Silicate mineralogy of the Behelvie cumulates, N E Scotland

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Abstract

Ultramafic, troctolitic and gabbroic rocks at the northern end of the Belhelvie layered intrusion display progressive cryptic variation over a stratigraphic thickness of approximately 800 m in steeply-dipping cumulates, which young from W to E. This variation is shown by olivine (Fo_{87-77}), orthopyroxene (En_{87-79}), clinopyroxene ($Ca_{45}Mg_{48}Fe_7$ to $Ca_{44.5}Mg_{45.5}Fe_{10}$) and plagioclase ($An_{81-75}$). The Belhelvie succession is believed to be equivalent to the poorly-exposed and structurally complex Insch Lower Zone. A laterally impersistent hypersthene-gabbro unit within the main sequence is re-interpreted as a downfaulted block of slightly more evolved cumulates. A repeat sequence of peridotites, troctolites and gabbros on the eastern side of the intrusion, and separated from the underlying main succession by a thin septum of country rock, is believed to represent a fresh influx of magma.

KEYWORDS: silicates, cryptic variation, cumulates, Belhelvie, Scotland.

Introduction

THE Caledonian Newer Gabbro intrusions of NE Scotland comprise a wide variety of rock types, including a cumulate sequence (ranging from peridotites and troctolites to gabbros, ferrodiorites and syenodiorites), non-cumulate norites and granular gabbros, as well as local xenolithic complexes (Wadsworth, 1982). The most extensive range of cumulates is found in the Insch intrusion, where the sequence has been subdivided into three successive fractionation stages (Lower Zone, Middle Zone and Upper Zone), but significant cumulate components also occur in the Huntly–Portsoy and Belhelvie intrusions.

One of the more intriguing problems posed by the New Gabbros is the extent to which the separate intrusions were originally connected. There can be little doubt that they relate to the same magmatic event, but it has also been argued that they may be parts of a single large intrusive sheet which was disrupted by later Caledonian tectonic activity. This idea was first suggested by Read (1923), and subsequently developed by Shackleton (in discussion of Read and Farquhar, 1956), Stewart and Johnson (1960), McGregor and Wilson (1967) and Wadsworth (1970). On the other hand, Weedon (1970), Ashcroft and Munro (1978) and Munro (1986*a*) considered it more likely that the individual intrusions evolved independently.

Cumulate sequences are particularly significant in this context, as pointed out by Wadsworth (1970) and Munro (1984). Similar cumulate successions, in terms of both phase and cryptic layering, would obviously favour the disrupted single sheet hypothesis, and any minor differences could be explained as due to local variations in crystallization history within a single large magma chamber. This type of variation is known to occur in the Bushveld intrusion for example (Eales *et al.*, 1988). Major differences in cumulate mineralogy from intrusion to intrusion would clearly require separate development.

It is only recently that sufficiently precise mineralogical data have become available for this approach to be applied to the Newer Gabbros, and there are still significant gaps in the evidence. This is partly due to the incompleteness of the cumulate record, resulting from a combination of structural complexity and generally poor exposure, but to some extent it stems from a lack of systematic microprobe investigations, especially among the cumulates representing the earliest fractionation stages. The detailed mineralogy of the intermediate (Middle Zone) and later (Upper Zone) stages of the Insch cumulate succession has been documented by Wadsworth (1988 and 1986, respectively), but unfortunately the Insch Lower Zone is virtually unexposed, and the available borehole evidence indicates that the original

