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SUBSOLIDUS EVOLUTION OF GNEISSIC BIOTITE SYENITE AND NEPHELINE SYENITE, OTTER LAKE AREA, QUEBEC

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Abstract

Three small (~1 km) bodies of gneissic biotite syenite (the Stag syenite) and one larger body (~2 km) of gneissic nepheline syenite (the Cawood nepheline syenite) occur 60 km northwest of Ottawa in the Central Metasedimentary Belt (Grenville Province of Quebec) of the Canadian Precambrian Shield. The Stag syenite consists of K-feldspar, sodic plagioclase, biotite [Fe^{2+} / ($Mg + Fe^{2+}$) = 0.5], local hornblende, and conspicuous titanite, apatite, and magnetite. Its chemical composition (major and 20 trace elements) is close to that of mean terrestrial syenite. The Cawood nepheline syenite consists of K-feldspar, sodic plagioclase, nepheline (close to ideal nepheline), and combinations of hornblende, biotite [in both, Fe^{2+} / ($Mg + Fe^{2+}$) = 0.9], and garnet, $(Ca_{2.7}Fe_{0.2})(Fe_{1.3}Al_{0.6})Si_3O_{12}$. Abundances of Mg, Sc, Y, the rare earths, Th, U, Zr, Hf, V, and Nb are very low, similar to some examples of nepheline syenite from the Bancroft area to the southwest. Following high-grade metamorphism, retrograde phase-separation occurred in the Stag and Cawood bodies, to produce discrete crystals of K-feldspar and sodic plagioclase, as well as perthite. A model of ductile emplacement of the dome-like syenite bodies is proposed, during which microstructures, including gneissic lineations, which in two bodies are discordant with those of the surrounding rock, were largely preserved.

Keywords: syenite, K-feldspar, sodic plagioclase, nepheline, biotite, hornblende, andradite, titanite, perthite, metamorphism, microstructure, emplacement, Central Metasedimentary Belt, Grenville Province, Quebec.

Sommaire

Trois petits massifs (~1 km) de syénite à biotite gneissique (la syénite de Stag) et un plus gros (~2 km) de syénite néphélinique gneissique (la syénite néphélinique de Cawood) sont situés à 60 km au nord-ouest d'Ottawa, dans la Ceinture Métasédimentaire Centrale (Province du Grenville du Québec), partie du Bouclier Canadien, d'âge précambrien. La syénite de Stag contient l'assemblage feldspath potassique, plagioclase sodique, biotite [Fe^{2+} / ($Mg + Fe^{2+}$) = 0.5], hornblende ici et là, et comme accessoires bien développés, titanite, apatite, et magnétite. Sa composition chimique (éléments majeurs et 20 éléments traces) se rapproche de la moyenne d'une syénite terrestre. La syénite néphélinique contient l'assemblage feldspath potassique, plagioclase sodique, néphéline (se rapprochant de la néphéline idéale), et des combinaisons de hornblende, biotite [les deux ayant Fe^{2+} / ($Mg + Fe^{2+}$) = 0.9], et grenat, $(Ca_{2.7}Fe_{0.2})(Fe_{1.3}Al_{0.6})Si_3O_{12}$. Les abondances de Mg, Sc, Y, des terres rares, de Th, U, Zr, Hf, V, et Nb sont très faibles, semblables à certains cas de syénite néphélinique de la région de Bancroft, vers le sud-ouest. Suite à un événement de métamorphisme intense, les massifs ont subi une séparation de phases rétrograde, menant à la formation de grains distincts de feldspath potassique et de plagioclase sodique, associés à des grains de perthite résiduelle. Dans les massifs syénitiques, mis en place en forme de dome à l'état ductile, les linéations gneissiques sont bien préservées, quoique qu'elles sont discordantes par rapport à l'encaissant dans deux cas.

(Traduit par la Rédaction)

Mots-clés: syénite, feldspath potassique, plagioclase sodique, néphéline, biotite, hornblende, andradite, titanite, perthite, métamorphisme, microstructure, mise en place, Ceinture Métasédimentaire Centrale, Province du Grenville, Québec.

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INTRODUCTION

Several bodies of syenite occur in the Central Metasedimentary Belt, which lies within the southern Grenville Province of the Canadian Precambrian Shield (Fig. 1). One of the largest is the Wakefield syenite, immediately northwest of Ottawa, which was mapped by Sabourin (1965), Hogarth (1970), Béland (1977) and Dupuy (1992). In Ontario 150 km southwest of Ottawa, there are the renowned occurrences of nepheline syenite of the Bancroft area, which were examined by Adams & Barlow (1910), Osborne (1930), Gummer & Burr (1946), Baragar (1953), Tilley (1957), Hewitt (1960), Gittins (1961) and Appleyard (1967), and in Québec (200 km north of Ottawa), the Cabonga nepheline syenite complex was recently described by Hudon *et al.* (2002), who obtained a date of ~1150 Ma. In addition, more than twenty-four small, late-tectonic plutons of syenite occur throughout the belt (Britton 1979); some of these plutons in Québec, which were described by Rive (1976), Durocher (1977), Corriveau *et al.* (1990) and Corriveau & Gorton (1993), contain minor nepheline.

In the present report, four dome-like bodies of gneissic syenite in the Otter Lake area (Fig. 1) are described. Three of these are small (~1 km) bodies of biotite syenite, characterized by abundant mafic inclusions and a pronounced gneissic lineation, whereas the fourth is a larger body (~2 km) of gneissic nepheline syenite with Fe-rich hornblende, biotite, and garnet. Data are presented on the structural setting of these bodies, and on minerals present, rock composition, and mineral composition. Following a chemical comparison of the two kinds of syenite, with each other and with occurrences elsewhere, attention will focus on metamorphic mineral reactions and equilibria, especially in the more complex nepheline syenite. Finally, the problem of emplacement will be discussed.

In the present report, the term "syenite" is used in place of the formal names monzonite, foid monzosyenite and foid monzodiorite.

SETTING

Nearly all the bodies of rock in the Otter Lake area, excluding the 590 Ma gabbro dikes, were affected by ductile deformation and high-grade metamorphism during the Proterozoic Grenvillian orogeny. The varieties of rock have been grouped as follows: Group 1, marble and skarn; 2, felsic to mafic gneiss and amphibolite, with sillimanite, garnet, biotite, hornblende, Ca pyroxene, and local orthopyroxene; minor quartzite and granulite; 3, metagabbro and metapyroxenite; 4, K-feldspar gneiss, including veined gneiss with biotite, local garnet, and rare sillimanite; 5, granitic and syenitic rock. Groups 1 to 4 were studied previously (Kretz 1978, 1980, 1990, 1994a, Kretz *et al.* 1989), whereas preliminary data on granite and syenite (Group 5) were

