

CHEMICAL VARIATIONS AMONG THE AMPHIBOLES OF SHEFFORD MOUNTAIN, A MONTEREGIAN INTRUSION IN SOUTHERN QUEBEC

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ABSTRACT

The amphiboles in a suite of nine rocks from the differentiation sequence, alkalic gabbro—diorite—monzonite—feldspathoidal and quartz syenites, in the Monteregian intrusive complex of Shefford Mountain, have been analyzed with the electron microprobe. With decreasing $Mg/Mg+Fe+Mn$ in the amphiboles, which grossly correlates with decreasing basicity of the host rocks, the amphiboles become poorer in Ti, Al and Ca and richer in Mn; enrichment in Na becomes apparent in the amphiboles of the syenites. Fluctuations in these trends are notable among the brown amphiboles of the earlier stages of differentiation and are probably attributable either to variations in chemical and physical conditions of crystallization of the magma or, in the case of amphiboles clearly replacing pyroxene, to chemical control by the parent mineral composition.

The characteristic amphibole of the gabbros and diorites is kaersutite, which, in the monzodiorites and monzonites, becomes increasingly zoned to green magnesian hastingsite (nomenclature of Leake 1968). In the feldspathoidal syenites, the amphibole is sodic magnesian hastingsite, whereas in the quartz syenite it is arfvedsonitic, containing little calcium but less sodium than true arfvedsonite. The kaersutite \rightarrow hastingsite transformation represents a continuous reaction. It could not be determined if the change from hastingsite to arfvedsonitic amphibole is continuous but the transitional nature of the latter suggests solid solution between hastingsite and alkali amphibole.

Amphiboles are unusually sensitive to changing conditions of crystallization and rarely is this property displayed to better advantage than in the Monteregian Hills igneous province of southern Quebec. As in some other Monteregian intrusions, amphibole is ubiquitous in the rocks of Shefford Mountain, where a sequence ranging from gabbro through diorites and monzonites to both nepheline and quartz syenites is well represented. The amphiboles correspondingly vary, largely continuously, from brown, titaniferous, calcic varieties to green, Ti- and Ca-poorer, more alkalic types. This chemical variation has been studied with the electron microprobe and the results are presented in the following pages and compared with data from other alkalic intrusions of similar character.

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GEOLOGICAL SETTING

Shefford Mountain, 45 miles east-southeast of Montreal, is the second largest of the Lower Cretaceous Monteregian Hills intrusive complexes. Crudely oval in shape, the intrusion has an area of 5.6 sq. miles. Previous work on the intrusion is reviewed by Gold (1967) in a summary description of the Monteregian province and a detailed study of Shefford by staff and students of École Polytechnique, Montreal, is currently underway. The following brief summary of the geology of Shefford Mountain is based on my own field work in 1963-64 and results of later detailed mapping by A. Carpentier and G. Pouliot (kindly provided by Dr. Pouliot).

The oldest intrusive rocks on Shefford are hornblende-rich gabbros, diorites, monzodiorites and monzonites, which form the bulk of the central and eastern parts of the intrusion (Fig. 1). The mafic rocks are composed

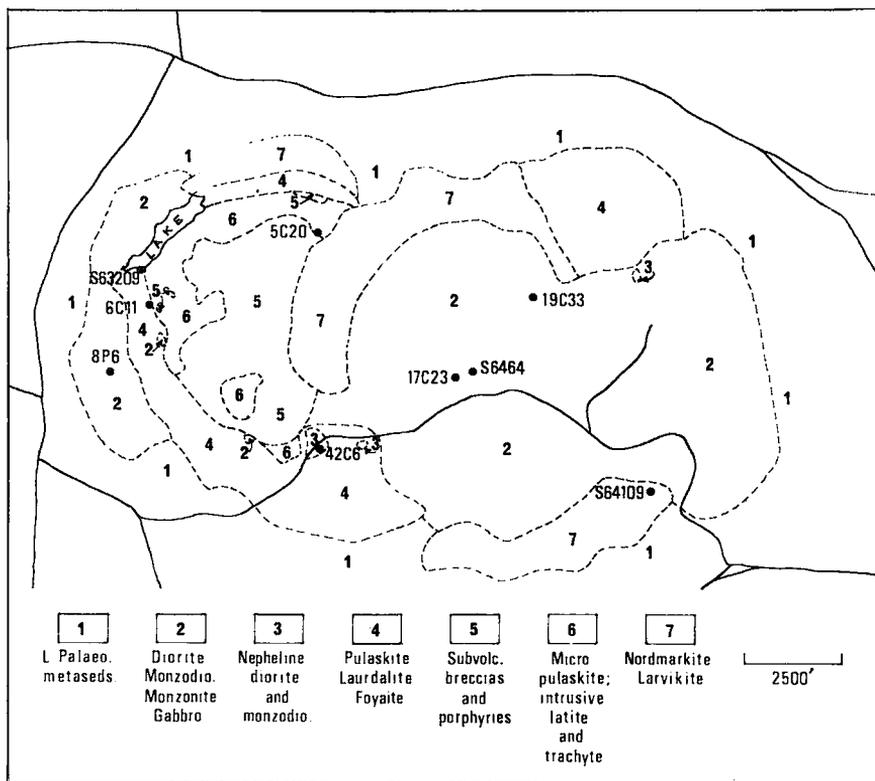


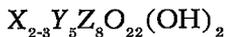
FIG. 1. Geological map of Shefford Mountain (after G. Pouliot and A. Carpentier, unpublished work), showing locations of specimens studied.

chiefly of plagioclase, kaersutite and augite; olivine (Fo_{65}), quartz and feldspaths are rare. The western end of Shefford is characterized by arcuate belts of more syenitic rocks, such as nepheline syenites and intrusive latite and trachyte. A dark sub-volcanic breccia, rich in plutonic and sedimentary rock fragments and plagioclase, underlies the highest part of the "mountain". Exclusive of diverse alkalic dykes, the youngest rock is nordmarkite (quartz syenite), whose outcrop pattern — discontinuously surrounding the central mafic to intermediate zone — is suggestive of a ring-dyke or cone sheet.