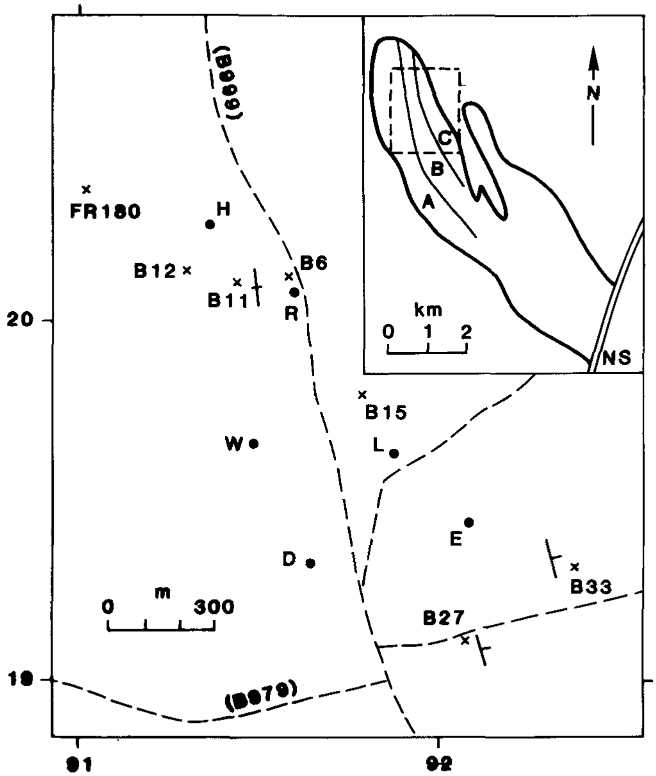

FIG. 1. Map of Craigie area, N.W. Belhelvie, showing specimen locations (×), roads (dashed) and farms(●) (H = Hillhead of Craigie, R = Roadside Craigie, W = Wester Craigie, L = Little Craigie, D = Dams of Craigie, E = Easter Craigie). Inset map shows the study area in relation to Belhelvie intrusion as a whole, with approximate boundaries of Units A, B and C (Wadsworth *et al.*, 1966) (NS = North Sea). The grid references related to National Grid Square NJ.

stratigraphic sequence has been thoroughly disrupted by faulting (Ashcroft and Munro, 1978; Munro, 1986*b*). However, there is considerable circumstantial evidence that the well-exposed and structurally straightforward Belhelvie cumulate succession may be equivalent to the Insch Lower Zone, and it is therefore important to establish the precise compositional range represented at Belhelvie in order to provide a more complete statement of the Newer Gabbro cumulate spectrum, and to extend the scope for testing the single sheet hypothesis.

Previous investigations of cryptic variation at Belhelvie have relied largely on optical determinations (Wadsworth *et al.*, 1966), although some preliminary microprobe data (from Boyd, 1972) have been reported by Munro (1986*a*). The following account, which is based on new microprobe analyses, records the systematic changes in mineral compositions along a traverse across the best exposed, least altered and most complete part of the Belhelvie stratigraphic sequence. The field locations of the principal samples investigated are shown in Fig. 1. The analytical methods and precision are the same as reported by Wadsworth (1988).

Summary of previous work

The Belhelvie intrusion was studied in detail by Stewart (1946), who recognised a steeply-dipping sequence of layered ultramafic rocks, troctolites and gabbros, younging from west to east. Wadsworth *et al.* (1966) referred these lithological changes to Units A, B and C of a layered cumulate succession, and were able to demonstrate progressive cryptic variation in mineral compositions through the succession, estimated to be approximately 1800 m thick. Ashcroft and Boyd (1976) re-investigated the intrusion by combining a ground magnetic survey with a programme of shallow drilling, in order to delineate more precisely the shape and extent of the whole body, as well as its individual lithological components. One of the most interesting results of this study was the recognition of a second peridotite–troctolite–gabbro unit, separated from the underlying main sequence by a septum of hornfelsed country rock, in the north-eastern part of the intrusion. This repetition was interpreted as of primary depositional origin, rather than as a tectonic feature associated with the later deformation of the Belhelvie mass, which resulted in the near-vertical layering (in the northern half of the intrusion at least), and the local zones of intense shearing and mylonitisation described by Boyd and Munro (1978). The available petrological and structural information is summarised by Munro (1986*a*) in the B.G.S. Memoir for Sheet 77 (Scotland).