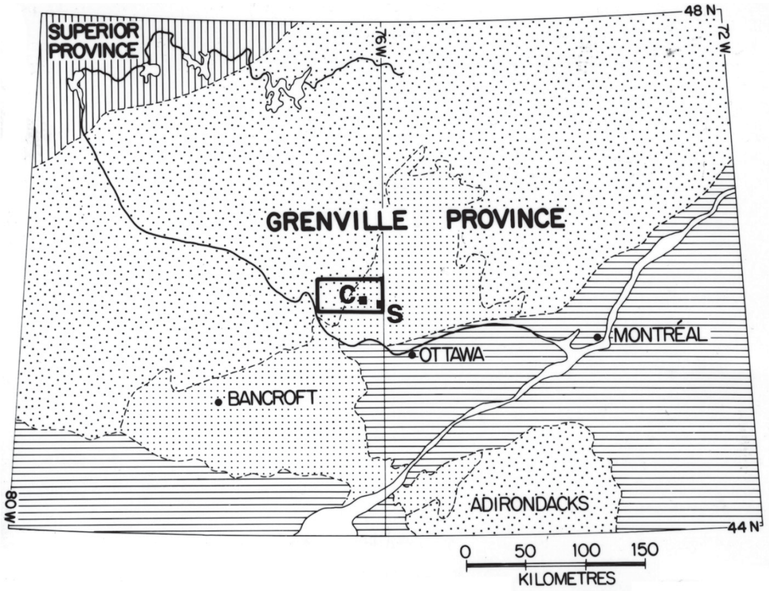

FIG. 1. Location of the Otter Lake area in the Grenville Province. The "lattice" stipple is the Central Metasedimentary Belt (Wynne-Edwards 1972), and the horizontal-line pattern indicates the area underlain by lower Paleozoic sedimentary strata. The location of the Stag syenite (S) and the Cawood nepheline syenite (C) is indicated.

presented in an open-file report (Kretz 1977). Metamorphic grade across the field area is nearly uniform, at high amphibolite facies, with local domains of granulite facies. Estimates of peak temperature and pressure of metamorphism, based principally on the garnet–biotite thermometer and the garnet–plagioclase barometer, are 700°C and 7 kbar (Kretz 1994a, b, p. 212, 219).

A prominent structural feature of the Otter Lake area is a zone of complex folding, 3 to 10 km wide, that separates dominantly northeast-trending layering and foliation in the east from dominantly northwest-trending layering and foliation in the west. Although much variation exists, fold axes and mineral lineations in the east plunge moderately to the northeast, and in the west they are horizontal or plunge gently to the southeast (Kretz 1977, 1994a, unpubl. data). The four bodies of syenite to be described below occur in the eastern (Gatineau) area, where marble (Group 1), gneiss and amphibolite (Group 2) and K-feldspar gneiss (Group 4) occur abundantly (Baker 1977, Kretz 1977).

METHODS

Mineral proportions in hand samples were measured on cut and stained surfaces by use of a grid overlay (100 points) or a grid in the eyepiece of a binocular microscope (400 points), combined with standard point-count measurements on thin sections. Examples of uncertainty in mineral proportions are 10 ± 3 and 40 ± 5 vol. %.

Rock analyses were made at the University of Ottawa by X-ray fluorescence (XRF, fused disc method) and at Activation Laboratories, Ancaster, Ontario by instrumental neutron activation (INA method); details are provided by Kretz *et al.* (1999). Mineral analyses were made at the McGill University microprobe laboratory and Carleton University SEM facility. Ferrous iron in rock samples and in highly pure mineral separates was determined by titration (Wilson method).

Estimates of analytical precision in the XRF results were obtained by the replicate analysis of basalt BAS–1 ($n = 10$), of rhyolite RHY–1 ($n = 10$), and of granite B8 from the field area ($n = 8$). For most elements reported here, standard deviation (s) can be related to concentration (C) by use of the equation $s = \mathrm{k}C^{2/3}$, with k = 0.0046 (Si, Ti, Al, Fe, Mg, Ca, K), 0.0020 (Mn), 0.010 (Na), 0.029 (Sr), 0.071 (V, Y, Zr, Nb), 0.15 (P, Rb), and ~ 0.4 (Ba) (Kretz & Hartree 1998).

Estimates of analytical precision in the INA results were obtained by the replicate ($n = 10$) analysis of a hornblende separate, with the finding that k in the relation $s = \mathrm{k}C$ is approximately 0.02 (Sc, Sm, Eu, Yb, Lu), 0.04 (La, Ce, Nd), 0.06 (Cs, Tb) and 0.10 (Hf, Th, U) (Kretz *et al.* 1999). Regarding titrimetric determinations of FeO, duplicate measurements indicate confidence levels of 10 ± 0.6 and 1.0 ± 0.15 wt% FeO, approximately. Calculations of analytical precision, expressed as 0.95 confidence limits ($\pm c = \pm 2.0\ s$) are presented in Table 1.

Very little within-sample variation in mineral composition was detected, and uncertainty in microprobe determinations (mean of 2 or 3) can be estimated by use of the relation $s = 0.04C^{1/2}$ (Potts *et al.* 1983). Confidence limits to atom ratios (see below) were obtained by propagation-of-error calculations (Kretz 1994b, p. 457).

A high level of accuracy in the XRF data was confirmed by analyzing several samples of granite by both XRF and INA (trace elements) and by both XRF and ICP (major elements), with nearly identical results.

TABLE 1. MINERAL PROPORTIONS AND ROCK COMPOSITION

	Stag syenite			Cawood nepheline syenite			
	S1	S2	S3	C1	C2	C3	± c
Quartz vol.%	<1						
K-feldspar	38	39	33	19	39	24	
Plagioclase	47	45	51	35	15	27	
Nepheline				28	25	40	
Hornblende	4	<1		13	19	7	
Biotite	7	13	12	3		<1	
Garnet					3		
Titanite	<1	1	2	1	<1	<1	
Zircon			<<1	<<1			
Apatite	1	<1	1	<1	<1		
Magnetite	1	1	1	<1	<1	<1	
Pyrite	<1	<1	<1			<1	
Calcite	<1		<1	<1	<1	2	
SiO_2 wt%	58.8	57.7	55	54.9	54.1	53.3	0.2
TiO_2	0.93	1.3	1.8	0.25	0.47	0.26	0.01
Al_2O_3	17.1	17.7	17.6	23.0	20.0	23.1	0.1
Fe_2O_3	2.8	2.7	2.8	1.1	2.9	1.8	0.03
FeO	2.8	3.0	4.0	1.2	4.1	2.2	0.03
MnO	0.09	0.09	0.10	0.05	0.16	0.09	0.001
MgO	1.13	1.7	2.12	0.05	0.15	0.09	0.02, 0.01
CaO	2.6	2.1	3.4	1.7	3.7	2.5	0.02
Na_2O	5.0	4.7	4.4	7.9	7.0	8.7	0.07
K_2O	6.1	6.4	5.8	7.2	5.7	5.7	0.03
P ppm	1770	2580	4180	375	410	244	64, 15
Sc	6.4	9.2	7.6	0.2	0.2	0.2	0.3, 0.01
V	23	19	50	<10	<10	<10	2
Rb	130	130	102	107	88	86	7
Sr	231	277	600	480	420	511	4
Y	42	44	40	<10	12	<10	1
Zr	2260	783	307	42	53	25	15, 2
Nb	63	39	17	<10	<10	<10	2
Cs	0.5	1	0.8	<0.2	0.6	0.6	0.1
Ba	564	697	2000	1660	1080	1470	80
Hf	33.8	12.6	6.1	1.3	1.3	1.3	4, 0.3
La	45	63	59	5.7	8	5.3	5, 0.6
Ce	101	140	130	15	19	12	10, 1
Nd	48	73	60	8	9	6	5, 0.6
Sm	8.7	12	11	1.8	2.5	1.2	0.5, 0.1
Eu	2.4	3.8	3.5	1.11	1.3	0.91	0.1, 0.04
Tb	1.3	1.5	1.5	0.3	0.4	0.2	0.2, 0.04
Yb	4.7	4.6	3.9	1.3	2.9	1.3	0.2, 0.1
Lu	0.7	0.61	0.5	0.21	0.44	0.83	0.03
Th	1.7	3.5	3.6	1.1	0.3	0.5	0.6, 0.1
U	1.3	0.8	0.8	0.6	0.3	<0.1	0.2, 0.06

Abundances of the major elements and P, V, Rb, Sr, Y, Zr, Nb, Ba were established by X-ray fluorescence spectroscopy; the remainder, by INA, and FeO by titration. ± c: 0.95 confidence limits, analytical precision.

