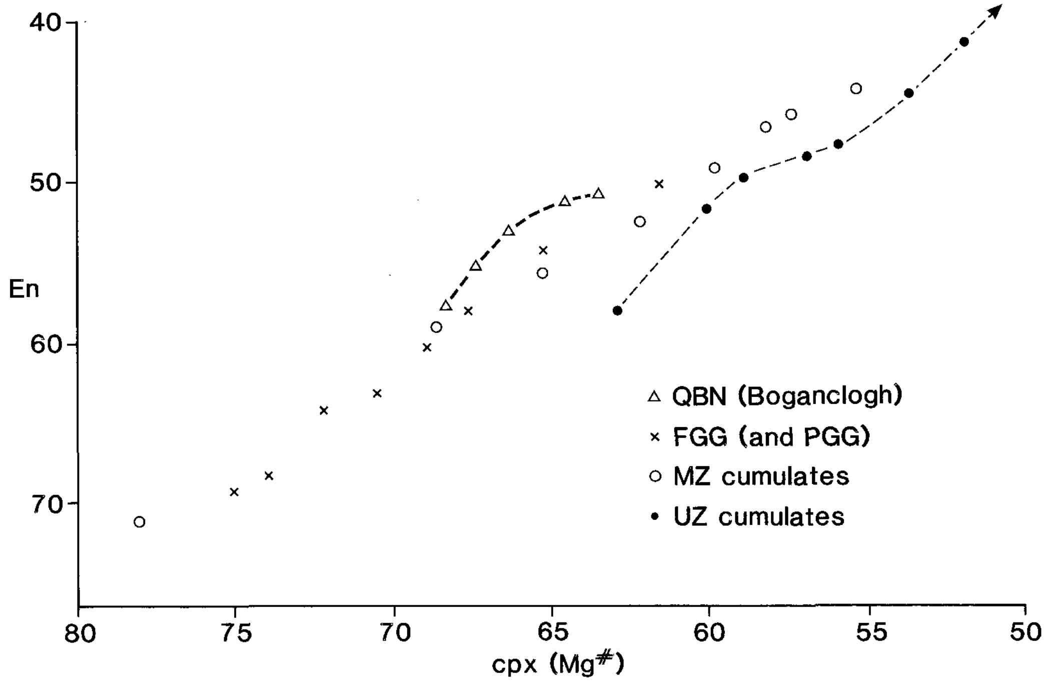

FIG. 3. Plot of orthopyroxene (En) against clinopyroxene compositions [Mg# = 100 × Mg/(Mg + Fe)] for the various Insch MZ components (cumulates, FGG and QBN).

cumulus pyroxenes are generally more Fe-rich than the FGG (and PGG) pyroxenes, but there is some degree of overlap, and the most magnesian sample (CC2) is texturally a cumulate, although not collected *in situ*. The overall composition range represented by the combined MZ cumulate–FGG association is En_{71-44} (opx) and $Ca_{46}Mg_{42}Fe_{12}$ to $Ca_{45}Mg_{30}Fe_{25}$ (cpx). The main MZ cumulate part of this range is almost identical to UZa, although for a given orthopyroxene composition the co-existing clinopyroxene is slightly more magnesian (by 1–3% Mg#) in the MZ compared with the UZ.

Many of the Insch MZ cumulate and FGG pyroxenes show exsolution textures, and the orthopyroxenes in the composition range En_{53-44} appear to be inverted pigeonites. This is similar to that recorded by Wadsworth (1986) for the UZ. However, the QBN orthopyroxenes show no evidence of inversion from pigeonite, despite the fact that they mostly fall within the same composition range.

Olivine. Among the MZ rocks, olivine is restricted in occurrence to the more magnesian members of the granular gabbro suite, including all the PGG rocks. Although individual analyses are not presented, the compositional range is shown in Table 1, and this indicates a systematic relationship with respect to varying Mg/Fe ratios in the pyroxenes. In addition, it should be noted that these granular olivines (Fo_{57-64}) lie precisely in the middle of the olivine compositional gap (Fo_{75-47}) previously established for the Insch cumulates (Wadsworth, 1986).