Cryptic variation

Wadsworth *et al.* (1966), mainly on the basis of optical methods (but with some supplementary chemical data on mineral separates), established a stratigraphic range of mineral compositions as follows: olivine (Fo_{86} to Fo_{80}), orthopyroxene (En_{85} to En_{79}), clinopyroxene ($Ca_{42}Mg_{51}Fe_7$ to $Ca_{41}Mg_{48}Fe_{11}$) and plagioclase (An_{81} to An_{74}). Most of this variation occurred over a stratigraphic thickness of approximately 1000 m, from the top of Unit A, through Unit B, into Unit C. The apparent lack of continued cryptic variation eastwards across the Unit C area was taken to indicate a significant change of attitude from vertical to horizontal in the eastern half of the intrusion, but it is now clear that the sequence in this area is complicated by the septum of country rock and the overlying repetition of the peridotite–troctolite–gabbro cycle.

The present investigation was based on essentially the same line of traverse and incorporated some of the original samples, as well as new material. The rocks concerned range from heavily serpentinised olivine cumulates (peridotites), with at least one horizon containing cumulus pyroxenes (both opx and cpx), of Unit A; through olivine–plagioclase cumulates (troctolites), with occasional cumulus pyroxenes and typically showing well-developed small-scale layering, of Unit B; to olivine–plagioclase–pyroxene cumulates (gabbros) of Unit C. These gabbroic cumulates contain both opx and cpx as cumulus phases in the lower part of Unit C, but higher in the succession opx is only of intercumulus occurrence. Small-scale lithological variations are less common than in Unit B, but occasional olivine-rich layers have been recorded.

The only deviation from this simple pattern is the apparently discontinuous hypersthene-gabbro and norite unit, mapped by Stewart (1946) in the area north of Easter Craigie, and generally interpreted as part of the layered succession (see Wadsworth *et al.*, 1966), rather than as a separate entity. However, there is now some evidence that these plagioclase–opx–cpx cumulates are out of position, and may represent a structural hiatus (see p. 118).

Despite the fact that the four principal minerals do not always occur as cumulus phases, they are generally present throughout the Belhelvie succession (although the intercumulus plagioclase in Unit A is now completely altered), and the cryptic variation pattern seems to be independent of textural status. This type of behaviour is already well-established for the Insch cumulates (Wadsworth, 1986 and 1988). Thus, although olivine is the only cumulus phase present throughout the main Belhelvie sequence, the other minerals (plagioclase and pyroxenes) show consistent compositional variations regardless of whether they occur in cumulus or intercumulus habit, and can be used to establish the cryptic variation characteristics of the intrusion. These rocks are all adcumulates, with no significant marginal zoning of the cumulus minerals, and only very minor traces of lower-temperature intercumulus minerals such as amphibole and biotite.

Olivine. Cumulus olivine occurs in all the rocks sampled, except for the anomalous hypersthene-gabbro (B15). The composition changes progressively upwards from $Fo_{86.5}$ to $Fo_{77.0}$ (Table 1). Chemically, the olivines are straightforward, with Ca, Ni and Mn below detection limits for EDS analyses. No trace of marginal zoning was found.

Orthopyroxene. Cumulus orthopyroxene is more sporadic in its occurrence than olivine, and is only present in half of the samples investigated (Table 4). However, there is a progressive compositional variation from $En_{87.3}$ to $En_{79.1}$, regardless of textural status (Table 2). The orthopyroxenes are slightly, but consistently, more magnesian than the associated olivines (Table 4 and Fig. 2), and Ca contents are low (generally less than 0.05 cations per formula unit), although care had to be taken to avoid the abundant exsolution lamellae of Ca-rich clinopyroxene. Mn was detected only in compositions more Fe-rich than En_{85}.

Clinopyroxene. Ca-rich clinopyroxene is also inconsistent in its appearance as a cumulus phase, especially in the lower part of the succession (Units A and B), but, as with the orthopyroxenes, the pattern of cryptic variation seems to be unaffected. Compositions range progressively

Table 1 Representative analyses of olivines

	FR180	B12	B11	B6	B27	B33
SiO_2	40.21	40.64	40.26	39.70	39.19	38.97
FeO	12.92	13.41	14.35	15.88	17.59	21.35
MgO	46.53	46.42	45.37	44.15	42.86	40.21
Total	99.66	100.47	99.98	99.73	99.64	100.53
Cations to 4 oxygens						
Si	1.000	1.005	1.003	1.000	0.999	1.001
Fe	0.269	0.277	0.299	0.335	0.375	0.459
Mg	1.726	1.712	1.685	1.658	1.628	1.540
Fo	86.5	86.1	84.9	83.2	81.3	77.0