THE STAG SYENITE

Three small bodies of biotite syenite occur near Stag Creek, in the eastern margin of the Otter Lake area (Fig. 2), and these are referred to as Stag I, Stag II, and Stag III. Stag I and II were mapped as granite by Baker (1977), and Stag III is not shown on his map. They appear to be dome-like bodies, emplaced into broadly interlayered and folded marble (Group 1) and gneiss (Group 2).

The syenite consists of K-feldspar (26 to 58%), plagioclase (35 to 51%), local quartz (to 2%) and approximately 12% of biotite (range: 3 to 28%), with hornblende present locally. Titanite, apatite, and magnetite are conspicuously present in all samples, whereas zircon, ilmenite, pyrite, and calcite occur sporadically. Mineral assemblages and proportions in three samples, one from each pluton, are listed in Table 1.

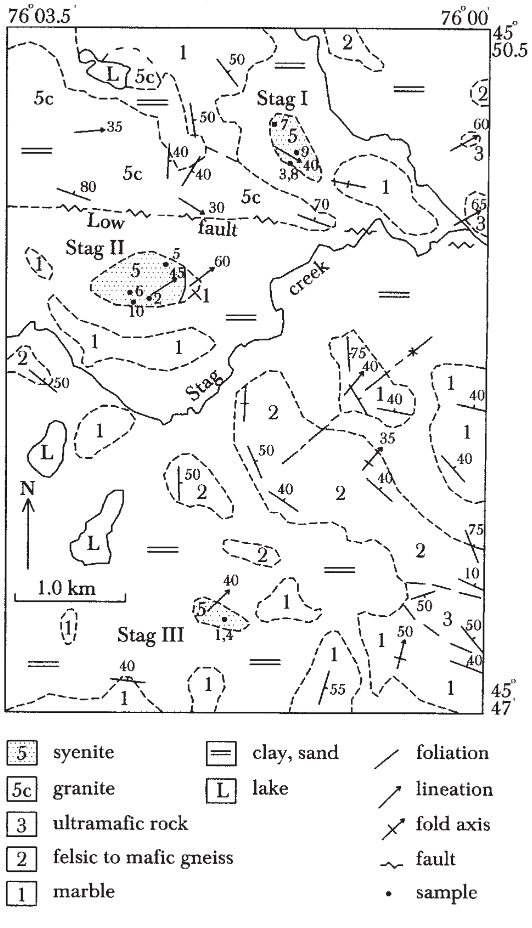

FIG. 2. Geological map of Stag subarea (located as S in Fig. 1), showing the three bodies of Stag syenite, Stag I, II, and III, and sample locations.

The Stag syenite is intermixed with mafic rock, which occurs as layers and inclusions. This rock is here referred to as metagabbro or amphibolite, depending on crystal size (~2 mm or ½ mm) and minerals present (Table 2). Some of the inclusions are tabular, whereas others are irregular in shape (Fig. 3), resulting possibly from interaction with syenite. The syenite and inclusions are cut by quartz–feldspar dikes that are not obviously related to the syenite.

On the scale of 1 m, the syenite is moderately homogeneous. The mean size of feldspar and biotite crystals in the mosaic microstructure is 1 mm, but locally crystals of microcline-twinned K-feldspar range to 5 mm. Irregular K-feldspar – plagioclase intergrowths are locally present, as well as microperthite. A conspicuous lineation is everywhere present, defined by elongate clusters of biotite crystals, and in places, these crystals also define a weak to moderate foliation. Lineation in the mafic inclusions is parallel to that in the enclosing syenite. In Stag II and III, the lineation plunges northeasterly, parallel to the axis of a well-defined major synform in the vicinity (Fig. 2), and parallel to most mineral lineations in the surrounding marble and gneiss. But in Stag I, the gneissic lineation in the syenite plunges southeast (Fig. 2).

THE CAWOOD NEPHELINE SYENITE

A body of nepheline syenite in Cawood Township was discovered on 23 October 1974 while the writer was remapping the eastern third of the Otter Lake area, which in 1954 was mapped by Baker (1977). The syenite body is roughly circular in plan, with a diameter of 2 km, and is well exposed on a south-facing cliff at sites 1 and 2 in Figure 4. The pluton is surrounded by calcite > dolomite marble with biotite and graphite, and by biotite–hornblende gneiss, amphibolite, and garnet amphibolite of Group 2; contacts with the syenite are not exposed.

The syenite consists of nepheline (20 to 40%) easily recognizable on weathered surfaces, and of K-feldspar

TABLE 2. METAGABBRO AND AMPHIBOLITE ASSOCIATED WITH THE STAG SYENITE

	S9	S10		S9	S10
Plagioclase vol.%	70	35	SiO_2 wt%	49.6	46.2
Ca pyroxene	6		TiO_2	3.4	1.5
Hornblende	5	48	Al_2O_3	14.5	15.6
Biotite	14	17	FeO	10.7	10.5
Titanite	<1	<1	MnO	0.18	0.18
Zircon	<1		MgO	4.0	8.1
Apatite	<1		CaO	6.5	8.9
Magnetite	3		Na_2O	4.3	3.5
Pyrite	<1	<1	K_2O	2.4	2.0
Calcite	<1	<1			

Total Fe as FeO. Rock types: S9 metagabbro, S10 amphibolite.

(microcline-twinned) and plagioclase (each 15 to 40%). Dark silicates, which comprise 5 to 20% of the total, are hornblende alone, biotite alone, hornblende–biotite, and hornblende–garnet, as determined by Galipeau (1981), Paris (1999) and the writer. Magnetite and calcite are commonly present, and titanite, zircon, apatite, ilmenite and pyrite were observed locally. Minerals in three representative samples are listed in Table 1.

In a typical exposure, the nepheline syenite is homogeneous on the 1 m scale, and exhibits a weak to moderate gneissic microstructure, defined by lens-like or elongate clusters of dark minerals. The orientation of the gneissic foliation varies, whereas the lineation plunges 20 to 40° east to southeast. The body lies in the axial region of a major northeast-plunging synform (Baker 1977), and most lineations in the vicinity plunge northeast. Hence, structures in this body, as in Stag I, are discordant with those in the surrounding rock.

Crystal size is typically 2 to 3 mm, but patches of coarse-grained rock (nepheline to 3 cm) with local magnetite or garnet are present. On the scale of 2 cm, the microstructure, especially that involving the shape and distribution of crystals, is highly variable. Nearly equidimensional inclusions of K-feldspar and plagioclase in nepheline are common, as are inclusions of plagioclase in K-feldspar (microperthite), and of hornblende in garnet (Fig. 5). Also present are reaction or replacement zones, for example plagioclase (with inclusions of garnet and calcite) at boundaries between nepheline and garnet, and of plagioclase, with inclusions of titanite, calcite, magnetite, and ilmenite, as embayments into crystals of hornblende. Thus, in detail, the microstructure is complex.

FIG. 3. Inclusions of amphibolite (dark) in Stag III syenite, viewed parallel to the lineation.