Plagioclase. Microprobe analyses of plagioclase in the MZ cumulates and granular gabbros indicate the same type of variation as found in the Insch UZ rocks, as well as in a number of other layered intrusions (Wadsworth, 1986). In each sample there is a relatively wide range of core compositions (3–7% An), which are too patchy in their distribution to represent growth zoning, and were interpreted to be the result of partial re-equilibration during the late stages of crystallization. The individual analyses are not presented here, but the results are summarized in Table 1. Despite this local variability, the average core compositions (based on at least ten microprobe analyses in each sample) display a systematic progression towards sodic compositions (An_{71} to An_{56}) in parallel with the iron-enrichment trend shown by pyroxenes. Plotting An against En (Fig. 4) again indicates a number of distinct but parallel composition trends. As in Fig. 3, the MZ cumulates can be clearly separated from the UZa cumulates,

Table 6 Representative analysis of pyroxenes from QBN (Boganclogh area)

	Orthopyroxene						Clinopyroxene				
	BG4	BG14	BG11	BG29	BG43		BG4	BG14	BG11	BG29	BG43
SiO_2	52.51	51.79	51.41	51.95	51.55		51.97	52.54	51.95	52.22	51.62
TiO_2	-	0.34	-	-	-		0.62	0.25	-	-	0.41
Al_2O_3	1.13	0.83	1.09	0.87	0.84		1.93	1.37	1.50	1.43	1.56
FeO+	25.94	26.77	28.39	28.64	28.99		10.88	11.20	11.46	12.12	12.49
MnO	0.47	0.40	0.76	0.65	0.60		-	0.29	-	0.39	-
MgO	19.82	19.07	17.95	17.82	17.09		13.10	13.01	12.64	12.30	12.16
CaO	0.95	1.40	1.38	0.88	1.35		21.55	21.91	21.88	21.54	21.72
TOTAL	100.82	100.60	100.98	100.81	100.42		100.05	100.57	99.43	100.00	99.96
Cations to 6 oxygens											
Si	1.973	1.964	1.960	1.980	1.980		1.949	1.966	1.968	1.972	1.955
Ti	0.000	0.010	0.000	0.000	0.000		0.017	0.007	0.000	0.000	0.012
Al	0.050	0.037	0.049	0.039	0.038		0.085	0.060	0.067	0.063	0.070
Fe	0.815	0.849	0.905	0.913	0.931		0.341	0.350	0.363	0.383	0.396
Mn	0.015	0.013	0.024	0.021	0.019		0.000	0.009	0.000	0.012	0.000
Mg	1.110	1.078	1.020	1.012	0.978		0.733	0.725	0.714	0.693	0.686
Ca	0.038	0.057	0.056	0.036	0.056		0.866	0.878	0.888	0.872	0.881
Ca	1.9	2.9	2.8	1.8	2.8		44.6	45.0	45.2	44.8	44.9
Mg	56.6	54.3	51.5	51.6	49.8		37.8	37.1	36.3	35.5	35.0
Fe	41.5	42.8	45.7	46.6	47.4		17.6	17.9	18.5	19.7	20.2
En	57.7	55.9	53.0	52.6	51.2	Mg#	68.2	67.4	66.3	64.4	63.4

\+ Total Fe as FeO Mg# = 100 x Mg/(Mg+Fe)

although the compositional ranges are broadly similar (apart from sample CC2). However, Fig. 4 also indicates slight but apparently significant differences between the MZ cumulates and FGG trends. For the most part, the FGG plagioclases are slightly more calcic (2–3% An) than those in the cumulates, for a given En value, although the trends appear to merge or intersect at the more magnesian end of the sequence.

In the PGG sub-group, the groundmass plagioclase is obviously similar to the FGG plagioclase, although in detail the compositions are slightly more calcic than would be expected from the olivine and clinopyroxene compositions (by 3–4% An). The plagioclase phenocrysts are significantly more calcic than any other MZ feldspars, averaging An_{79-80}, although the range of phenocryst core compositions in individual rocks is quite wide (approximately 6% An). In general, these phenocrysts show prominent marginal zoning towards the groundmass plagioclase compositions. The groundmass feldspars are apparently unzoned.

The QBN plagioclases are quite distinct from those in the other Insch gabbroic rocks. They are strongly zoned, generally with small but distinct cores close to An_{70}, and wide, normally zoned, margins, extending the compositional range to approximately An_{50} (Table 1). For comparative purposes, the most calcic composition for each sample is considered significant, and when plotted against orthopyroxene En content (Fig. 4), there is clear evidence of an internally consistent fractionation trend and one which is quite independent of the other Insch trends. The QBN plagioclase cores are distinctly more calcic than the average core compositions of the FGG group (by 6–7% An), the MZ cumulates by (9–10% An), and the UZa cumulates (by 11–12% An), and only the PGG plagioclase phenocrysts are significantly more calcic (An_{79-80}).