Although chemical data on bulk rock compositions are lacking, field relations and petrography clearly point to the Shefford Mountain rocks being related by continuous magmatic differentiation. Pouliot (1962) recognized two trends of differentiation, one leading to quartz-bearing, the other to nepheline-bearing residua. The general chemical trend in the Monteregian Hills leads to an increase in alumina and alkalis and a decrease in the ferromagnesian elements and lime with increasing silica (Gold, 1967, p. 299). This trend is well reflected by the composition of the amphiboles, with the exception of alumina and iron.

NOMENCLATURE OF THE AMPHIBOLES

All but one of the amphiboles investigated in the present study fall into the calcium group, for which the general formula reads



where X = Ca, Na and K; Y = Al, Ti, Fe, Mn and Mg; Z = Si and Al (Deer, Howie & Zussman 1963, p. 207). As has been pointed out by Leake (1968, p. 5) and others before him, considerable confusion exists in the naming of the calcium amphiboles; misidentifications have been made in the Monteregian province (see below). The classification adopted here is that proposed by Leake (1968), slightly extended by referring the half-unit cell to 23, rather than 24 oxygens. It is strictly a chemical scheme, based chiefly on the Si, Ca + Na + K, Niggli's Mg, and Ti values in the half-cell, it being evident that optical properties cannot reliably distinguish the calciferous amphiboles. The members of this group found in this study belong to the kaersutite, ferroan pargasite and magnesian hastingsite subdivisions of Leake (1968, Fig. 2). As it happens and as might be expected, the kaersutites and Ti-Fe pargasites may be distinguished from the hastingsites by their colours, the former being brown while the latter are green.

Alkali amphiboles are those whose X positions are occupied chiefly by Na, such that $(\text{Na} + \text{K}) > 2$ atoms (Deer, Howie & Zussman 1963, p. 209).

PREVIOUS WORK ON AMPHIBOLES FROM THE MONTEREGIAN HILLS

Prior to the present work, only five analyses of amphiboles from the Montereian Hills had been published. Two are from essexite and diorite of Mount Royal and a third is from essexite of Mount Johnson (analyses 614, 639 and 676 in Leake (1968), who also gives the original references). Billings (1928, Table II) placed all three amphiboles in the hastingsite series. Despite their low $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, (0.34 to 0.49), Beall (1962, p. 160) termed them oxyhornblendes and unfortunately this misnomer reappears in the summary description of the Montereian Hills by Gold (1967, p. 297), who cites Beall. In both Leake's (1968) and Wilkinson's (1961) classifications, these amphiboles are kaersutites. The two other published analyses come from the Oka carbonatite-syenite complex, which is rather atypical of the province as a whole. They are "hornblende" (subsilicic ferri-ferroan pargasite) from an ijolite-calcite rock contact zone and "lamprobolite" (subsilicic ferroan pargasite) from alnoite (Gold 1966, Table Z). In an unpublished dissertation, Gandhi (1966, Table 8) presents six new analyses of amphiboles from basic rocks of Mount Yamaska and correctly describes them as kaersutites.

Optical data on brown and green amphiboles of Mount Royal and Mount Johnson have been provided by Tertsch (1906) and Billings (1928) (cf. also Leake 1968). The analyzed hornblende from Mount Johnson (No. 639 in Leake, 1968) has $c\Lambda\gamma = 11^\circ$, $2V_\alpha = 79^\circ$, and $\gamma - \alpha = 0.025$ (Tertsch, 1906, p. 474), properties entirely consistent with those of kaersutite given by Wilkinson (1961, Table 3), Deer, Howie & Zussman (1963, p. 321) and Leake (1968). Brown hornblende from "essexite" of Mount Royal, with $c\Lambda\gamma = 10^\circ$, $2V_\alpha = 70^\circ$, and $\gamma - \alpha = 0.031$ (Tertsch, 1906, p. 474) may be similarly classified as kaersutite, although Tertsch calls it barkevikite. Billings (1928) measurements on brown amphiboles from the same two intrusions, quoted by Leake (1968), are in substantial agreement with Tertsch's data.

Intergrown with the analyzed Mount Johnson kaersutite were small amounts of (a) amphibole with $\alpha =$ pale yellow, $\beta =$ greenish brown, $\gamma =$ moss green, $c\Lambda\gamma = 14^\circ$, $2V_\alpha = 72^\circ$, and $\gamma - \alpha = 0.0195$, and (b) a deep blue amphibole in tiny grains (Tertsch, 1906, pp. 464-466). The Mount Royal brown amphibole examined by Tertsch (1906, p. 473) was rimmed by a green amphibole with $\alpha =$ almost colourness, $\beta = \gamma =$ moss

green, $c\Delta\gamma = 12-13^\circ$, and $\gamma - \alpha = 0.029$. These relations between brown and green hornblende are typical of the Monteregeian province. The optical data do not serve to identify the green amphiboles, as they apply to both the hornblende and the hastingsite series of Deer, Howie & Zussman (1963) and to several subdivisions in Leake's (1968) scheme.