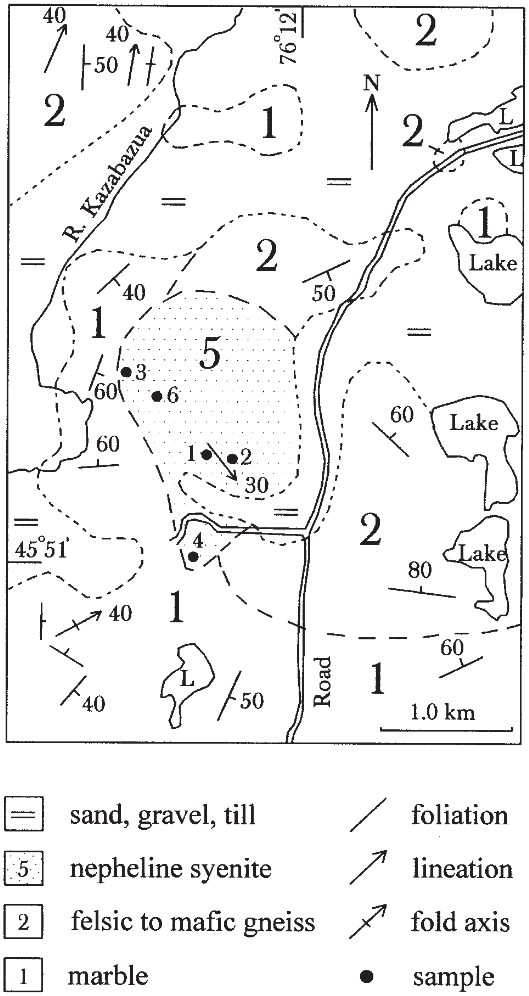

FIG. 4. Geological map of the Cawood subarea (located as C in Fig. 1) showing the body of nepheline syenite (5) and its surroundings.

ROCK COMPOSITION

Chemical compositions of three samples of Stag syenite (one from each pluton) are similar with regard

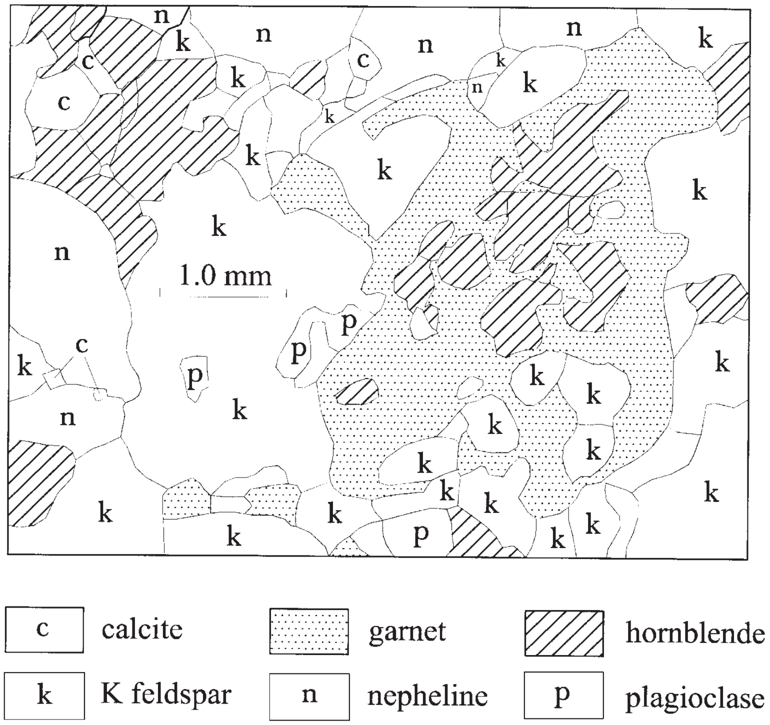

FIG. 5. Microstructure of nepheline syenite sample C2, showing inclusions of hornblende and K-feldspar in garnet and other aspects of crystal shape and distribution.

to major and trace elements (Table 1), including rare-earth elements (Fig. 6). With regard to major elements and the twenty trace elements that were determined, the Stag syenite compares very favorably with mean terrestrial syenite (Fairbridge 1972, Le Maitre 1976), except that P is higher by a factor of 3, and Th and U are lower by a factor of 0.3.

The composition of two mafic inclusions in the Stag syenite (Table 2) is similar to that of mean terrestrial gabbro. Compared with Grenville gabbro of the study area (Kretz *et al.* 1985), K and Rb in the inclusions are higher by a factor of 4 to 5, resulting possibly from interaction with the enclosing syenite.

Chemical compositions of three samples of the Cawood nepheline syenite (Table 1) are similar, and in each, the ratio (Na_2O + K_2O)/Al_2O_3, which is referred to as the agpaitic coefficient (Sørensen 1974a) is equal to 0.89. A small variation in rare-earth elements is indicated in Figure 6. With regard to major elements, the Cawood nepheline syenite compares favorably with mean terrestrial nepheline syenite (Le Maitre 1976) except that Mg is very low, by a factor of 0.13. Trace-element abundances in nepheline syenite worldwide vary enormously (Gerasimovsky 1974); the *ranges* for certain elements, and (in brackets) the mean concentra-

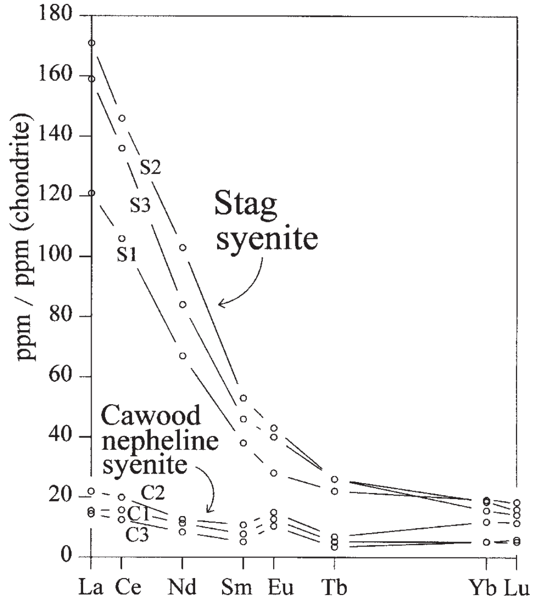

Fig. 6. Normalized rare-earth element plots for samples of the Stag syenite and the Cawood nepheline syenite.

tion in the Cawood nepheline syenite (in ppm) are as follows: V 100 – 42 (<10), Rb 950 – 85 (94), Zr 4700 – 47 (10), Nb 700 – 20 (<10), Cs 9 – 1 (0.4), Th 38 – 0.5 (0.5). This holds true for the rare-earth elements as well, which in the Cawood body are less abundant than mean values reported by Gerasimovsky (1974) by a factor of 0.02 to 0.08.

Abundances of the major elements, including Mg, and of P, Rb, Sr, Zr, and Ba in some occurrences of nepheline syenite of the Bancroft area, to the southwest (Lumbers *et al.* 1990), are similar to those at Cawood. Abundances of other trace elements at Bancroft were not reported.

Without implying a genetic link between the Stag syenite and the Cawood nepheline syenite, it is of interest to compare the two kinds of syenite, one moderately common, the other rare, especially with regard to trace elements. This comparison is carried out in Table 3, by first grouping the elements as in the periodic table, and then calculating the ratio, C/S = (ppm in Cawood)/(ppm in Stag). Note that, with the conspicuous exception of Mg, Group-1 and -2 elements in the Cawood nepheline syenite are somewhat similar to those in Stag syenite, whereas elements in Groups 3, 4 and 5 are very much lower, by factors ranging, with a few exceptions, from 0.30 to 0.03.

