Pyroxenes and coexisting minerals in the Cheviot granite

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ABSTRACT. Orthopyroxene and clinopyroxene, with biotite, are widespread in the high-level Cheviot granite, while amphibole is rare. The pyroxene compositions are very close to $(Mg,Fe)_2Si_2O_6$ and $Ca(Mg,Fe)Si_2O_6$. Biotite compositions, with low Si and Al, are characteristic of biotites coexisting with pyroxenes. Geothermometric estimates based on oxide and pyroxene compositions show that present mineral compositions result from post-consolidation equilibration.

KEYWORDS: granite, Cheviot, rare earth elements, pyroxene, biotite, geothermometry.

THE Cheviot granite is one of the youngest of the British Caledonian granites, emplaced under tensional conditions (Read, 1961; Brown and Locke, 1979). It is associated with a negative residual gravity anomaly, indicative of a large volume of granitic rock, and with a pronounced aeromagnetic anomaly (Brown and Locke, 1979). It was intruded into a sequence of volcanic rocks of Devonian age, and solidified at a high level in the crust. Exposed rocks range from granite to monzonite, but the evidence of the geochemistry and mineralogy of stream sediments (Haslam, 1975; Leake and Haslam, 1978) suggests that there may also be some more basic rocks within the pluton.

In the first published description of the petrology of the Cheviot granite, Teall (1885) drew attention to its most distinctive petrographic feature, namely that it was the first recorded British example of an augite-bearing granite. He also noted the presence of orthopyroxene in one specimen, and Kynaston (1899) later observed that this was a widespread constituent of the granite. Kynaston's statement that the occurrence of augite in the granite is always extremely characteristic was disputed by Carruthers et al. (1932) who considered that the normal granite was a granophyric type, biotite-bearing but free of pyroxene, and that where pyroxene occurred its presence was due to contamination (except for some of the orthopyroxene which they conceded had crystallized from a melt).

Jhingran (1943) found that the pyroxene-bearing types occupied more than half of the complex. He agreed with Carruthers et al. (1932) that the pyroxenes in the marginal variety were xenocrystal or, more likely, the recrystallization products of incompletely digested inclusions. It was subsequently shown, in a study of the Ben Nevis igneous complex (Haslam, 1968) that, when crystallization took place at low pressure, at a high level in the crust, pyroxenes, not amphiboles, could be the stable phases in calc-alkaline granite magmas with as much as 67% SiO_2. From this study it was concluded that pyroxene would be expected to be stable crystallizing from the Cheviot magma, and that it was therefore not necessary to invoke contamination in order to account for the presence of pyroxene in high-level granitic rocks.

The Cheviot granite may be compared with other high-level granitic intrusions, such as the Ben Nevis complex (Haslam, 1968) and the Finnmarka complex in Norway (Czamanske, 1965; Czamanske and Mihalik, 1972; Czamanske and Wones, 1973). In these two complexes a strongly oxidizing trend led to the ferromagnesian minerals becoming more Mg-rich in the more acid rocks. At Finnmarka there is, in addition, strong Mn enrichment in the ilmenites.

Rock chemistry and petrography. Chemical analyses of six specimens of the Cheviot granite are given in Table I. The analyses show ranges of values similar to those shown by Jhingran's samples (1943, Table II, analyses 1-3). In mineralogical composition these specimens are quartz monzodiorites and granites, using the nomenclature of Streckeisen (1976). Zoned plagioclase (around andesine in composition) is the principal constituent, with subordinate orthoclase and interstitial quartz. All the specimens contain biotite. Two pyroxenes are generally present, but in CH1 they have been largely replaced by a pale fine-grained amphibole. CH7 is unusual in that it contains a well-crystallized green amphibole. This green amphibole appears to have crystallized from the magma, possibly at the expense of pyroxene, but the pale

Table I. Whole rock analyses of the Cheviot granite

	CH1	CH3	CH5	CH6	CH7	CH9
SiO_2	62.96	64.98	67.62	66.16	68.25	63.80
TiO_2	0.91	0.76	0.59	0.61	0.56	0.74
Al_2O_3	15.40	14.98	14.69	14.77	14.98	15.24
Fe_2O_3	1.37	1.37	1.19	1.58	1.10	1.36
FeO	2.07	2.26	1.81	1.58	1.51	2.42
MnO	0.07	0.06	0.05	0.06	0.05	0.06
MgO	3.06	2.67	2.04	2.22	1.70	3.06
CaO	4.40	3.29	2.82	2.94	2.07	3.45
Na_2O	4.16	3.97	3.97	4.01	3.64	4.18
K_2O	4.29	4.53	4.78	4.85	5.66	4.70
LoI	0.61	0.61	0.52	0.77	0.71	0.69
H_2O-	0.10	0.09	0.07	0.08	0.06	0.05
P_2O_5	0.31	0.27	0.22	0.22	0.22	0.31
Total	100.61	99.84	100.37	99.85	100.51	100.06