Amphibole and biotite. Many of the Insch and Boganclogh MZ rocks contain interstitial amphibole or biotite (or both). Selected analyses of these are presented in Tables 7 and 8. The MZ cumulates and granular gabbros may be regarded as complementary to some extent, in that amphibole (pargasitic hornblende) is more abundant in the less evolved rocks (mostly FGG) and biotite in the relatively evolved rocks (mostly cumulates). Compared with UZa, the MZ cumulate biotites appear to be slightly less titaniferous, while the amphiboles are poorer in Al, Na, and K, and richer in Si. The cumulate biotites show an increase in Ba, and the

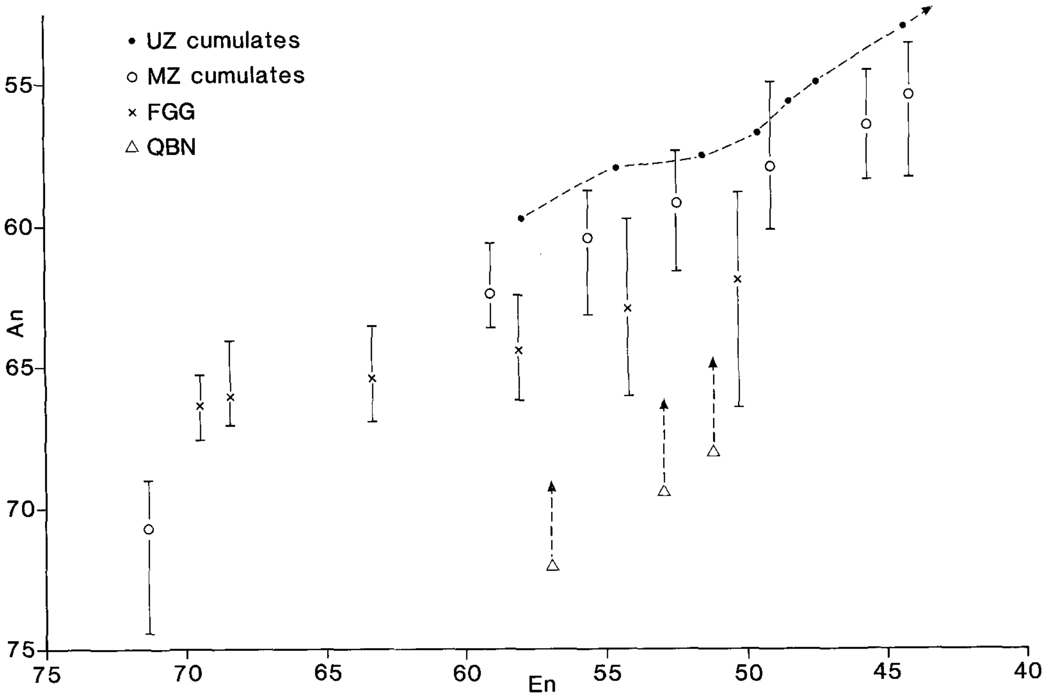

FIG. 4. Plot of plagioclase (An) against orthopyroxene (En) compositions for the various Insch MZ components. The bar lines indicate the range of apparent plagioclase core compositions. In the case of QBN, the open triangles represent the most calcic compositions recorded, and the arrows indicate the direction (but not the full extent) of the zoning.