TABLE 3. ABUNDANCE OF SOME ELEMENTS IN THE CAWOOD NEPHELINE SYENITE (C) RELATIVE TO THAT IN THE STAG SYENITE (S), WITH ELEMENTS ARRANGED AS IN THE PERIODIC TABLE

Group	Element	S	C	C/S
1	Na	34870	58600	1.7
	K	50600	51500	1.0
	Rb	120	94	0.8
	Cs	0.8	0.4	0.5
2	Mg	9650	600	0.06
	Ca	19300	19300	1.0
	Sr	370	470	1.3
	Ba	1090	1400	1.3
3	Sc	8	0.2	0.03
	Y	42	<10	~0.12
	La	56	6.3	0.11
	Ce	124	15	0.12
	Nd	60	8	0.13
	Sm	11	1.8	0.16
	Eu	3.2	1.1	0.34
	Tb	1.4	0.3	0.21
	Yb	4.4	1.8	0.41
	Lu	0.6	0.49	0.82
	Th	2.9	0.63	0.22
	U	1	0.3	0.30
4	Ti	7790	1980	0.25
	Zr	1120	40	0.04
	Hf	18	1.3	0.07
5	V	31	<10	~0.2
	Nb	40	<10	~0.2

The group numbers are taken from Emsley (1998). The abundances are quoted in ppm.

MINERAL COMPOSITIONS

Hornblende and biotite

In the Stag syenite, the ratio $Fe^{2+}/(Mg + Fe^{2+})$, denoted X_{Fe}, of hornblende and biotite is close to 0.50, whereas in the Cawood nepheline syenite, the Fe content of these minerals is much higher, with X_{Fe} close to 0.90 (Table 4). Concentrations of Na, K, Fe^{3+} and Al for both minerals in the Cawood nepheline syenite are also relatively high. In the Cawood suite (sample C4), fluorine is virtually absent in hornblende and biotite. Despite these differences, the hornblende in both kinds of syenite is hastingsite.

Titanite

The composition of titanite in the Stag syenite, where it is present to 2 or 3%, is not unusual; fluorine is present, but unlike the associated hornblende and biotite, chlorine is absent (Table 4).

Garnet

The composition of garnet from the Cawood nepheline syenite is listed in Table 4. With high levels of Fe^{3+} (Fe^{2+} : Fe^{3+} by calculation), and Ca, the composition approaches most closely that of andradite. Garnet in another sample (C5) and in one studied by Paris (1999) are nearly identical to that reported in Table 4.

The composition of garnet (and of hornblende and biotite) in the Cawood nepheline syenite is similar to the composition of these minerals in the Blue Mountain nepheline syenite of the Bancroft area (Duke & Edgar 1977) and elsewhere (Mitchell & Platt 1979, Mitchell 1990), except that garnet in these occurrences commonly contains more Ti.

The feldspars

Although various intergrowths of sodic plagioclase and K-feldspar occur in both Stag and Cawood suites (to be described below), these two minerals occur, for the most part, as discrete crystals, and compositions of such crystals are listed in Table 4. The $NaAlSi_3O_8$ content of plagioclase [Na/(Na + Ca)] in the Stag syenite is 0.91 (two samples), and in the Cawood nepheline syenite, it ranges from 0.80 to 0.95 (four samples). The ratio Na/(K + Na) of K-feldspar in the Stag syenite is 0.06, and in the Cawood nepheline syenite, it is 0.10 to 0.12 (Table 4 and additional data). Thus the variation in feldspar composition is small.

Nepheline

The composition of nepheline was determined in samples C2 and C4 (Table 4) and in C5. Apart from minor Fe in nepheline C4, the three compositions are

TABLE 4. MINERAL COMPOSITIONS, STAG SYENITE AND CAWOOD NEPHELINE SYENITE

	Stag syenite					Cawood nepheline syenite							
			S4					C2				C4	
	Kfs	Pl	Hbl	Bt	Ttn	Ne	Kfs	Pl	Hbl	Grt	Ne	Kfs	Bt
SiO_2 wt%	65.4	66.9	40.9	35.1	29.3	42.9	65.4	67.4	36.7	36.7	44.0	64.5	33.1
Al_2O_3	18.4	21.3	9.6	13.6	1.4	34.0	19.1	20.9	12.9	6.1	34.4	18.9	16.2
TiO_2			1.2	2.9	36.4				1.7	1.9			4.1
Fe_2O_3			9.0	5.3					12.5	21.5			12.6
FeO	0.04	0.07	14.6	17.3	1.4	0	0	0	20.0	2.9	0.1	0.04	21.0
MgO			7.8	10.3	0.28				0.82	0			2.2
MnO			0.63	0.38	0.14				0.74	0.96			0.54
CaO	0	1.96	11.2	0	27.9	0.41	0	1.1	8.7	31.2	0.49	0.01	0.01
Na_2O	0.73	10.5	1.65	0.07	0.04	15.3	1.35	10.9	2.8		15.4	1.15	0.18
K_2O	16.9	0.24	1.73	10.2	0	6.5	15.3	0.11	2.5		6.7	15.8	9.9
F			0.36	0.79	0.71								0
Cl			0.68	0.57	0								
Si *apfu*	2.99	2.91	6.28	2.73	0.98	1.04	2.98	2.94	5.82	2.99	1.05	2.97	2.55
^{IV}Al	0.99	1.09	1.72	1.25	0.02	0.97	1.03	1.07	2.18		0.96	1.03	1.47
^{VI}Al			0.02		0.03				0.23	0.59			
Ti			0.13	0.17	0.91				0.20	0.12			0.24
Fe^{3+}			1.04	0.31					1.49	1.30			0.73
Fe^{2+}			1.83	1.13	0.04				2.65	0.21			1.35
Mg			1.79	1.19	0.01				0.19	0.00			0.25
Mn			0.08	0.02	0.004				0.10	0.07			0.03
Ca		0.09	1.85		1.00	0.01	0.00	0.05	1.48	2.72	0.01		
Na	0.06	0.90	0.49	0.01	0.003	0.72	0.12	0.92	0.87		0.71	0.10	0.03
K	0.98	0.013	0.34	1.01		0.20	0.89	0.006	0.50		0.20	0.93	0.97
F			0.17	0.19	0.07								0.00
Cl			0.18	0.07									
Na/(Na+Ca)		0.91						0.95					
Na/(K+Na)	0.06					0.78	0.12				0.78	0.10	
$Fe^{2+}/(Mg+Fe^{2+})$				0.51	0.49				0.93	1.0			0.84

In Ttn, Kfs, Pl, Ne, total Fe as FeO.

indistinguishable. The formula of nepheline C2, taken from Table 4, is $(Na_{0.72}K_{0.20}Ca_{0.01})Al_{0.97}Si_{1.04}O_4$, which is close to "ideal" nepheline, as defined by Buerger *et al.* (1954), $(Na_{0.75}K_{0.25})Al_{1.0}Si_{1.0}O_4$. Departures of the Cawood nepheline from ideal nepheline can be explained by proposing that Ca atoms are distributed between the large K-sites (nine-fold coordination) and the smaller Na-sites (eight-fold coordination), with vacancies present in both sites, accompanied by the presence of some Si atoms at the Al site. This formula is $(Na_{0.72}Ca_{0.005}\square_{0.03})_{\Sigma 0.75}(K_{0.20}Ca_{0.005}\square_{0.05})_{\Sigma 0.25}(Al_{0.97}Si_{0.03})Si_{1.00}O_4$.

METAMORPHISM

The dominantly mosaic microstructure of the four bodies of syenite described above, and the gneissic lineation, which in two of the bodies is nearly parallel to major fold axes in the eastern half of the Otter Lake area, are taken as evidence that the bodies were affected by the same tectonometamorphic event that caused deformation and metamorphism in the surrounding rock. The oblique orientation of lineations in the other two bodies then presents a problem, to be discussed below. Hence, the mineral assemblages of the Stag and Cawood suites will initially be viewed in terms of regional metamorphism, including possible retrograde transformations.

