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PETROLOGY OF THE BLACK BROOK GRANITIC SUITE, CAPE BRETON ISLAND, NOVA SCOTIA

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ABSTRACT

The *ca.* 375 Ma Black Brook Granitic Suite was emplaced at the boundary between the Aspy and Bras d'Or terranes in northeastern Cape Breton Island. It consists of three main units distinguished on the basis of texture and modal mineralogy. All units contain muscovite and biotite, and are peraluminous. The least felsic unit consists mainly of granodiorite (on average 70.9% SiO_2), and the most felsic unit is fine-grained monzogranite (on average 73.5% SiO_2). The medium-grained monzogranite unit has average composition intermediate between the other two units (on average 72.2% SiO_2) but displays a range in composition similar to that in the other two units combined. Mineral compositions and whole-rock major- and trace-element (including *REE*) trends indicate that compositional variation in the Black Brook Granitic Suite resulted from fractional crystallization of biotite, plagioclase, K-feldspar, zircon, and apatite from a peraluminous magma derived from a metasedimentary source. However, the suite is less aluminous than the South Mountain Batholith in the Meguma Terrane of southern Nova Scotia, and is syntectonic in contrast to post-tectonic.

Keywords: monzogranite, granodiorite, syntectonic, peraluminous, Devonian, petrology, geochemistry, Black Brook Granitic Suite, Cape Breton Island, Nova Scotia.

SOMMAIRE

La suite granitique de Black Brook a été mise en place il y a environ 375 Ma le long d'une suture entre les socles de Aspy et de Bras d'Or, dans le nord-est du Cap Breton (Nouvelle-Ecosse). Elle contient trois unités principales, distinguées selon des critères texturaux et minéralogiques. Toutes les unités contiennent muscovite et biotite, et sont hyperalumineuses. L'unité la moins felsique contient surtout de la granodiorite (70.9% de SiO_2, en moyenne), et la plus siliceuse, un monzogranite à granulométrie fine, en contient 73.5%. Le monzogranite à grains plus grossiers a une composition intermédiaire moyenne entre celle des deux autres unités (72.2%), mais le spectre de compositions est aussi étendu que les deux autres unités combinées. D'après la composition des minéraux et l'évolution des teneurs en éléments majeurs et en traces (y inclus les terres rares), la différenciation dans cette suite résulterait du fractionnement de biotite, plagioclase, feldspath potassique, zircon et apatite d'un magma hyperalumineux dérivé d'une source métasédimentaire. La suite est toutefois moins fortement hyperalumineuse que celle du batholite de South Mountain, dans le socle de Meguma, dans le sud de la Nouvelle-Ecosse, qui est de plus post-tectonique plutôt que syntectonique.

(Traduit par la Rédaction)

Mots-clés: monzogranite, granodiorite, syntectonique, hyperalumineux, dévonien, pétrologie, géochimie, suite granitique de Black Brook, Cap Breton, Nouvelle-Ecosse.

INTRODUCTION

The Black Brook Granitic Suite (BBGS) forms one of the largest plutons in Cape Breton Island, Nova Scotia, and together with related dykes and satellite bodies, it is the only pluton in Cape Breton Island with "S-type" character (Barr 1990). U–Pb dating of monazite from the suite has yielded an age of 375^{+7}_{-2} Ma (Dunning *et al.* 1990), which confirms the mid-Devonian age indicated by earlier Rb–Sr geochronology (Cormier 1972, Yaowanoiyothin 1988). Barr & Raeside (1989) suggested that the BBGS is located along the boundary of the Aspy and Bras d'Or terranes of central Cape Breton Island (Fig. 1, inset map), and hence provides a minimum date for terrane amalgamation.

This paper reports the results of a detailed petrological study of the Black Brook Granitic Suite; it extends the earlier work of Barr & Pride (1986), which focussed on only part of the suite. The Black Brook suite is compared to the well-known South Mountain Batholith, which is of similar age and composition to the BBGS but located in the Meguma Terrane of southern Nova Scotia (Fig. 1, inset map). Although both of these intrusive bodies have been considered to be