Table 7 Representative analysis of amphiboles

	MZ Cumulates		FGG (including PGG*)					QBN (Boganclogh area)		
	M39	254	SS1	V	CN1*	75	19	BG14	BG11	BG29
SiO_2	44.54	42.82	41.93	41.70	41.78	43.52	45.36	50.60	46.50	44.22
TiO_2	1.85	2.03	3.87	4.20	4.06	2.79	1.72	0.31	1.48	2.49
Al_2O_3	10.62	10.68	12.69	12.59	12.16	11.04	9.63	5.32	7.93	9.32
FeO+	15.11	20.00	11.64	12.30	13.59	15.14	16.13	15.61	16.19	16.70
MgO	12.53	8.48	12.46	12.29	11.64	11.36	11.53	13.78	12.48	11.19
CaO	11.94	11.62	11.76	11.68	11.62	11.92	11.96	11.64	11.42	11.54
Na_2O	1.21	1.75	2.93	2.37	2.17	1.60	1.14	0.85	1.42	1.75
K_2O	0.96	0.76	1.11	1.21	1.21	1.19	1.07	0.34	0.80	0.98
Total	98.76	98.14	98.39	98.34	98.23	98.56	98.54	98.45	98.22	98.19
Cations to 23 oxygens										
Si	6.545	6.489	6.159	6.142	6.180	6.440	6.704	7.357	6.877	6.605
Ti	0.204	0.231	0.428	0.465	0.452	0.311	0.191	0.034	0.164	0.280
Al	1.840	1.908	2.198	2.185	2.120	1.926	1.678	0.912	1.383	1.640
Fe	1.856	2.535	1.430	1.515	1.681	1.873	1.994	1.898	2.002	2.086
Mg	2.744	1.915	2.729	2.699	2.567	2.505	2.540	2.988	2.752	2.491
Ca	1.879	1.887	1.850	1.843	1.842	1.889	1.894	1.814	1.809	1.847
Na	0.343	0.513	0.834	0.677	0.621	0.459	0.327	0.239	0.407	0.507
K	0.180	0.148	0.208	0.228	0.228	0.225	0.201	0.063	0.151	0.187
Mg#	59.7	43.0	65.6	64.0	60.4	57.2	56.0	61.2	57.9	54.4

Table 8 Representative analyses of biotites

	MZ cumulates						FGG			QBN (Boganclogh area)				
	CC2	M39	152	PY1	254	CM1	V	75	19	BG4	BG14	BG11	BG29	BG43
SiO_2	37.51	36.56	36.19	35.16	35.12	34.46	37.08	36.25	36.96	36.68	36.65	36.23	36.26	36.71
TiO_2	4.38	3.60	4.51	5.03	4.88	4.22	5.56	5.93	4.42	6.03	6.00	5.48	5.70	5.50
Al_2O_3	14.47	15.76	15.06	14.78	14.82	15.45	15.37	14.07	14.46	14.26	13.91	13.88	13.83	13.65
FeO+	13.26	16.94	17.21	20.28	21.88	22.40	11.18	16.34	20.98	16.61	17.58	19.07	19.38	19.39
MgO	17.21	14.24	12.79	10.89	9.51	9.04	16.12	12.87	11.26	13.06	12.13	11.58	11.50	11.29
BaO	-	-	1.26	1.46	1.58	1.75	-	1.14	-	0.79	0.86	0.80	-	-
K_2O	8.39	8.54	9.36	8.83	8.72	8.74	9.93	9.33	9.13	9.25	9.40	9.26	9.24	9.52
Total	95.22	95.64	96.38	96.43	96.51	96.06	95.24	95.93	97.21	96.68	96.53	96.30	95.91	96.06
Cations to 22 oxygens														
Si	5.527	5.463	5.464	5.393	5.424	5.375	5.445	5.479	5.559	5.482	5.521	5.509	5.510	5.572
Ti	0.486	0.404	0.512	0.580	0.567	0.495	0.614	0.674	0.499	0.678	0.680	0.626	0.651	0.628
Al	2.514	2.775	2.680	2.673	2.698	2.840	2.661	2.547	2.563	2.511	2.470	2.488	2.476	2.442
Fe	1.635	2.117	2.173	2.602	2.826	2.922	1.373	2.066	2.639	2.076	2.214	2.426	2.463	2.461
Mg	3.780	3.171	2.878	2.491	2.189	2.101	3.529	2.899	2.524	2.910	2.725	2.625	2.604	2.555
Ba	0.000	0.000	0.075	0.088	0.096	0.107	0.000	0.067	0.000	0.046	0.050	0.048	0.000	0.000
K	1.577	1.629	1.803	1.727	1.718	1.738	1.861	1.800	1.752	1.764	1.806	1.797	1.791	1.843
Mg#	69.8	60.0	57.0	48.9	43.6	41.8	72.0	58.4	48.9	58.4	55.2	52.0	51.4	50.9

+ Total Fe as FeO   Mg# - 100 x Mg/(Mg+Fe)

FGG amphiboles show a significant reduction in Ti, Al, and Na, with progressive Fe enrichment. The QBN amphiboles are distinguished by relatively low Ti, Al, and Na, and high Si compared with the main Insch MZ. The biotites are also relatively low in Al, but are generally more titaniferous than their cumulate and granular gabbro counterparts.