Mineral stability, Stag syenite

Upper-amphibolite-facies conditions for the Stag syenite are indicated by the absence of epidote (lower amphibolite facies) and of orthopyroxene (granulite facies), in agreement with previous conclusions regarding metamorphism in the study area as a whole (Kretz 1980). The association hornblende – biotite – plagioclase – K-feldspar, although present, is not common in Group 2 and 4 gneisses of the study area, but is found in other metamorphic terranes (Turner 1981), and the association is evidently stable in the upper amphibolite facies.

Mineral stability, Cawood nepheline syenite

The presence or absence of minerals in the Cawood nepheline syenite is now considered in terms of equations in which most formulae are not phases, but solution components. For example, $NaAlSi_3O_8$, denoted ab, refers to this component in crystals of plagioclase, and $NaAlSiO_4$, denoted ne, refers to this component in crystals of nepheline. The presence of H_2O and CO_2 in the equations implies that volumes of rock, before or during metamorphism, were, for an increment of time, open to these species, and the presence of O_2 introduces the assumption that the activity of oxygen was subject to variation.

1) Calcic clinopyroxene is commonly present in nepheline syenite (Sørensen 1974a), but was not detected in the Cawood nepheline syenite. The absence of this mineral can be attributed to an introduction of CO_2 and H_2O, which produced amphibole from pyroxene:

$$\text{hd} + \text{an} + \text{ne} + CO_2 + H_2O \rightarrow \text{hbl} + \text{ab} + \text{cal}$$
$$8\ CaFeSi_2O_6 + 2\ CaAl_2Si_2O_8 + 3\ NaAlSiO_4 + 6\ CO_2 + 2\ H_2O \rightarrow 2\ Ca_2Fe_4AlAlSi_7O_{22}(OH)_2 + 3\ NaAlSi_3O_8 + 6\ CaCO_3.$$

This equation also explains the common presence of calcite.

2) Garnet in Group 2 and 4 gneiss and in garnet-bearing granite of the field area is invariably rich in the almandine component, and the virtual absence of this component in the Cawood andradite–grossular garnet can possibly be understood in terms of the following two equations:

$$\text{alm} + \text{cal} + O_2 \rightarrow \text{grs} + \text{mgt} + CO_2$$
$$Fe_3Al_2Si_3O_{12} + 3\ CaCO_3 + ½\ O_2 \rightarrow Ca_3Al_2Si_3O_{12} + Fe_3O_4 + 3\ CO_2$$

$$\text{alm} + \text{ab} + \text{cal} + H_2O + O_2 \rightarrow \text{adr} + \text{hbl} + \text{an} + \text{ne} + CO_2$$
$$2\ Fe_3Al_2Si_3O_{12} + 3\ NaAlSi_3O_8 + 6\ CaCO_3 + H_2O + ½\ O_2 \rightarrow Ca_3Fe_2Si_3O_{12} + Ca_2Fe_4AlAlSi_7O_{22}(OH)_2 + CaAl_2Si_2O_8 + 3\ NaAlSiO_4 + 6\ CO_2.$$

These equations imply that in the upper amphibolite facies, the presence of calcite and a relatively high activity of oxygen, grossular and andradite are stable in nepheline syenite, relative to almandine. Garnet–hornblende intergrowths (Fig. 5) were possibly produced by a displacement of the second equation to the right.

3) The high Ti concentrations normally found in garnet that occurs in nepheline syenite can also be examined in terms of an oxidation equation:

$$\text{usp} + \text{cal} + O_2 \rightarrow \text{Ti grt} + \text{mgt} + CO_2$$
$$3\ Fe^{2+}{}_2TiO_4 + 2\ CaCO_3 + O_2 \rightarrow (Fe^{2+}Ca_2)Fe^{3+}{}_2Ti_3O_{12} + Fe_3O_4 + 2\ CO_2,$$

which implies that Ti atoms, where present in garnet, are more stable than where present in magnetite (as ülvospinel), under the given conditions.

4) The absence of jadeite places an upper limit to pressure. The boundary curve for the equilibrium

$$\text{Ab} + \text{Ne} \rightarrow \text{Jd}$$
$$NaAlSi_3O_8 + NaAlSiO_4 \rightarrow 2\ NaAlSi_2O_6$$

was located by Hlabse & Kleppa (1968), and at 700°C, it lies at 12 kbar, well above the 7 kbar estimate for the field area, based on the garnet–plagioclase barometer.

Mg–Fe^{2+}–Mn exchange equilibrium, hornblende–biotite

The distribution of Mg, Fe^{2+}, and Mn between associated hornblende (Hbl) and biotite (Bt) can be examined in relation to the attainment of exchange equilibrium. The Mg–Fe^{2+} distribution coefficient is defined as

$$K_D\ (\mathrm{Mg} - \mathrm{Fe}^{2+}) = \left(\frac{\left(X_{\mathrm{Mg}}\ /\ 1 - X_{\mathrm{Mg}}\right)^{\mathrm{Bt}}}{\left(1 - X_{\mathrm{Mg}}\ /\ X_{\mathrm{Mg}}\right)^{\mathrm{Hbl}}} \right)$$

where $X_{Mg} = Mg / (Mg + Fe^{2+})$. The value of K_D in samples S4 and C4 is 1.1 and 1.3, which compares with $K_D = 1.0$ (mean) in Group-2 gneisses of the field area (Kretz 1978). The Mn distribution coefficient is

$$K_D\ (\mathrm{Mn} - \mathrm{Mg}, \mathrm{Fe}^{2+}) = X_{\mathrm{Mn}}{}^{\mathrm{Hbl}} / X_{\mathrm{Mn}}{}^{\mathrm{Bt}}$$

where $X_{Mn} = Mn / (Mg + Fe^{2+} + Mn)$. In samples S4 and C4, $K_D = 2.1$ and 1.2, which compares with 3.0 in Group-2 gneisses.

Distribution of F and Cl

The distribution of F and Cl among hornblende, biotite, and titanite (Ttn) can be examined in Stag sample S4, where the proportions of these elements and of OH and O (obtained by difference) are: $(F_{0.174}Cl_{0.177}OH_{1.6})_{\Sigma 2}$ in Hbl, $(F_{0.195}Cl_{0.075}OH_{1.7})_{\Sigma 2}$ in Bt, and $(F_{0.15}Cl_{0.0}OH_{1.8})_{\Sigma 2}$ in Ttn. Thus, K_D (F, Bt / Hbl) = 1.1, K_D (F, Bt / Ttn) = 1.3, and K_D (Cl, Hbl / Bt) = 2.4. The findings for F are in near agreement with experimental results of Westrich (1981), *i.e.*, at 900°C, 0.5 kbar, K_D (F, phlogopite / pargasite) = 1.4, and with data from Sweden reported by Ekström (1972), *i.e.*, K_D = 1.3. The findings for Cl are comparable with those of Leelanandam (1969) from the granulite facies in India, *i.e.*, K_D (Cl, Hbl / Bt) = 1.6.

From the above preliminary findings for Mg, Fe^{2+}, Mn, F, and Cl, no large-scale departures from exchange equilibrium in the bodies of syenite are apparent.

Feldspar equilibria

The K-feldspar limb of the $NaAlSi_3O_8$–$KAlSi_3O_8$ solvus, as located experimentally by Orville (1963) at 2.0 kbar, is shown in Figure 7; it is nearly identical to that proposed by Barth (1969). Also shown in this figure is the limb of the 5.0 kbar solvus of Luth (1974), based on experimental data of Seck (1972). This solvus is nearly identical to that located experimentally by Martin (1974). The 5 kbar limb could be used to evaluate equilibrium in the Stag syenite and Cawood nepheline syenite, but the plagioclase contains approximately 10% of the anorthite component, and the appropriate solvus is therefore a curved surface within the albite – orthoclase – anorthite prism. The approximate location of a line on this surface at X_{an} = 0.10, based on the 5 kbar, 650°C, $X_{an}^{Pl} \approx 0.10$ results of Seck (1971, Fig. 3b), is shown as a broken line in Figure 7.