ANALYTICAL TECHNIQUE

Analyses were made on beryllium-coated polished thin sections with an Applied Research Laboratories EMX-SM electron probe x-ray micro-analyzer. Operating conditions were: accelerating potential 15 kV, specimen current 0.07 to 0.15 microampere, spot size 1 to 2 microns, and counting times on scalars 20 seconds. No volatilization was detected under these conditions. Three elements were analyzed simultaneously, using LiF, ADP and/or KAP spectrometer crystals: Si, Ti and Al; Ca, Fe and Mg; Mn, Na and K. The analyses given in Table 1 represent the averages of 5 to 15 spot determinations in each of 3 to 4 grains per thin section. A single standard was used: homogeneous kaersutite from Kakanui, New Zealand, containing SiO_2 40.37 wt. %, TiO_2 4.38%, Al_2O_3 14.90%, total Fe as FeO 10.92%, MnO 0.09% MgO 12.80%, CaO 10.30%, Na_2O 2.60%, and K_2O 2.05% (values that have been carefully determined by both classical and microprobe methods on pure material, according to B. Mason, pers. comm., 1969). All counts were corrected for background, for deadtime when counts exceeded 4000/sec (which was rarely) and for mass absorption, using Duncumb & Shields' (1966) modification of Philibert's method and absorption coefficients of Heinrich (1966) and Henke et al. (1967). Instrument drift was negligible to absent, due to long warm-up times before making quantitative measurements. Accuracy is estimated to be about 2% of the amount present for the major elements and about 5% for the minor ones, except for Mn, for which, due to the low Mn content of the standard, the accuracy is about 20% (according to comparative checks made with other Mn-rich minerals of well-known composition).

Because H_2O , F and Cl could not be determined, the chemical formulae have been calculated on the basis of 23 oxygens. In order to provide a better picture of the true composition of the Shefford amphiboles, the total iron as FeO values for the calcium amphiboles have been recalculated to Fe_2O_3 and FeO in the following manner.

The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios for the six kaersutites from Yamaska (Gandhi 1966, Table 8), a neighbouring intrusion to Shefford and almost certainly genetically related to it, have been averaged and this average (0.43) is assumed to apply to the Shefford amphiboles. Because of the uncertainty

TABLE I. ANALYSES OF AMPHIBOLES.

Specimen Number	8P6	6C11	S63209	17C23	42C6	19C33	S6464	19C33	42C6	S63209	6C11	5C20	S64109
SiO ₂	40.0	38.3	40.8	41.3	40.1	38.5	39.2	39.8	40.0	38.8	38.6	39.3	47.8
TiO ₂	5.5	5.7	5.2	3.8	4.5	5.5	5.2	4.4	2.9	1.6	1.3	0.9	1.1
Al ₂ O ₃	12.9	14.8	12.5	10.3	12.1	12.9	13.1	11.7	11.6	12.1	10.4	10.0	1.9
Fe ₂ O ₃ ^a	3.6	3.7	3.6	4.5	4.4	4.6	4.5	5.0	5.9	7.1	7.4	7.3	
FeO ^a	8.4	8.5	8.4	10.5	10.2	10.7	10.5	11.7	13.6	16.4	17.2	16.9	
FeO ^b	(11.6)	(11.8)	(11.7)	(14.5)	(14.2)	(14.9)	(14.6)	(16.2)	(18.9)	(22.8)	(23.8)	(23.5)	33.3
MnO	0.4	0.2	0.4	0.8	0.6	0.5	0.4	0.5	0.8	1.9	3.2	4.3	3.8
MgO	12.6	12.5	12.0	11.7	11.1	11.0	10.7	10.8	8.9	6.9	6.3	5.8	1.4
CaO	12.6	12.7	11.8	10.9	11.5	12.4	12.2	12.3	11.1	10.7	10.2	9.0	5.4
Na ₂ O	2.6	3.0	3.0	2.3	3.1	3.1	3.1	2.9	3.1	3.1	3.6	4.1	4.3
K ₂ O	1.1	1.0	1.0	1.0	1.0	0.9	0.9	1.2	1.4	1.7	1.7	1.7	1.1
Total	99.7	100.4	98.7	97.1	98.6	100.1	99.8	100.3	99.3	100.3	99.9	99.3	100.1
FORMULAE ON THE BASIS OF 23 OXYGENS													
Si	5.83	5.56	5.98	6.21	5.95	5.68	5.77	5.88	6.03	5.93	6.01	6.15	7.63
Al ^a	2.17	2.44	2.02	1.79	2.05	2.23	2.23	2.04	1.97	2.07	1.91	1.84	0.36
Ti	—	—	—	—	—	0.09	—	0.08	—	—	0.08	0.01	0.01
Al ^b	0.03	0.09	0.13	0.03	0.07	—	0.04	—	0.09	0.11	—	—	—
Ti	0.60	0.62	0.57	0.43	0.50	0.53	0.58	0.41	0.33	0.18	0.07	0.10	0.12
Fe ^a	0.38	0.40	0.39	0.51	0.50	0.51	0.50	0.55	0.67	0.81	0.86	0.86	—
Fe ^b	1.02	1.03	1.03	1.32	1.27	1.32	1.29	1.45	1.71	2.09	2.24	2.21	4.40
Mn	0.05	0.03	0.05	0.10	0.07	0.06	0.05	0.06	0.10	0.25	0.42	0.57	0.51

TABLE 1 (continued)