Discussion

The major unsolved problems of the Insch intrusion concern (*a*) the status of the MZ rocks with respect to the established cumulate successions of the LZ (Ashcroft and Munro, 1978) and the UZ (Wadsworth, 1986), and (*b*) the precise relationship between the proposed MZ cumulates and the associated granular gabbros. Various interpretations of these two distinct, but closely related, problems have been presented in the past. Whittle (1936) described only the eastern part of the intrusion, and was not concerned with the overall fractionation series. He interpreted the granular gabbros as being older than, and metamorphosed by, the coarser grained gabbros, although he did not speculate about the pre-metamorphic origin of the granular material. Read *et al.* (1965) hardly commented on the grain size and textural variations within their 'hypersthene gabbro' group (MZ of this account), which they believed to be younger than the adjacent ultramafic rocks (LZ) and olivine gabbros (UZ), and unrelated to them except in terms of possible large-scale contamination of the same parent magma. Clarke and Wadsworth (1970) stressed the essential continuity of the LZ, MZ (coarse-grained component), and UZ as a cumulate succession, although they recognized the incompleteness of the MZ sequence. They regarded the granular gabbro as a later intrusion, intricately invading the MZ cumulates, but possibly representing a later pulse of the same regionally available parental magma.

The detailed mineralogical studies reported here do not provide clear-cut solutions to the problems of the MZ rocks, but they at least help to clarify a complex situation. In general, they are consistent with the view that the Insch LZ–MZ–UZ sequence represents a coherent fractionation series, although it is impossible to define a stratigraphically continuous cumulate succession, especially in the MZ. The textural evidence supports the conclusion of Clarke and Wadsworth (1970) that the coarse-grained MZ gabbros are cumulates, but the minerals do not show the predicted progression from less evolved compositions in the SE (adjacent to the LZ) to more evolved compositions in the NW (adjacent to the UZ). Instead, the texturally convincing MZ (olivine-free) cumulates show considerable compositional overlap with the UZ (olivine-bearing) cumulates, and there is an almost complete absence of relatively primitive MZ rocks with typical cumulate textures. Further, the variations in mineral composition appear to be completely haphazard in terms of geographical distribution within the MZ area (Fig. 1). Despite this, the cryptic variation recorded independently by the cumulus plagioclase, clinopyroxene, and orthopyroxene (Table 1) is consistent with the interpretation of these rocks as a progressive fractionation sequence. One possible explanation of the complex geographical expression of this sequence is that the original MZ cumulate succession has been disrupted by faulting, similar to that recognized in the LZ (Ashcroft and Munro, 1978). The combination of minor block faulting, gentle dips and poor exposure could account for much of the observed variation.

The substantial mineralogical overlap between the MZ cumulates and UZa is taken to indicate that the overall Insch fractionation sequence was not a simple closed-system progression, but involved replenishment with slightly more primitive magma after deposition of the MZ cumulates. The fresh magma which gave rise to the UZ cumulates differed from its MZ precursor in that it was capable of precipitating Fe-rich olivine at an earlier stage of evolution. This type of repetitive pattern is well established from a number of layered intrusions, notably Bushveld, where it occurs within the olivine-free Main Zone (Von Gruenewaldt, 1973) and Kapalagulu (Wadsworth *et al.*, 1982). In some intrusions (e.g. Rhum and Muskox) there are multiple repetitions, or cycles, but there is no evidence of more than one replenishment episode at Insch.

Any interpretation of the Insch granular gabbros must take account of all their salient features:

(1) The granular gabbros are restricted to the MZ area, where they are at least as abundant as the cumulates with which they are closely associated.

(2) Direct evidence of age relationships is scarce, but where it exists (e.g. Candle Hill), FGG occurs as xenoliths in the cumulates.

(3) Despite their fine grain size, the granular gabbros never display doleritic (interlocking) textures, but they sometimes show a hint of igneous lamination.

(4) The granular gabbros display a range of mineral compositions which are almost perfectly overlapped by the MZ cumulates.