Trace elements (ppm)

	CH1	CH3	CH5	CH6	CH7	CH9
Be	4	4	5	4	6	3
B	12	<10	17	<10	38	14
F	990	950	690	790	950	860
V	92	62	63	71	81	77
Cr	63	69	57	62	59	82
Co	37	25	23	40	35	29
Ni	35	37	25	29	21	44
Y	14	10	13	12	12	11
Zr	313	167	137	163	193	191
Ba	550	416	414	449	517	429

National Grid References of the sample collection sites are:
CH1 (NT 978178), CH3 (967184), CH5 (942184), CH6 (944180),
CH7 (945174), CH9 (958171)

Table II. Electron microprobe analyses of minerals in the Cheviot granite

	Orthopyroxene		Clinopyroxene		Biotite	
	CH3	CH5	CH3	CH5	CH3	CH5
SiO_2	51.85	52.78	52.17	52.98	37.33	37.78
TiO_2	0.40	0.10	0.22	0.17	6.17	5.68
Al_2O_3	1.09	0.50	0.68	0.64	13.33	12.87
FeO	20.72	21.83	8.57	8.98	11.76	13.14
MnO	0.88	1.04	0.53	0.48	0.09	0.06
MgO	21.70	21.77	14.06	14.03	15.38	15.05
CaO	1.11	0.87	21.90	21.97	0.04	0.04
Na_2O	0.01	0.02	0.31	0.32	0.22	0.15
K_2O	0.01	0.00	0.01	0.01	9.64	9.75
Cr_2O_3	0.10	0.03	0.01	0.02	0.06	0.04
V_2O_3	0.02	0.04	0.02	0.03	0.08	0.18
NiO	0.02	0.03	0.01	0.02	0.05	0.07
Total	97.91	99.01	98.49	99.65	94.15	94.81

Ions on the basis of 6 [O](pyroxenes), 22 [O] (biotites)

	Orthopyroxene		Clinopyroxene		Biotite	
	CH3	CH5	CH3	CH5	CH3	CH5
Si	1.969	1.989	1.978	1.985	5.59	5.65
Al^{IV}	0.031	0.011	0.022	0.015	2.35	2.27
Al^{VI}	0.018	0.012	0.008	0.013	0.00	0.00
Ti	0.011	0.003	0.006	0.005	0.69	0.64
Cr	0.003	0.001	0.000	0.000	0.01	0.00
V	0.001	0.001	0.001	0.001	0.01	0.02
Fe	0.658	0.688	0.272	0.281	1.47	1.64
Mn	0.028	0.033	0.017	0.015	0.01	0.01
Mg	1.228	1.223	0.794	0.784	3.43	3.36
Ni	0.001	0.001	0.000	0.001	0.01	0.01
Ca	0.045	0.035	0.889	0.882	0.01	0.01
Na	0.001	0.001	0.023	0.023	0.06	0.04
K	0.000	0.000	0.000	0.000	1.84	1.86

amphibole in other specimens probably formed from pyroxene after consolidation of the magma, either during the initial cooling or during later hydrothermal activity. Magnetite, ilmenite, and rare apatite are accessory minerals. Small pyroxene grains occur rarely as inclusions in plagioclase, evidence that they began to appear in the magma at an early stage of crystallization.

The chondrite-normalized REE patterns (fig. 1) are similar to those for the plutons at Foyers and Strontian (Pankhurst, 1979), Ballachulish (Haslam and Kimbell, 1981), and Criffell (Stephens et al., 1985) but with stronger light-to-heavy REE enrichment. There are small negative Eu anomalies, contrasting with the large negative anomalies for the Cairngorm granite (Plant et al., 1980).

Mineral chemistry. Pyroxenes, biotites, ilmenites, and magnetites in specimens CH3 and CH5 were analysed by electron microprobe. In Table II (pyroxenes and biotites) each analysis is the mean of at least four analyses from at least two grains in a single section. Spots were analysed at cores and margins of grains, but no systematic zoning was noted in any of the phases.

The pyroxenes are close to $(Mg,Fe)_2Si_2O_6$ and $Ca(Mg,Fe)Si_2O_6$ in composition (Table II). Of particular note are the low Al_2O_3 in each analysis, the low CaO in the orthopyroxenes, and the high CaO in the clinopyroxenes. Similar features, though less marked, are seen in analyses of pyroxenes from dioritic rocks from Ben Nevis (Haslam, 1968) and Doon (Brown et al., 1979). The CaO levels can be taken as evidence of low temperatures of equilibration. The Lindsley (1983) geothermometer gives temperatures in the range 650–850 °C at < 2 kbar. This suggests that the pyroxene compositions were modified after consolidation of the granite magma.