Specimen Number	8P6	6C11	S63209	17C23	42C6	19C33	S6464	19C33	42C6	S63209	6C11	5C20	S64109
Mg	2.73	2.70	2.63	2.62	2.45	2.42	2.35	2.38	2.00	1.57	1.46	1.35	0.33
Ca	1.97	1.97	1.85	1.75	1.83	1.96	1.93	1.95	1.79	1.75	1.70	1.50	0.91
Na	0.74	0.84	0.85	0.67	0.89	0.89	0.89	0.84	0.90	0.92	1.08	1.24	1.31
K	0.21	0.19	0.19	0.20	0.20	0.18	0.18	0.23	0.27	0.33	0.34	0.34	0.23
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	4.81	4.87	4.80	5.01	4.86	4.84	4.81	4.85	4.90	5.01	5.05	5.09	5.36
X	2.92	3.00	2.89	2.62	2.92	3.03	3.00	3.02	2.96	3.00	3.12	3.08	2.45
	NAME (NOMENCLATURE OF LEAKE, 1968)												
Host rock (see Appendix)	Kaersu-tite	Sub-silicic kaersu-tite	Kaersu-tite	Titani-ferrous parga-site	Kaersu-tite	Sub-silicic kaersu-tite	Kaersu-tite	Titani-ferrous parga-site	Titani-ferrous mag-nesian hast-ing-site	Mag-nesian hast-ing-site	Sodic mag-nesian hast-ing-site	Sodic mag-nesian hast-ing-site	Arfved-sonitic nesian amphi-bole
Remarks		Xeno-cryt phase	Cf. Fig. 4	Replaces pyro-xene cf. Fig. 2	Most Mg-rich hbl. in rock cf. Fig. 3	Compo-sition of core	Diorite	Monzo-diorite	Monzo-diorite	Monzo-diorite	Pulas-kite	Foid. syenite	Nord-markite
								Compo-sition of rim	Most Mg-poor hbl. in rock cf. Fig. 3	Cf. Fig. 4	G' mass hbl. and rims on kaersu-tite		

^a Calculated value (see text).

^b Total iron as FeO (measured value).

TABLE 1 (continued).

Specimen Number	8P6	6C11	S63209	17C23	42C6	19C33	S6464	19C33	42C6	19C33	42C6	S63209	6C11	5C20	S64109
SiO ₂	40.0	38.3	40.8	41.3	40.1	38.5	39.2	39.8	40.0	39.8	40.0	38.8	38.6	39.3	47.8
TiO ₂	5.5	5.7	5.2	3.8	4.5	5.5	5.2	4.4	2.9	4.4	2.9	1.6	1.3	0.9	1.1
Al ₂ O ₃	12.9	14.8	12.5	10.3	12.1	12.9	13.1	11.7	11.6	11.7	11.6	12.1	10.4	10.0	1.9
Fe ₂ O ₃ ^a	3.6	3.7	3.6	4.5	4.4	4.6	4.5	5.0	5.9	5.0	5.9	7.1	7.4	7.3	—
FeO ^a	8.4	8.5	8.4	10.5	10.2	10.7	10.5	11.7	13.6	11.7	13.6	16.4	17.2	16.9	—
FeO ^b	(11.6)	(11.8)	(11.7)	(14.5)	(14.2)	(14.9)	(14.6)	(16.2)	(18.9)	(16.2)	(18.9)	(22.8)	(23.8)	(23.5)	33.3
MnO	0.4	0.2	0.4	0.8	0.6	0.5	0.4	0.5	0.8	0.5	0.8	1.9	3.2	4.3	3.8
MgO	12.6	12.5	12.0	11.7	11.1	11.0	10.7	10.8	8.9	10.8	8.9	6.9	6.3	5.8	1.4
CaO	12.6	12.7	11.8	10.9	11.5	12.4	12.2	12.3	11.1	12.3	11.1	10.7	10.2	9.0	5.4
Na ₂ O	2.6	3.0	3.0	2.3	3.1	3.1	3.1	2.9	3.1	2.9	3.1	3.1	3.6	4.1	4.3
K ₂ O	1.1	1.0	1.0	1.0	1.0	0.9	0.9	1.2	1.4	1.2	1.4	1.7	1.7	1.7	1.1
Total	99.7	100.4	98.7	97.1	98.6	100.1	99.8	100.3	99.3	100.3	99.3	100.3	99.9	99.3	100.1
FORMULAE ON THE BASIS OF 23 OXYGENS															
Si	5.829	5.558	5.983	6.206	5.951	5.681	5.774	5.881	6.029	5.881	6.029	5.929	6.007	6.150	7.629
Al ^a	2.171	2.442	2.017	1.794	2.049	2.233	2.226	2.043	1.971	2.043	1.971	2.071	1.909	1.843	0.961
Ti	—	—	—	—	—	0.086	—	0.076	—	0.076	—	—	0.084	0.007	0.010
Al ^b	0.034	0.088	0.133	0.031	0.074	—	0.041	—	0.093	0.113	—	0.113	—	—	—
Ti	0.604	0.620	0.573	0.434	0.500	0.526	0.576	0.413	0.326	0.413	0.326	0.184	0.066	0.096	0.123
Fe ^a	0.385	0.401	0.388	0.506	0.500	0.514	0.496 ₆	0.551	0.670	0.551	0.670	0.808	0.861	0.865	—
Fe ^b	1.024	1.030	1.031	1.319	1.267	1.321	1.293	1.448	1.711	1.448	1.711	2.093	2.236	2.210	4.404
Mn	0.052	0.026	0.053	0.099	0.071	0.062	0.053	0.062	0.100	0.062	0.100	0.248	0.421	0.574	0.514

TABLE I (continued)