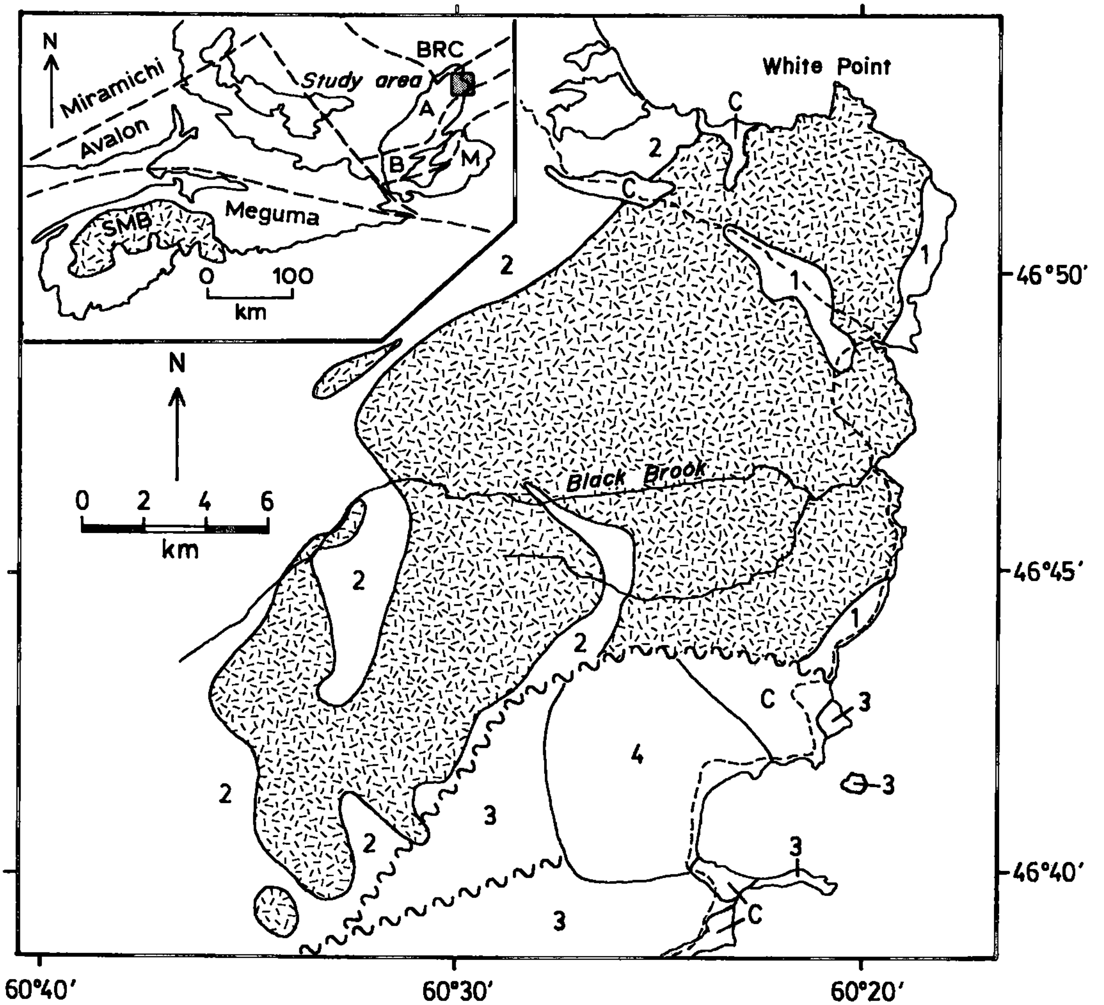

FIG. 1. Simplified geological map of the Black Brook area in northeastern Cape Breton Island, after Barr *et al.* (1987). The maps shows the distribution of the Black Brook Granitic Suite (slash pattern) and adjacent units (1 Neils Harbour Gneiss, 2 Cheticamp Lake Gneiss, 3 McMillan Flowage Formation and other units of the Bras d'Or Terrane, 4 Cameron Brook Pluton, C Carboniferous sedimentary rocks). The Z-pattern marks the Eastern Highlands Shear Zone and related faults. The dashed line is the Cabot Trail highway. Inset map shows location of the study area, the terranes of Barr & Raeside (1989) in Cape Breton Island (M Mira Terrane, B Bras d'Or Terrane, A Aspy Terrane, BRC Blair River Complex), and the location of South Mountain Batholith (SMB) in the Meguma Terrane of southern Nova Scotia. Miramichi and Avalon terranes in New Brunswick are after Fyffe & Fricker (1987).

examples of Acadian plutonism in the northern Appalachian Orogen, they display differences in texture, mineralogy, and chemistry that indicate contrasts in origin and evolution.

On the basis of a reconnaissance mapping and petrological study, Wiebe (1975) divided the BBGS into four areas, the White Point, Black Brook, Warren Brook, and Clyburn Brook plutons. However, subsequent studies have indicated that all four areas are part of a single contiguous intrusive suite, and that the use of separate names is not justified (Barr *et al.* 1987, Raeside & Barr, in press, Yaowanoiyothin 1988).