\+ Total Fe as FeO (Ca, Ni and Mn below EDS detection limits)

upwards from $Ca_{45.3}Mg_{48.1}Fe_{6.6}$ to $Ca_{44.5}Mg_{45.5}Fe_{10.0}$ (Table 3), and are consistently more magnesian than the associated orthopyroxenes and olivines, with Mg# ranging from 87.9 to 82.0, compared with $En_{87.3-79.1}$ and $Fo_{86.5-77.0}$ respectively (Table 4 and Fig. 2). Ca contents show little variation, provided that exsolution lamellae of orthopyroxene are avoided (see discussion in Appendix to Wadsworth, 1988). Cr contents show a general tendency to decrease with progressive Fe-enrichment, but Mn is below detection limits.

Plagioclase. Cumulus plagioclase is found throughout the Belhelvie sequence except in Unit A. Microprobe analyses show the same type of patchy intra-crystal variation in composition as recorded in the Insch Upper and Middle Zone rocks (Wadsworth, 1986, 1988), and therefore individual analyses are not presented here. However, the results are summarised in Table 4 and Fig. 2, which indicates a systematic upward progression towards more sodic compositions. The average core compositions (based on at least ten microprobe analyses in each sample) range from $An_{80.8}$ to $An_{74.3}$, in parallel with the Fe-enrichment trends of the olivines and pyroxenes. True marginal zoning is rarely developed.

One of the advantages of the Belhelvie intrusion, compared with Insch, is the combination of relatively good exposure, well-developed small-scale lithological layering, and the lack of obvious structural complexity, at least within the area shown in Fig. 1 where the full range of cryptic variation has been established. The combination of extremely consistent strike (340–350°) and dip (vertical to 85°E) of the layering means that not only can the stratigraphic sequence be reliably established despite the rather complicated line of traverse, but, in addition, reasonably accurate estimates of stratigraphic thickness between samples may be made. The total thickness of cumulates between FR180 and B33 is approximately

Table 2 Representative analyses of orthopyroxenes

	FR180	B12	B11	B6	B27	B33	B15
SiO_2	54.19	54.82	55.61	55.49	55.23	55.31	54.91
TiO_2	0.28	0.40	-	0.38	0.29	0.37	-
Al_2O_3	3.01	2.94	2.70	2.59	3.06	1.59	1.37
FeO^+	8.24	8.74	9.40	10.33	11.42	13.66	13.83
MnO	-	-	0.35	0.31	0.32	0.38	0.26
MgO	31.60	32.01	30.70	30.08	28.97	28.89	28.42
CaO	1.48	1.00	1.06	1.12	1.35	0.66	0.70
Total	99.38*	99.91	99.82	100.30	100.64	100.86	99.49
Cations to 6 oxygens							
Si	1.908	1.911	1.949	1.943	1.932	1.958	1.971
Ti	0.007	0.011	0.000	0.010	0.008	0.010	0.000
Al	0.125	0.121	0.111	0.107	0.126	0.066	0.058
Fe	0.242	0.255	0.276	0.303	0.334	0.404	0.415
Mn	0.000	0.000	0.010	0.009	0.010	0.011	0.008
Mg	1.658	1.664	1.604	1.570	1.511	1.525	1.521
Ca	0.056	0.037	0.040	0.042	0.051	0.025	0.027
Ca	2.9	1.9	2.1	2.2	2.7	1.3	1.4
Mg	84.8	85.1	83.5	82.0	79.7	78.0	77.5
Fe	12.3	13.0	14.4	15.8	17.6	20.7	21.1
En	87.3	86.7	85.3	83.8	81.9	79.1.	78.6