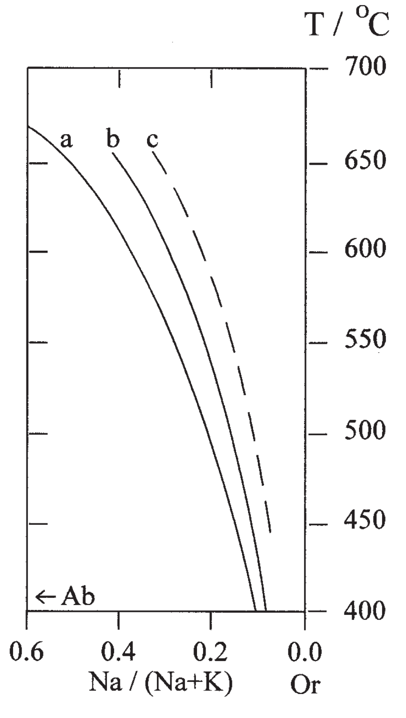

FIG. 7. K-feldspar limb of the alkali feldspar solvus (a) 2.0 kbar, from Orville (1963), (b) 5.0 kbar, from Luth (1974), (c) 5.0 kbar, 10% anorthite in associated plagioclase, based on data of Seck (1971, Fig. 3b).

Values of X_{ab} = Na / (K + Na) in K-feldspar that occurs as discrete crystals (no exsolution lamellae visible) in the Stag syenite are 0.06 (S4), and 0.06 (S5), and in the Cawood nepheline syenite, 0.12 (C2), 0.10 (C4), 0.11 (C5), and 0.12 (C6), all associated with discrete crystals of plagioclase. In relation to the broken-line limb in Figure 7, these ratios are those that are expected, at equilibrium, at temperatures between 400 and 450°C for the Stag syenite, and between 450 and 500°C for the Cawood nepheline syenite. These temperatures are well below the 700°C estimate for the peak of regional metamorphism in the study area, and must be interpreted in terms of phase separation, and the nucleation and growth of discrete crystals of two feldspar phases during uplift and cooling.

Although most of the feldspar present in the Stag syenite occurs as discrete, apparently homogeneous crystals, relatively large (5 mm) grains composed of an irregular intergrowth of K-feldspar and plagioclase were observed in some samples; such an intergrowth was possibly produced from an initial single "hypersolvus" feldspar, or by some other mechanism. In addition, crystals of K-feldspar with lamellae, lenses, or irregular patches of plagioclase were observed in some samples of Stag syenite and in several samples of Cawood nepheline syenite, and these are almost certainly products of exsolution.

An example of near-equidimensional or elongate inclusions of plagioclase in K-feldspar from the Cawood nepheline syenite is presented in Figure 8. An electron-microprobe traverse across one of these inclusions is plotted in Figure 9, which shows that concentration gradients of Na, K, and Ba, somewhat similar to ones reported by Mason (1982), exist about the inclusion. Traverses across two other inclusions gave nearly identical results.

The profiles in Figure 9 can be described by use of the equation

$$\frac{C - C_0}{C_1 - C_0} = \frac{a}{r}\,\mathrm{erfc}\,\frac{(r - a)}{(Dt)^{1/2}}$$

which applies to the diffusion of a component into or out of a sphere of radius a. In relation to Figure 9, C is

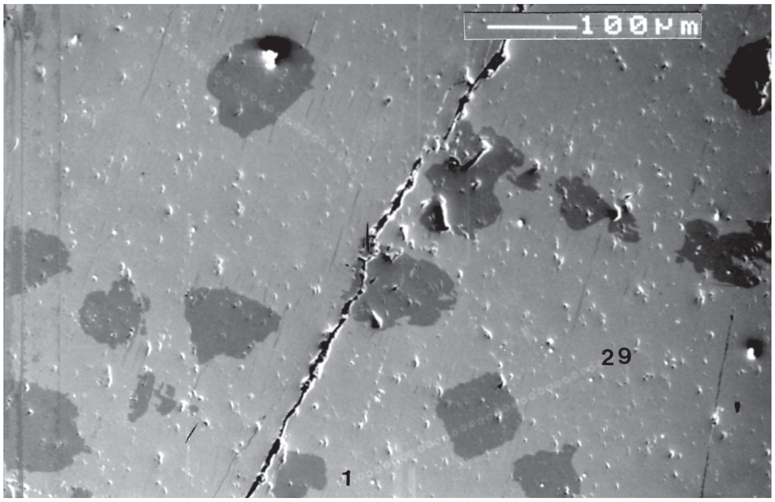

FIG. 8. Pods of plagioclase (dark) in K-feldspar in the Cawood nepheline syenite, sample C5, SEM image.

concentration of an element in K-feldspar at distance r from the center of the plagioclase crystal, C_0 and C_1 are concentrations far from and near the crystal, D is the diffusion coefficient, and t is elapsed time (Crank 1975, p. 102, equation 6.60). The equation does not apply rigorously because radius (a) must have increased with time, and D is a function of concentration and temperature. Nevertheless, the results provide evidence that the plagioclase inclusions in K-feldspar had indeed formed by exsolution, which involved the diffusion of Na and Ca toward the inclusions and of K and Ba away from the inclusions. Assuming that a condition of near-equilibrium existed at inclusion–host boundaries, the Na content of the K-feldspar there [Na / (K + Na) = 0.074] corresponds to a solvus temperature (Fig. 7, curve b) of approximately 400°C. The calculated composition of K-feldspar in the vicinity, prior to exsolution, gives Na / (K + Na) = 0.23, corresponding to a solvus temperature of 550°C (Fig. 7, curve b), which is an estimate of the temperature at which nucleation and growth of the plagioclase microcrystal was initiated, as temperature declined.

Nepheline – K-feldspar equilibrium

Equilibrium in the system nepheline ± K-feldspar was considered by Perchuk & Ryabchikov (1968), and geothermometers based on the distribution of Na and K between the two phases were proposed by Zyrianov *et al.* (1978), who carried out experiments with both ordered and disordered K-feldspar, and by Powell & Powell (1977), who combined selected experimental results with thermodynamic calculations. The first of these thermometers, applied to the Cawood nepheline syenite (samples C2 and C4) yields ~580°C (disordered) and ~560°C (ordered K-feldspar), whereas the second thermometer gives ~400°C.

Crystals of K-feldspar with a higher proportion of Na, as they might have existed at the peak of metamorphism, say with Na / (K + Na) ≈ 0.25 rather than 0.10, would yield a temperature of ~700°C by use of the Zyrianov *et al.* (1978) thermometer.

EMPLACEMENT

The prevailing view on bodies of syenite, including nepheline syenite, is that they were produced by partial melting in the upper mantle or lower crust, followed possibly by crystal fractionation and crustal contamination, and that during emplacement, the bodies were in a molten or semimolten state (Verhoogen *et al.* 1970, Bailey & Schairer 1966). With regard to nepheline syenite, this view has not, however, been adopted universally, and Sørensen (1974b) has summarized the various mechanisms of emplacement that have been proposed. For example, in the Bancroft area, to the southwest, some bodies of homogeneous nepheline syenite were, according to Tilley & Gittins (1961), emplaced as a silicate melt, prior to being affected by regional metamorphism, whereas other, more heterogeneous bodies, according to Gummer & Burr (1946), Baragar (1953), Gittins (1961) and Appleyard (1967), formed by the metasomatic transformation of marble, amphibolite, and other rock types.