FIELD RELATIONS

The BBGS is in contact with three different metamorphic units on its eastern, western, and southern margins; the northern margin of the pluton is not exposed (Fig. 1).

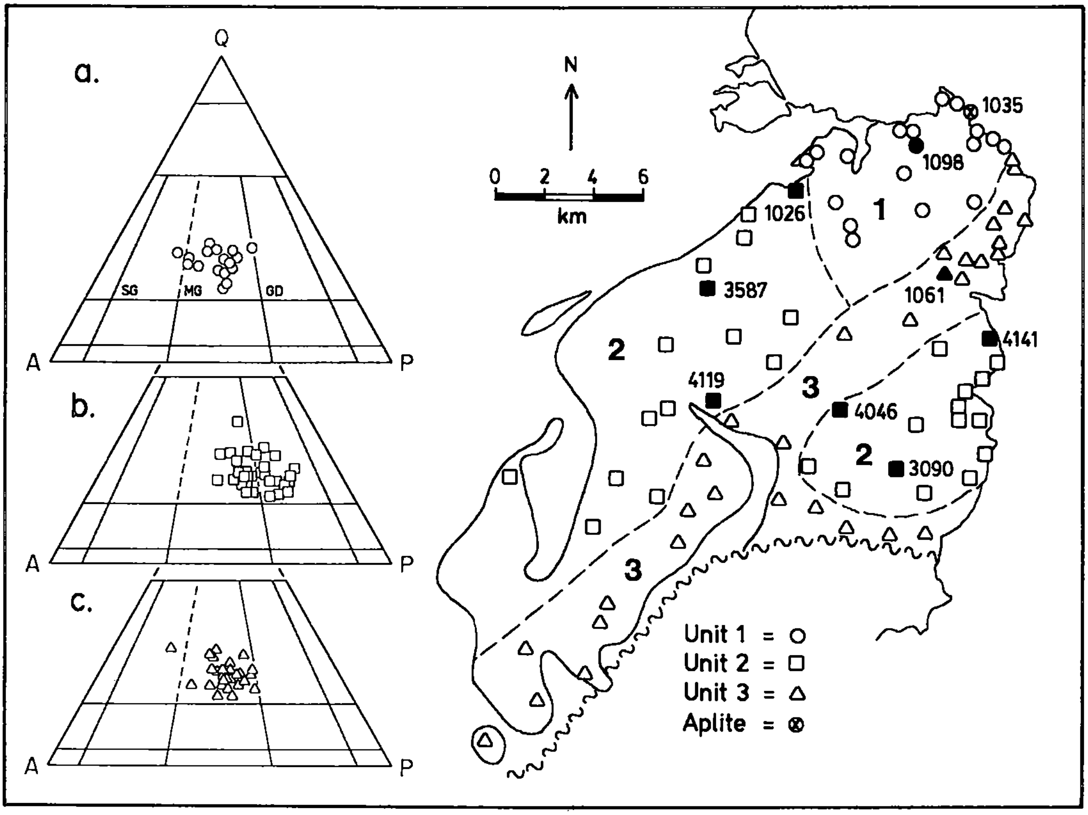

FIG. 2. Map showing division of the Black Brook Granitic Suite into units 1, 2 and 3, as described in text. Circles, squares, and triangles indicate distribution of samples used for chemical analysis; numbered solid symbols indicate samples also analyzed for rare-earth elements. On left, triangular plots of modal quartz (Q), alkali feldspar (A), and plagioclase (P) are shown for analyzed samples from (a) unit 1, (b) unit 2, and (c) unit 3 to illustrate variation in modal compositions. Fields on diagrams are from Streckeisen (1976): SG syenogranite, MG monzogranite, GD granodiorite. Modes were determined by point counting at least 400 points on slabs stained for K-feldspar (method of Hutchison 1974).

On the east, the BBGS intruded the Neils Harbour Gneiss (Barr *et al.* 1987), mainly an orthogneissic unit consisting of feldspar-megacrystic biotite gneiss and biotite ± hornblende gneiss. Local biotite schist bands, 15 cm to 1 m in width, may represent deformed metasedimentary xenoliths. Igneous zircon from the megacrystic biotite gneiss has yielded a U–Pb age of 403 ± 2 Ma (Dunning *et al.* 1990); the gneiss is similar in both age and composition to the Cameron Brook Pluton (Dunning *et al.* 1990), located south of the BBGS in the Bras d'Or terrane (Fig. 1).