On the above basis, it is almost impossible to sustain the hypothesis of Clarke and Wadsworth (1970) that the granular gabbros intrude the cumulates. Not only is there a lack of intrusive relationships in the field, and doleritic or quench textures in thin section, but the occurrence of FGG xenoliths in the cumulates clearly indicates their pre-cumulate existence.

The combination of textural and structural (xenolithic) evidence supports Whittle's (1936) contention that the granular gabbros represent recrystallized basic material, but the original nature of this material, and the reasons for its mineralogical variation and overlap with the cumulates are more obscure. Rather similar granular gabbros occur in the Caledonian synorogenic Fongen–Hyllingen intrusion in Norway. This has already been shown to compare closely with the Insch mass in terms of its later fractionation history (Wadsworth, 1986). The Fongen–Hyllingen granular rocks, described by Wilson and Larsen (1985) as metabasites, are concentrated in a 700 m thick zone in the lower part of the Hyllingen Series, where they appear to form an irregular network of inclusions which range in scale from tens of centimetres to hundreds of metres. They are mostly fine- to medium-grained granoblastic aggregates of plagioclase and augite (±olivine, orthopyroxene and brown hornblende), but there are also some dyke-like bodies which contain abundant plagioclase phenocrysts, and appear to be analogous to the Insch PGG. Wilson and Larsen (1985) interpreted the inclusions as basaltic lavas (together with associated plagioclase-phyric dykes), invaded and recrystallized by the layered gabbros. Similar basaltic material (now amphibolite due to regional metamorphism) is abundant in the country rocks nearby. However, despite the overall similarities between the Fongen–Hyllingen metabasite inclusions and the FGG (and associated PGG) rocks at Insch, there is no equivalent major source of basaltic material within the Dalradian country rock adjacent to the Insch mass, nor is there any evidence within the Insch FGG of original basaltic structures such as flow units, or textural features such as relict amygdales. Further it is difficult to see why such an accidental origin should produce the observed mineralogical variations within the Insch granular gabbros, and the overlap with the associated cumulates, even if they came from similar magmas.

Therefore, a closer genetic relationship between the Insch granular gabbros and MZ cumulates is proposed. Texturally similar associations occur in a number of layered intrusions (Thy and Esbensen, 1982), and have conventionally been regarded as quench rocks incorporated as xenoliths from the intrusion margins. This situation is clearly demonstrated by the Klokken intrusion in SW Greenland, where layers of fine-grained granular syenite are interleaved with syenitic cumulates, and are believed to represent large sheets of chilled material which were stoped from the roof zone and settled to the floor as extensive platy xenoliths (Parsons, 1979). These granular rocks are characterized by their own distinctive mineralogical and chemical variations, compared with the cumulates, but are clearly an integral part of the overall crystallization history. Thy and Esbensen (1982) discussed the possibility that the granular gabbros in the Fongen-Hyllingen intrusion represent a chilled marginal facies, but preferred to interpret them as layers formed *in situ* within the cumulate succession, as conditions favouring a high rate of nucleation were developed from time to time in response to fluctuations in volatile pressure. This is in marked contrast to the metavolcanic origin proposed for the same rocks by Wilson and Larsen (1985).

It is now considered likely that the Insch granular gabbros are an intrinsic part of the MZ fractionation sequence, rather than accidental xenoliths, although there is no indication of the precise conditions under which they crystallized, or to what extent they have been displaced since crystallization. Some are obviously xenolithic on a small scale, but the majority of granular gabbro occurrences are more massive and, because of the poor exposure, it is impossible to decide whether they represent large detached fragments or *in situ* crystallization. The granular texture is interpreted to be a primary crystallization feature, although it is not clear whether a high nucleation rate implied by the fine grain size was a quench effect, or involved some other mechanism for achieving the necessary degree of supercooling, as discussed by Thy and Esbensen (1982).

The general mineralogical coherence of the granular gabbros and the MZ cumulates provides the clearest evidence of a comagmatic origin. The fact that the more basic MZ compositions are mostly represented by granular gabbros, and the more evolved compositions by cumulates, although there is some overlap, suggests that the crystallization conditions changed significantly with time. It is possible that the early part of the MZ history was dominated by wall or roof crystallization, and the later part by crystal settling. The minor mineralogical differences between the granular gabbros and the cumulates, as expressed in terms of plagioclase composition (Fig. 4) and the sporadic occurrence of olivine (in FGG and PGG), provide confirmatory evidence of slightly different crystallization regimes locally, within the overall constraints of a single magma chamber. The PGG is interpreted as yet another minor variant of FGG, marked by the local concentration of plagioclase megacrysts, possibly representing wall or roof accretion.