The homogeneity of the Stag and Cawood bodies, both with regard to the distribution of crystals, as seen

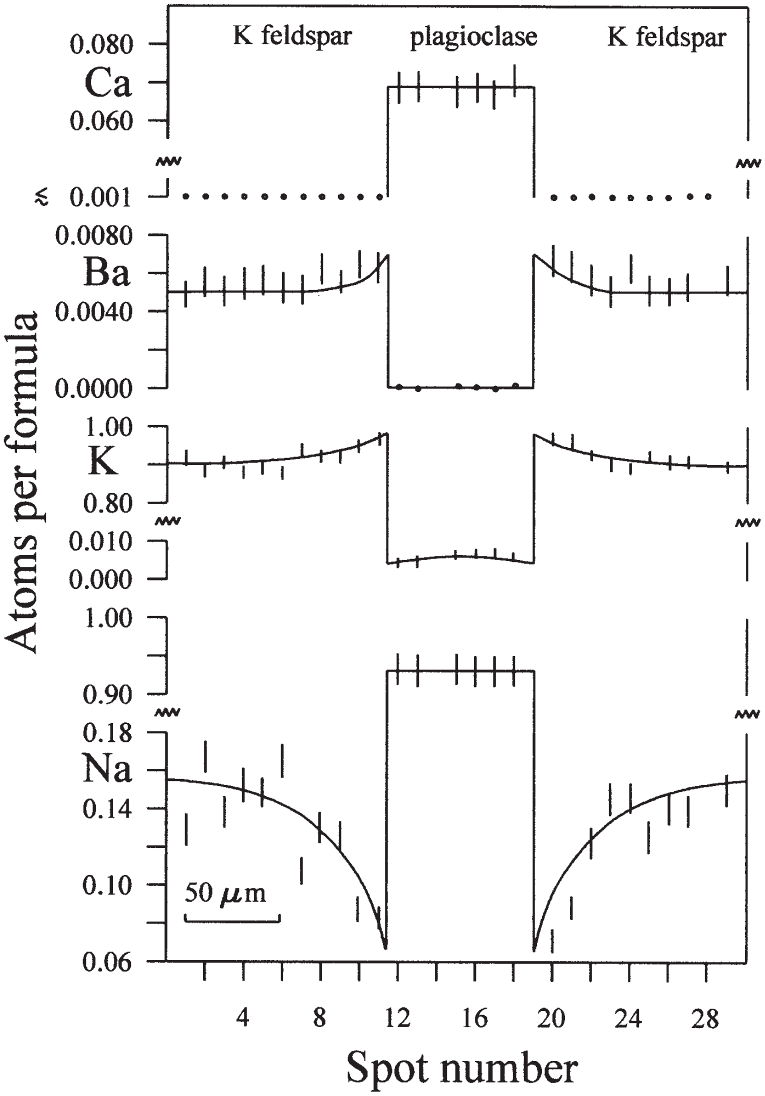

FIG. 9. Concentration profiles (in atoms per formula unit) along a traverse across a plagioclase pod in K-feldspar (points 1 to 29, located in Fig. 8). Error bars represent 0.95 confidence limits. Concentration–distance curves in K-feldspar follow a diffusion equation given in the text.

in the field, and their chemical and mineral composition, as described above, could be viewed as being compatible with crystallization of a melt, rather than with metasomatism. The presence of many inclusions of metagabbro in the Stag bodies is also somewhat supportive of this interpretation.

It does not follow, however, that the syenite was *emplaced* as molten material. In general, the upward movement of a dome-like body of melt of necessarily low viscosity (~10^5 Pa s, Persikov 1991) into a segment of solid crust of much higher viscosity (~10^{20} Pa s, Ranalli 1987) is, from a rheological viewpoint, a difficult, if not impossible process. Indeed, the scale-model experiments of Ramberg (1981) have demonstrated that for the domal ascent to occur, the syenite must have had a viscosity similar to that of the country rock, *i.e.*, it must have been solid. Another requirement is that the syenite must have a density less than that of the enclosing rock. Galipeau (1981) has shown that with regard to Cawood, the mean density of the syenite is

2.6, whereas that of the surrounding marble is 2.7 and the gneiss–amphibolite is 2.9 g cm^{-3}, and the density requirement is satisfied.

The model of emplacement of granite and syenite domes by ductile flow was previously adopted by Wegmann & Kranck (1931), Fletcher (1972), Breaks & Shaw (1973), Stephansson (1975), Sweeney (1975), Brun (1977), Kretz *et al.* (1982) and others. In an attempt to rescue the magmatic emplacement hypothesis, Marsh (1982) has suggested that both the domes and the surrounding rock were in a partially molten condition (with near-equal viscosity), but with regard to the study area, there is no evidence that the marble, gneiss, and amphibolite that surround the syenite bodies, were ever partially molten. Meanwhile, S.B. Lumbers (Lumbers *et al.* 1990), L. Corriveau (Corriveau & Leblanc 1995) and others working in the Southern Grenville Province have continued to adopt the conventional model (Miller & Paterson 1999) of magmatic emplacement of bodies of granitic and syenitic rock.

The gneissic foliation and lineation in the Stag and Cawood bodies (including the mafic inclusions) indicate that they were deformed, but the magnitude of the ductile strain cannot be determined. These microstructures appear to intersect the boundaries of the bodies, and evidently were not produced entirely during emplacement. One possibility is that they were produced during deformation at a lower level, and were largely preserved during emplacement. This model explains the discordance in the orientation of linear structures in Stag I and Cawood, relative to these structures in the surrounding rock. But several questions remain; for instance, are the southeast-plunging lineations in Stag I and Cawood plutons related to those that dominate in the western part of the Otter Lake area, and what events in the evolution of Stag II and Stag III caused lineations in these to differ from those in Stag I?

CONCLUSIONS

The results presented here form a small contribution to the large amount of information that exists on the various kinds of granite and syenite that occur in the Central Metasedimentary Belt of the Canadian Shield. Of special interest is the newly discovered Cawood nepheline syenite, that resembles nepheline syenite in the Bancroft area to the southwest, some of which have been dated, indirectly, at ~1270 Ma (Lumbers *et al.* 1990). Assuming that the Cawood body is of the same age, one can define a northeast-trending "nepheline zone", 200 km long, that, following Baer (1976), could mark the location of an ancient rift structure. Apparently undeformed bodies of syenite (with minor nepheline) that occur to the northeast of Cawood, three of which have been dated at ~1080 Ma (Corriveau *et al.* 1990), must be attributed to a later and unrelated event.

No attempt is made at present to construct a model capable of producing syenite of the present study by partial melting or other mechanisms. Any model of this kind that might be proposed, must explain the very low abundances of Mg and of groups 3, 4, and 5 elements in the Cawood nepheline syenite.

Mineral assemblages and mineral compositions in the Stag and Cawood bodies are compatible with upper-amphibolite-facies conditions, as found in the study area as a whole, except that two-feldspar and feldspar–nepheline thermometers give temperatures as low as 400 to 500°C. Evidently, phase separation occurred during slow cooling to produce discrete crystals of potassic feldspar and sodic plagioclase. In some of these crystals, additional separation produced perthite, in which stranded diffusion-gradients of Na, K, and Ba were detected.

The well-developed gneissic lineation that is present, especially in the Stag syenite, indicates that the bodies of rock experienced ductile deformation. The lineations were possibly produced during deformation at a deeper level, and were largely preserved during subsequent solid-state emplacement of the dome-like bodies. This interpretation accommodates the observation that in two of the bodies of syenite, lineation directions are discordant with those in the surrounding rock.

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