Specimen Number	8P6	6C11	S63209	17C23	42C6	19C33	S6464	19C33	42C6	S63209	6C11	5C20	S64109
Mg	2.731	2.705	2.626	2.620	2.454	2.420	2.347	2.381	2.000	1.569	1.460	1.354	0.333
Ca	1.969	1.972	1.850	1.753	1.829	1.959	1.931	1.946	1.792	1.753	1.703	1.504	0.913
Na	0.735	0.838	0.846	0.669	0.892	0.886	0.886	0.835	0.905	0.918	1.085	1.241	1.313
K	0.210	0.192	0.194	0.199	0.196	0.177	0.177	0.231	0.272	0.330	0.337	0.339	0.228
Z	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Y	4.83	4.87	4.80	5.01	4.87	4.84	4.81	4.86	4.90	5.02	5.04	5.10	5.37
X	2.91	3.00	2.89	2.62	2.92	3.02	2.99	3.01	2.97	3.00	3.12	3.08	2.45
	NAME (NOMENCLATURE OF LEAKE, 1968)												
Host rock (see Appendix)	Kaersu-tite	Sub-silicic kaersu-tite	Kaersu-tite	Titani-ferrous ferroan parga-site	kaersu-tite	Sub-silicic Kaersu-tite	Kaersu-tite	Titani-ferrous ferroan parga-site	Titani-ferrous mag-nesian hasti- site	Mag-nesian hasti- site	Sodic mag-nesian hasti- site	Sodic mag-nesian hasti- site	Arved-sonitic amphi-bole
Remarks	Xeno-cyst phase	Xeno-cyst phase	Cf. Fig. 4	Replaces pyroxene cf. Fig. 2	Most Mg-rich hbl. in rock cf. Fig. 3	Compo-sition of core	Compo-sition of rim	Most Mg-poor hbl. in rock cf. Fig. 3	Cf. Fig. 4	C' mass hbl. and rims on kaersu-tite	Pulas-kite	Foid. syenite	Nord-marlite

^a Calculated value (see text).

^b Total iron as FeO (measured value).

in extrapolating this method to an amphibole of totally different composition, the total iron content of the arfvedsonitic amphibole S64109 is given as FeO only.

THE AMPHIBOLES OF SHEFFORD MOUNTAIN

The amphiboles in nine rocks were analyzed and the results are presented in Table 1. Brief petrographic descriptions of the host rocks are given in the Appendix.

The characteristic amphibole of the Shefford Mountain gabbros, diorites, monzodiorites and monzonites is a kaersutite or titaniferous ferroan pargasite, with α = pale or yellowish brown, β = brown and γ = reddish brown (there is commonly little difference between the β and γ colours). Distinct zoning in brown amphibole was detected in only one specimen, a micro-monzodiorite (19C33), in which cores of crystals are subsilicic kaersutite, while narrow rims are titaniferous ferroan pargasite. It is interesting to note that, despite the significant and abrupt chemical change, there is no perceptible difference in either colour or extinction angle from core to rim. Indeed, the pleochroic formula given above applies, with but slight modification, to the entire range of kaersutites and pargasites here analyzed.

In many of the rocks there is no evidence to suggest that brown amphibole did not form directly from the magma as a primary precipitate, but in others it is clearly a replacement product of pyroxene. Pseudomorphs of titaniferous ferroan pargasite after augite are a feature of mafic diorite 17C23 (Fig. 2). The replacing amphibole has distinctly lower Ti than the other brown amphiboles of the suite. This may reflect late formation in a relatively Ti-poor environment (sphene is absent and the abundant Fe-Ti oxides present may have crystallized early) or, perhaps more likely, the composition of the amphibole was controlled by that of the parent mineral, which contains little titanium (as shown by semi-quantitative microprobe analysis).

Rocks more salic than gabbro contain kaersutite that is zoned to, or partly replaced by, green or brownish green magnesian hastingsite. In monzodiorite 42C6, the amphibole shows continuous zoning from typical kaersutite to titaniferous magnesian hastingsite with α = yellow, β = dark greenish brown and γ = dark brownish green. The more green the γ colour, the more iron rich is the amphibole. Clearly a continuous reaction relation exists between kaersutite and hastingsite. Fig. 3 depicts one aspect of the coexistence of these two amphiboles in specimen 42C6: relict kaersutite occurs in the core of a clinopyroxene grain, which is partly replaced

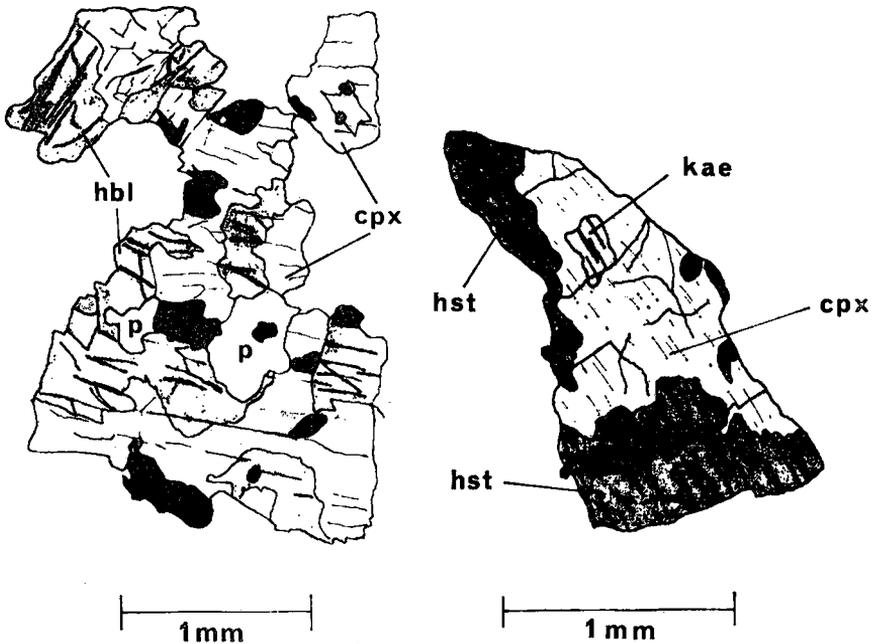


FIG. 2. (Left) Replacement of colourless clinopyroxene (cpx) by brown titaniferous ferroan pargasite (hbl) in diorite 17C23. Black grains are Fe-Ti oxides, p = plagioclase.

FIG. 3. (Right) Relict brown kaersutite (kae) in the core of a colourless clinopyroxene crystal, which is partly replaced at the margins by green magnesian hastingsite (hst), in monzodiorite 42C6.

at the margins by titaniferous magnesian hastingsite. More common in this rock are amphibole grains, whose cores are kaersutite and whose rims are hastingsite and in which the zoning is fairly abrupt. Other grains are of overall intermediate composition and display continuous zoning between kaersutite or Fe-Ti pargasite and hastingsite.