* Includes 0.58% Cr_2O_3
\+ Total Fe as FeO

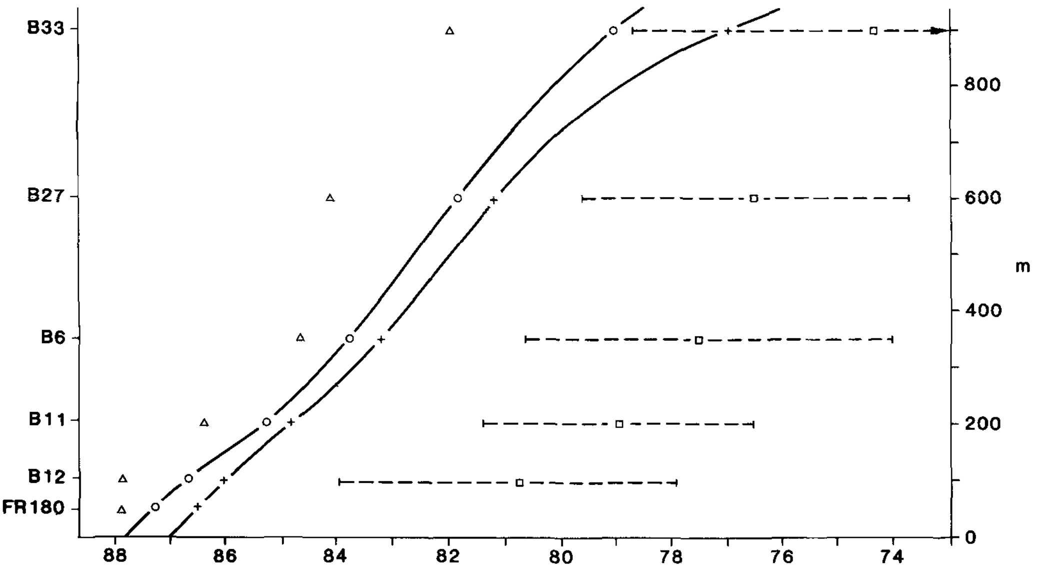

FIG. 2. Cryptic variation of Fo in olivine (crosses), En in orthopyroxene (circles), Mg# in clinopyroxene (triangles), and An in plagioclase (squares) plotted against stratigraphic height. Plagioclase bar lines indicate the recorded range of core compositions.

800 m. Fig. 2 summarises the cryptic variation pattern by plotting the compositional variation of the four principal minerals against stratigraphic height. The only significant assumption here is that the anomalous hypersthene-gabbro unit does not seriously distort the thickness estimates.

The re-interpretation of this hypersthene-gabbro unit as being out of position relative to the main Belhelvie cumulate sequence is based on the detailed mineralogy. Not only is there a distinct area of olivine-free, two-pyroxene gabbros and norites (represented by B15), but the compositions of the orthopyroxene ($En_{78.6}$), clinopyroxene ($Ca_{44.4}Mg_{45.7}Fe_{9.9}$; Mg#$_{82.2}$) and plagioclase

Table 3 Representative analyses of clinopyroxenes

	FR180	B12	B11	B6	B27	B33	B15
SiO_2	52.06	51.73	53.15	52.75	51.35	52.17	52.59
TiO_2	0.53	0.85	0.52	0.55	0.80	0.98	0.67
Al_2O_3	4.42	4.33	3.39	3.45	4.40	3.57	3.00
Cr_2O_3	0.90	0.99	0.62	0.43	1.18	0.24	0.34
FeO+	4.04	4.14	4.56	5.15	5.90	6.20	6.10
MgO	16.46	16.83	16.24	16.01	15.68	15.86	15.37
CaO	21.55	21.24	21.48	21.55	21.09	21.55	21.95
Total	99.96	100.11	99.96	99.89	100.40	100.57	100.02
Cations to 6 oxygens							
Si	1.895	1.882	1.935	1.926	1.877	1.905	1.931
Ti	0.015	0.023	0.014	0.015	0.022	0.027	0.018
Al	0.189	0.185	0.145	0.149	0.190	0.154	0.130
Cr	0.026	0.028	0.018	0.013	0.034	0.007	0.018
Fe	0.123	0.126	0.139	0.157	0.180	0.189	0.187
Mg	0.893	0.912	0.881	0.871	0.854	0.863	0.864
Ca	0.840	0.828	0.838	0.843	0.826	0.843	0.841
Ca	45.3	44.4	45.1	45.0	44.4	44.5	44.4
Mg	48.1	48.9	47.4	46.6	45.9	45.5	45.7
Fe	6.6	6.7	7.5	8.4	9.7	10.0	9.9
Mg#	87.9	87.9	86.4	84.7	84.2	82.0	82.2