The biotite analyses (Table II) show unusually high TiO_2 contents. Apart from this, they are similar to other biotite analyses from Caledonian plutons (Nockolds and Mitchell, 1948; Haslam, 1968). A feature common to most of these Caledonian plutonic biotites, and to biotites in the Finnmarka complex (Czamanske and Wones, 1973), is that the total Si and Al is insufficient, or barely sufficient, to fill the tetrahedral sites. Nockolds (1947) found that this was characteristic
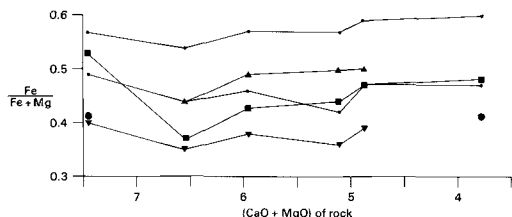
FIG. 1. Chondrite-normalized rare-earth element abundances. REEs determined by instrumental neutron activation analysis.

of biotites coexisting with pyroxene and/or olivine in calc–alkali igneous rocks.

Pyroxenes, biotites, and amphiboles in CH1, 6, 7, and 9, where present, were analysed semiquantitatively by electron microprobe. The pyroxene and biotite analyses show the same characteristics as the minerals in CH3 and CH5. Secondary actinolitic amphibole in CH1 has low Al_2O_3 (1.7%) and Na_2O (0.5%). Primary green amphibole in CH7 has slightly higher, but variable, Al_2O_3 (1.7 to 4.7%) and similar Na_2O (0.5%).

Fig. 2 shows the $FeO/(FeO + MgO)$ ratios of the analysed rocks and minerals, plotted against $(CaO + MgO)$ of the host rock. In each case, the value of this ratio remains generally constant from more basic to more acid rocks, in contrast to the rising trend observed in most rock suites and the
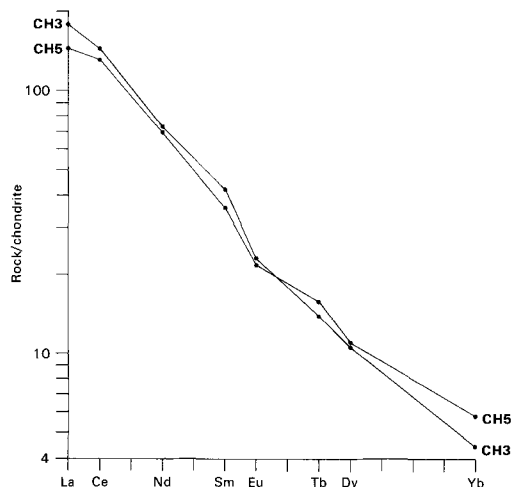

FIG. 2. $FeO/(FeO + MgO)$ in coexisting minerals and their host rocks. Dots represent rock analyses, squares biotites, circles amphiboles, triangles orthopyroxenes, and inverted triangles clinopyroxenes. In the minerals and in the upper rock data points, FeO represents total Fe expressed as FeO. In the lower rock data points FeO represents true FeO.

falling trend shown by ferromagnesian minerals at Ben Nevis (Haslam, 1968) and Finnmarka (Czamanske and Wones, 1973). This suggests that the Cheviot granite crystallized under conditions more oxidizing than most granites but less so than Ben Nevis and Finnmarka.

Magnetite and ilmenite grains were analysed in CH3 and CH5. The analysed spots were from centres and margins of grains, and included some spots in small inclusions in plagioclase. There was found to be wide compositional variation, both between grains and also, in some instances, within grains, but no consistent pattern in the variation could be recognized, either in the major elements Fe and Ti or in the minor elements. The principal components of magnetite varied from $Usp_{0.5}Mt_{99.5}$ to $Usp_{7.1}Mt_{92.9}$ in CH3 and from $Usp_{3.8}Mt_{96.2}$ to $Usp_{4.4}Mt_{95.6}$ in CH5. Those of ilmenite varied from $Hm_{5.6}Il_{94.4}$ to $Hm_{11.6}Il_{88.4}$ in CH3 and from $Hm_{2.3}Il_{97.7}$ to $Hm_{10.4}Il_{89.6}$ in CH5. Application of the Buddington–Lindsley (1964) geothermometer to three pairs of adjacent grains in CH3 and one pair in CH5 showed in each instance that equilibration took place below 500 °C. The compositions of these minerals were modified, therefore, during post-consolidation cooling and they do not provide information about conditions at the time of consolidation. In conformity with the usual partition relationships, Al and Cr are higher and Mn is lower in the magnetites than in the ilmenites. MnO in ilmenite reaches 5.3% in CH3 and 2.3% in CH5, much lower than the 10–20% in the granodiorite at Finnmarka, which has a broadly similar whole-rock composition (Czamanske, 1965; Czamanske and Mihalik, 1972).

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