The monzodiorite S63209 exhibits an amphibole crystallization sequence identical to that figured by Iwao (1939, Fig. 14a) and also described by Yagi (1953, p. 784) in monzonites from Sakhalin Island. Reddish brown kaersutite crystallized before reddish brown titanbiotite (identified by semi-quantitative microprobe analysis), which, in turn, was followed by green magnesian hastingsite (Fig. 4).

In the syenites, brown hornblende is no longer present as a cognate constituent. In the feldspathoidal syenite 6C11 (pulaskite), kaersutite similar to that in the gabbro 8P6 occurs in crystals 2 mm in size that are apparently xenocrysts: the grains are heavily altered and are in part

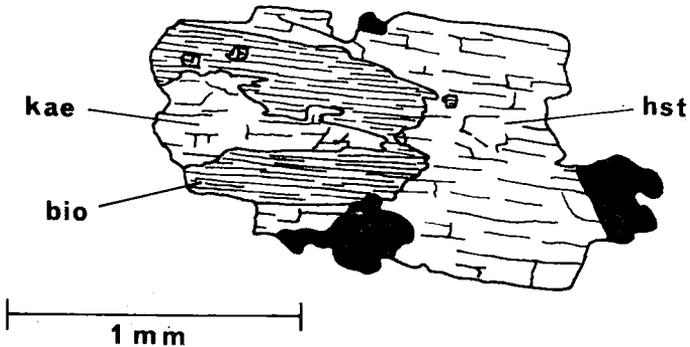


FIG. 4. Composite grain of kaersutite, titanbiotite (bio) and magnesian hastingsite in monzodiorite S-63-209. The two inclusions in the biotite are kaersutite. Note the titanbiotite inclusion in the hastingsite.

markedly resorbed. The xenocrysts are rimmed by sodic magnesian hastingsite, with α = pale greenish yellow, β = pale yellowish green and γ = green, which is identical to the amphibole of the groundmass. The amphibole of the feldspathoidal microsyenite 5C20 has a similar composition but a distinctly different pleochroism, α = yellowish green, β = dark green with brown tinge and γ = very dark bluish green.

The amphibole of the nordmarkite S64109 is difficult to classify, as it shows affinities to both the calcium and the alkali amphibole groups. Its pleochroism (α = dark bluish green, β = dark greyish violet, γ = pale brown), almost uniaxial character, and relatively high silica and low calcium suggest an alkali amphibole, specifically arfvedsonite, but its alkali content ($\text{Na} + \text{K} = 1.5$ atoms) is too low. I believe this amphibole to be evidence of solid solution between calcium and alkali amphiboles. A comparable hornblende, containing 5.90% CaO and 4.54% Na_2O , from a quartz-fayalite porphyry in Nigeria, has been described and similarly interpreted by Borley & Frost (1963, Table II, A.25). In the Shefford rock, the amphibole occurs chiefly as an overgrowth on strongly zoned aegirine-augite, less commonly as discrete, small crystals interstitial to perthite; it is the only amphibole present.

Comparison of the kaersutite analyses reported here with those available from other Montereian Hills shows close similarities, as might be expected in rocks with such obvious genetic relations (cf. Gold, 1967). As regards the green amphiboles, the Shefford specimens are very probably also typical but lack of data from the other intrusions prevents a comparison.

The overall variation in chemical composition of the Shefford amphiboles is illustrated in Fig. 5, wherein weight per cent Si, Al, Ti, Mn, Ca, Na and K are plotted against $100 \text{ Mg}/(\text{Mg} + \text{Fe} + \text{Mn})$ (*i.e.* Niggli's mg times 100). (The ionic proportions in this case have been calculated on the basis that all the iron is present as Fe^{2+} .) Assuming that the sequence gabbro-diorite-monzonite-syenite is one of decreasing basicity, a gross correlation between Mg of the host rocks and Mg of the amphiboles is apparent. The most Mg-rich, Fe-poor amphibole comes from the most basic rock of the suite studied, a gabbro. The least magnesian, most sodic amphiboles come from the syenites.

The clearest trends are the decrease in Ti and Ca and the increase in Mn, as a function of decreasing $\text{Mg}/(\text{Mg} + \text{Fe} + \text{Mn})$. In the later stages of differentiation, Al falls rapidly while Na rises. Aluminum shows the usual inverse relationship to silicon: when Si is low, Al is compensatingly high. A generally sympathetic relationship exists between Al and Ti in the brown amphiboles. At the kaersutite stage of crystallization, the magma was apparently enriched in both Al and Ti and the incorporation of Al in tetrahedral sites of the silicate structure facilitates the entry of Ti (Verhoogen 1962, p. 217). Incorporation of Ti in either Z or Y sites is further favoured by low silica activity and high temperatures (Verhoogen 1962, p. 216), conditions that were probably realized during the early stages of evolution of the Shefford Mountain rocks.

The relatively high potassium contents of the hastingsites probably reflect concentration of K in the melt at a time when large amounts of alkali feldspar had not yet begun to crystallize. In contrast, the arfvedsonitic amphibole, one of the last minerals to crystallize in the nordmarkite, which is composed largely of alkali feldspar, has markedly lower K_2O than the hastingsites.