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

(Mn below EDS detection limits)

Table 4 Summary of Belhelvie Mineralogy

	Olivine Fo	Orthopyroxene En	Clinopyroxene Ca	Mg	Fe	(Mg#)	Plagioclase Mean An (range)
B15	-	78.6	44.4	45.7	9.9	(82.2)	75.2 (73.9-76.4)
B33	77.0	79.1*	44.5	45.5	10.0	(82.0)*	74.3 (71.2-78.7)
B27	81.3	81.9*	44.4	45.9	9.7	(84.2)	76.6 (73.1-79.6)
B6	83.2	83.8	45.0	46.6	8.4	(84.7)	77.6 (73.9-80.6)
B11	84.9	85.3	45.1	47.4	7.5	(86.4)	79.0 (76.5-81.4)
B12	86.1	86.7*	44.4	48.9	6.7	(87.7)*	80.8 (77.9-84.0)
FR180	86.5	87.3	45.3	48.1	6.6	(87.9)	-

* Intercumulus only

(average $An_{75.2}$; range $An_{73.9-76.4}$) assemblage are almost identical to the most evolved compositions at Belhelvie, represented by B33. The only obvious difference is the presence of cumulus olivine ($Fo_{77.0}$) in the latter. Therefore, it is assumed that the hypersthene-gabbro represents either a later intrusion, or, more likely, in view of its cumulate textures, a downfaulted slice of cumulates from higher in the original succession. The absence of olivine in these hypersthene-gabbros suggests that they may represent the earliest stages of the Middle Zone, at Belhelvie. This agrees well with the Insch sequence where the olivine gap was reported to be from Fo_{76} to Fo_{47} (Wadsworth, 1988).

Reconnaissance studies of the cumulates occurring to the east of the country rock septum, described by Ashcroft and Boyd (1976), are consistent with the lithological evidence that these rocks represent a repetition of the main sequence. The troctolites sampled in drill core from Hillhead (near Balmedie Quarry) appear to be from near the base of this succession, and contain cumulus olivine (Fo_{87}) and cumulus plagioclase (An_{84}). Stratigraphically higher cumulates from close to the eastern margin of the intrusion at Sparcraigs contain olivine (Fo_{83}) and plagioclase (An_{78}). Although the latter compositions almost exactly match the olivine and plagioclase in sample B6 from the main sequence, the lower troctolites are more distinctive in terms of their co-existing olivine and plagioclase (unusually calcic) compositions. This suggests that the repetition is not the result of faulting, but represents a separate crystallization cycle resulting from a fresh influx of magma.

Comparison with Insch LZ cumulates

Earlier comparisons between the Insch Lower Zone and Belhelvie cumulates indicated a general similarity, both in terms of the phase layering and the cryptic layering (Munro, 1984), despite the fact that the Insch sequence is not continuous, but has been fragmented into a number of small fault blocks (Ashcroft and Munro, 1978). New microprobe data on selected Insch Lower Zone samples, including material from the gas pipeline trench across the eastern end of the intrusion (Munro, 1986*b*) confirm this similarity. The highly serpentised olivine cumulates, believed to be equivalent to Unit A of the Belhelvie succession, contain olivines in the same composition range (Fo_{86-87}). The most evolved cumulates from the Insch Lower Zone comprise the assemblage olivine (Fo_{77}), orthopyroxene (En_{79}), clinopyroxene ($Ca_{44}Mg_{47}Fe_9$) and plagioclase (An_{75}), which is almost identical in terms of mineral compositions to B33, at the top of the Belhelvie *main* sequence. This information is certainly consistent with the proposal that the Belhelvie cumulates should be regarded as equivalent to the Insch Lower Zone, and therefore as complementary to the Insch Middle and Upper Zones. On this basis, the combination of Belhelvie and Insch cumulates provide a reasonably complete record of progressive fractional crystallization from ultramafic to syenodioritic compositions.

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