The significance of the apparently haphazard spatial variations in mineral compositions within the granular gabbros (Fig. 1) is unclear. They may be the result of block faulting, as postulated earlier to explain the MZ cumulate variations, or they may indicate that the granular gabbros comprise a number of independent crystallization domains, or very large xenoliths, although the poor exposure precludes their closer delineation. Further, if the development of the granular gabbros involved large-scale foundering of xenolithic rafts, it is possible that some of the complex geographical variations in MZ mineral compositions were produced by the disruptive effects of such rafts as they fell into the cumulus mush.

Despite their intermediate mineralogical characteristics, broadly equivalent to the middle part of the Insch MZ trend (and the lower part of the UZ trend), the QBN component of the Boganclogh mass shows no obvious textural affinities to either the cumulates or the granular gabbros. Since these rocks contain relatively abundant late-stage components, represented by interstitial quartz and biotite as well as strongly-zoned plagioclase, they are taken to be the products of *in situ* crystallization without any effective segregation of the early crystals from the residual magma. However, the QBN rocks define a reasonably coherent, if limited, fractionation trend, so that some degree of differentiation was achieved. They are similar in many respects to norites from both the Haddo–Arnage, and Morven–Cabrach intrusions, and the group as a whole is believed to represent a sample of the regional basic magma which crystallized under relatively hydrous conditions (Gribble, 1967; Busrewil *et al.*, 1973). This could account for the slight but significant differences in mineralogical signature between the QBN rocks of the Boganclogh area and the other Insch units, as shown by Figs. 3 and 4.

To summarize, the mineralogical evidence indicates that the various MZ components identified in the main Insch intrusion (cumulates, FGG, and PGG) and in the Boganclogh extension (QBN) were essentially comagmatic, but that each one represents a slightly different situation in terms of location or conditions of crystallization. The Insch MZ rocks in particular are believed to be an integral part of the overall cumulate sequence from ultramafic (LZ) to ferrodioritic (UZ) compositions, but only the coarse-grained gabbros may have developed by crystal settling. The associated granular gabbros probably represent crystal fractions formed elsewhere in the same magma chamber, possibly near the roof, under the influence of relatively high nucleation rates. The precise relationship between these rock types is still a matter for conjecture rather than certainty, but it is hoped that the interim conclusions reached here will be further clarified by geochemical investigations (including *REE* and isotope analyses) currently in progress.

Acknowledgements

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Appendix

Analytical methods. The mineral analyses were made using a Cambridge Instrument Company Geoscan fitted with a Link System model 290-2KX energy-dispersive spectrometer (using 15 kV, a specimen current of approximately 3 nA on cobalt metal, and ZAF-4/FLS quantitative analysis software system). For orthopyroxenes and olivines the apparent composition range in each rock was generally less than 0.7% (En and Fo respectively), and for clinopyroxenes less than 1% Mg#.

Exsolution lamellae in pyroxenes were avoided as far as possible by optical inspection. However, this was not always feasible, due to the scale or orientation of the lamellae, and chemical methods of discrimination were then used. In the case of orthopyroxenes, most analyses were relatively low in CaO (generally less than 1.5 wt.%) and the occasional spot with unusually high CaO was assumed to include part of a Ca-rich pyroxene lamella, and was discarded. Among the Ca-rich clinopyroxenes the situation was more difficult, as the incorporation of Ca-poor pyroxene lamellae in the analysed volume produced a less distinctive chemical signature. It was found that when sufficient spots were analysed (at least 10) the majority always belonged to a high-Ca group (21.5–22.2 wt.% CaO), but there was also a 'tail' of analyses with variable but lower Ca content, in which Ca-depletion was compensated by slightly higher Fe. These analyses were assumed to represent some dilution of the host Ca-rich pyroxene by Ca-poor pyroxene lamellae. This was confirmed by analyses of unusually wide exsolution lamellae, and also by the use of a broad beam to encompass host pyroxene plus lamellae. The clinopyroxene analyses quoted in this account were deliberately selected from the Ca-rich group, rather than the complete spread of compositions, in each case.

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