COMPARISON WITH OTHER ALKALIC INTRUSIONS

Aside from the results of Russian studies, regrettably unavailable to me at the time of writing, chemical data on amphiboles from alkalic gabbro-monzonite-syenite intrusions comparable to Shefford Mountain and other Monteregean Hills are scanty, but two studies are important. The alkalic rocks of the Morotu-Nayosi district, Sakhalin Island (off the southern Siberian coast) display remarkable similarity to the more differentiated intrusions of the Monteregean Hills. Yagi (1953) has written a comprehensive account of their mineralogy and petrochemistry (including two amphibole analyses) and Iwao (1939) has dealt with the optics and paragenesis of the minerals in a suite of specimens. Comparable rocks from

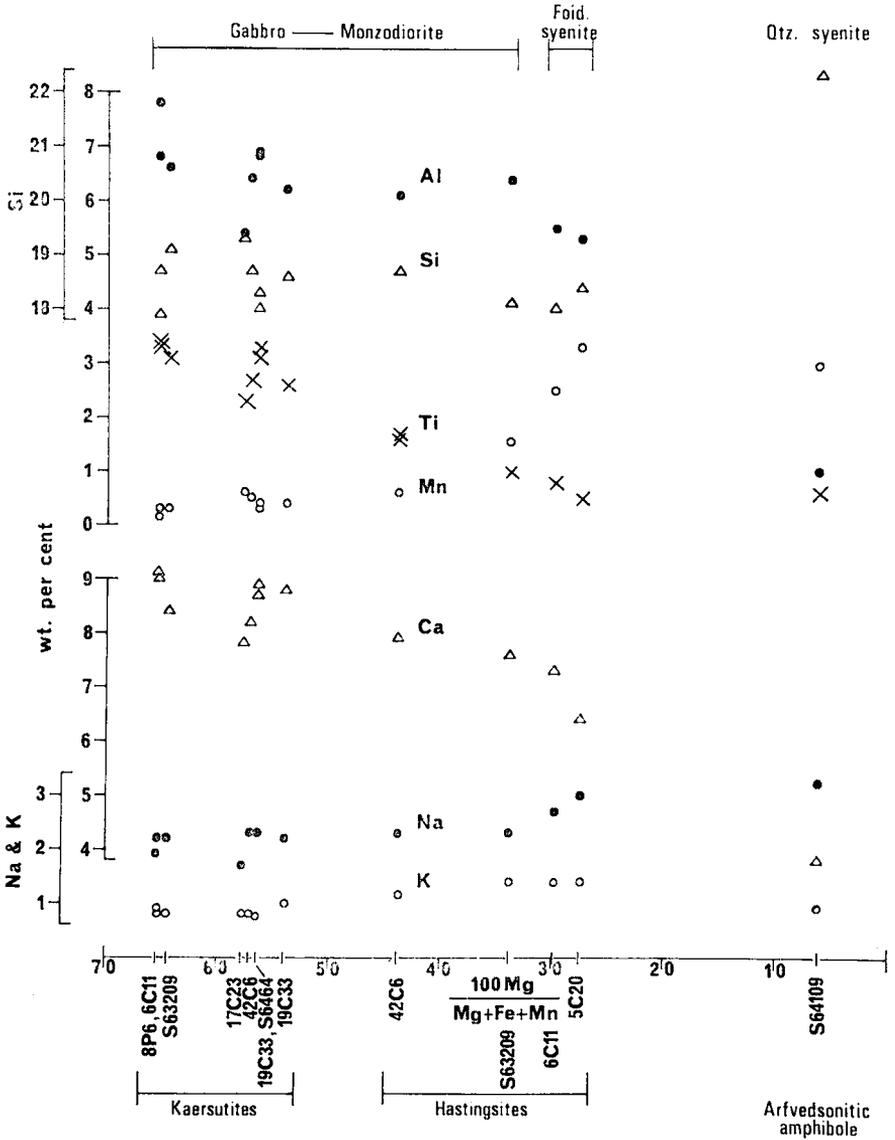


FIG. 5. Plot of weight per cent Si, Al, Ti, Mn, Ca, Na and K versus $100\text{Mg}/\text{Mg} + \text{Fe} + \text{Mn}$ in each amphibole. Niggli's mg has been calculated assuming all the iron to be divalent.

the alkalic series of Koraput, Orissa, India and Bose (1964) has described their amphiboles (with three analyses).

Yagi (1953) presents clear evidence of differentiation *in situ* that produced a dolerite-monzonite-syenite series in Sakhalin. He states (1953, p. 783) that the brown amphibole in the dolerites is barkevikite, whereas in the monzonites and syenites, kaersutite is present and may be mantled or intergrown with green hastingsitic amphibole. Arfvedsonite (analyzed) is confined to alkali-rich syenites carrying aegirine. From these observations, Yagi postulated a crystallization sequence barkevikite → kaersutite → hastingsite → arfvedsonite. As has already been pointed out by Deer, Howie and Zussman (1963, p. 331), the conclusion that crystallization of barkevikite preceded that of kaersutite is not warranted, as no chemical analysis of the alleged barkevikite was given and because barkevikite has less magnesium and more iron than kaersutite. The optical data given for "barkevikite" by Yagi (1953, p. 783) could apply equally well to kaersutite. The results of the present study indicate that kaersutite would precede barkevikite in the normal crystallization of alkalic igneous rocks.

Bose (1964) gives analyses of brown titaniferous magnesian hastingsitic hornblende from "alkali gabbro" (the plagioclase is andesine), greenish brown ferro-kaersutite from calc-alkali syenite (composed largely of alkali feldspar), and green titaniferous sodic potassic hastingsitic hornblende from nepheline syenite (*cf.* Leake, 1968, analyses 1187, 1216 and 1210).

Borley & Frost (1963, Table II) list the analyses of five green amphiboles from nepheline- and quartz-bearing syenites of the Marangudzi ring complex of Southern Rhodesia. They termed them ferrohastingsites; in Leake's classification these amphiboles are hastingsites or magnesian hastingsites (Leake 1968, analyses 922, 924, 927, 928 and 930).

The green amphiboles from Shefford have more magnesium and sodium and considerably more manganese than the Marangudzi amphiboles. The manganese content of the Shefford hastingsites is notably high when compared with the hastingsite analyses given by Deer, Howie & Zussman (1963, Table 43) and Billings (1928).

EVOLUTION OF AMPHIBOLES IN ALKALIC ROCKS

Considering the chemical data from the Montereian Hills, Sakhalin and Koraput, as well as the purely petrographic descriptions of other alkalic bodies, one may conclude that the normal amphibole crystallization sequence in well-differentiated alkalic intrusions is the formation of brown, titaniferous, relatively magnesian amphibole (generally kaersutite) followed by hastingsite, which becomes increasingly iron-rich as differentiation

proceeds. Barkevikite (as defined by Deer, Howie & Zussman 1963, p. 328 : brown amphibole with high iron and low Fe^3/Fe^2 ratio) is probably a mineral of quite restricted occurrence.

This is essentially the evolution proposed by Billings (1928, p. 293), partly on the evidence from the Monteregeian Hills. Billings suggested that "ferrohastingsite" ($Fe^2/Mg > 2$) is the characteristic amphibole in both nepheline syenite and nordmarkite. In the Shefford nordmarkite, the amphibole is more akin to an alkali amphibole than to an iron-rich hastingsite. Billings further contended that riebeckite is the end-product of the hastingsite evolutionary series and that riebeckite granite evolves from nepheline syenite, nordmarkite and/or hastingsite syenite. More recent work (e.g. Yagi 1953, Borley 1963) has shown that arfvedsonite is the more common final member of this series. According to experimental evidence obtained by Ernst (1962), the crystallization of riebeckite and arfvedsonite depends on temperature and oxygen fugacity : at high temperature and low oxygen fugacity, arfvedsonite precipitates, whereas riebeckite forms under the reverse conditions. On the basis of this evidence, the former set of conditions appears to have held in the Sakhalin intrusions, the Younger Granite province of Nigeria (Borley 1963) and the Shefford Mountain complex.

In agreement with Billings' conclusion, kaersutite \rightarrow hastingsite is a continuous reaction series. On the other hand, whereas Billings suggested that a discontinuity exists between hastingsite and alkali amphibole, there is reason to suspect, on the chemical evidence from Shefford Mountain (and from the Nigerian Younger Granite province), that the sequence hastingsite \rightarrow arfvedsonite may also be continuous. However, this could not be confirmed, as the two minerals do not coexist in any of the samples studied. It would be of interest to follow this question up, as it bears on the problem of whether the Shefford nordmarkite is a differentiate of the nepheline syenite or merely the end-product of a differentiation trend toward silica oversaturation that paralleled one toward silica undersaturation.

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APPENDIX

BRIEF PETROGRAPHIC DESCRIPTIONS OF ROCKS STUDIED

Note 1. Specimen numbers including "C" or "P" refer to rocks from the collection at École Polytechnique, Montreal. Others are from the author's own collection.

Note 2. Apatite is a major accessory in all rocks studied. 8P6. Biotite-kaersutite gabbro. Foliated; grain size 1-2 mm. Plagioclase An 50; altered, colourless augite, rimmed by green amphibole; biotite intergrown with kaersutite; abundant Fe-Ti oxides.

17C23. Biotite-Ti-ferroan pargasite-augite diorite. Plagioclase An 45 (3-6 mm); colourless augite (1-6 mm) is partly replaced by the brown amphibole; abundant Fe-Ti oxides; no sphene.

S-63-209. Titanbiotite-augite-kaersutite-Mg-hastingsite monzodiorite. Phenocrysts (2-3 mm) of oligoclase; in groundmass, plagioclase An 23 mantled by alkali feldspar (0.7 mm); kaersutite mantled by titanbiotite, which is rimmed by hastingsite; colourless augite, partly replaced by brown amphibole; abundant sphene; Fe-Ti oxides associated with mafics.

42C6. Ti-Mg-hastingsite-kaersutite-biotite-augite feldspathoidal monzodiorite. Grain size 1-3 mm. Plagioclase An 23; interstitial perthitic alkali feldspar and altered feldspathoids; very pale green augite, partly replaced by kaersutite and rimmed by hastingsite; abundant sphene; minor Fe-Ti oxides.

S-64-64. Augite-biotite-kaersutite diorite. Grain size: phenocrysts (kaersutite) 1-2 cm; groundmass 1-2 mm. Plagioclase An 45-25; minor colourless augite; abundant sphene and Fe-Ti oxides; accessory calcite.

19C33. Augite-titanbiotite-kaersutite micromonzodiorite. Phenocrysts of kaersutite zoned to Ti-ferroan pargasite and of oligoclase (zoned), both up to 2 mm; minor augite partly replaced by brown amphibole; abundant Fe-Ti oxides.

5C20. Biotite-Na-Mg-hastingsite feldspathoidal microsyenite (pulaskite?). Amphibole microphenocrysts 0.5 mm, groundmass feldspar 0.01-0.02 mm. Plagioclase An 30; altered feldspathoids; minor biotite (lepidomelane?) intergrown with amphibole; finely disseminated Fe-Ti oxides.

6C11. Na-Mg-hastingsite-Na-augite micropulaskite. Xenocrysts (2 mm) of kaersutite, partly resorbed and rimmed by hastingsite identical to that in groundmass; phenocrysts of soda augite (1 mm) and of oligoclase An 27 (3 mm), which are mantled by alkali feldspar; alkali feldspar in groundmass (0.1-0.5 mm), with decussate texture; abundant sphene; Fe-Ti oxides partly mantled by sphene.

S-64-109. Arfvedsonitic amphibole-fayalite-aegirine-augite nordmarkite. Grain size: perthite 2-3 mm, other minerals 0.5-1 mm. Coarsely perthitic alkali feldspar with interstitial quartz; zoned aegirine-augite (rims more Fe- and Na-rich than cores) partly mantled by amphibole; fayalite slightly iddingsitized.