On its western margin and part of its southern margin, the BBGS intruded the Cheticamp Lake Gneiss (Fig. 1), which consists of semipelitic gneiss, biotite schist, and quartzofeldspathic orthogneiss. Igneous monazite in migmatitic portions of the Cheticamp Lake Gneiss has yielded a U–Pb age of 396 ± 2 Ma (Dunning *et al.* 1990), only *ca.* 7 Ma younger than the protolith of the orthogneissic part of the Neils Harbour Gneiss. The monazite date for the Cheticamp Lake Gneiss is interpreted to represent the time of regional amphibolite-facies metamorphism under conditions of bathozone 5 (Raeside & Barr, in press, Dunning *et al.* 1990, R. Raeside, pers. comm. 1991).

The positions of the eastern and western margins of the BBGS are difficult to pinpoint because numerous dykes from the BBGS occur in the host rocks, and host-rock xenoliths and roof pendants are abundant in the granitic rocks. The abundance of xenoliths throughout the BBGS suggests that the present level of exposure is near the roof of the pluton. Yaowanoiyothin (1988) showed that a discernible change in the composition of xenoliths occurs in the central part of the BBGS (approximately coinciding with the position of unit 3 on Fig. 2), interpreted to mark the change from the Cheticamp Lake Gneiss to the Neils Harbour Gneiss as host. Barr & Raeside (1989) suggested that this change marks the boundary between the Aspy and Bras d'Or terranes.

Along its southern margin, the BBGS and its host rocks are in faulted contact with low-grade metamorphic rocks assigned by Barr *et al.* (1987) to the McMillan Flowage Formation, a unit of the Bras d'Or terrane (Fig. 1). In contrast to the eastern and western margins of the pluton, no dykes from the BBGS occur in the McMillan Flowage Formation, and no xenoliths from that formation were recognized in the BBGS, which suggests that the two units were not yet in close proximity during emplacement of BBGS.

The BBGS is locally overlain unconformably by Late Devonian to Early Carboniferous sedimentary rocks (Fig. 1), which include conglomerate and arkosic sandstone derived mainly from the underlying BBGS, as well as limestone and gypsum. The presence of these sedimentary rocks attests to rapid exhumation of the pluton, also supported by a $^{40}Ar/^{39}Ar$ plateau age for muscovite from the BBGS of about 360 Ma (Reynolds *et al.* 1989). This indicates the time of cooling of the pluton through the blocking temperature of Ar in muscovite, about 350°C (McDougall & Harrison 1988). Faults in Carboniferous rocks southeast of the BBGS (Fig. 1) indicate that movement on the Eastern Highlands Shear Zone persisted into the Carboniferous.

The BBGS typically displays foliation of varying intensity, marked by parallel alignment of mica flakes and some elongation of the feldspars and quartz. This foliation, measured at about 230 locations over the BBGS, generally trends northeasterly, with steep dips to NW or SE (Yaowanoiyothin 1988). Foliations (gneissic layering and schistosity) in metamorphic host-rocks and in xenoliths (256 measurements) also trend northeasterly. Some scatter in foliation orientation from xenoliths (Yaowanoiyothin 1988) probably resulted from xenolith rotation during intrusion of the BBGS.

The foliation characteristics of the BBGS suggest that intrusion was syntectonic, in terms of the criteria of Paterson *et al.* (1989). Foliation is especially well developed in a northeasterly trending belt (generally coincident with unit 3 shown on Fig. 2) through the central part of the pluton and associated host-rocks that approximately coincides with the change in xenolith composition described above. This foliated belt may mark a former position of the Eastern Highlands Shear Zone at the Aspy – Bras d'Or terrane boundary, with emplacement of the BBGS localized by the shear zone along the terrane boundary. Subsequently, the shear zone apparently moved to the location south of the pluton shown on Figures 1 and 2. A mylonitic foliation parallel to the shear zone is widely developed in unit 3 in the southern part of the BBGS. This foliation is defined by aggregates of small grains of quartz and mica draped around larger deformed grains of feldspar and quartz, and is interpreted to have resulted from low-grade deformation along the shear zone after pluton emplacement (Lin & Williams 1990).

PETROGRAPHY

Based on modal mineralogy and texture of 300 rock slabs stained for K-feldspar (Hutchison 1974) and the study of 170 thin sections, the BBGS is divided into three major units (Fig. 2). Unit 1 consists mainly of fine- to medium-grained monzogranite (Fig. 2a). It forms much of the northern part of the BBGS, and coincides approximately with the White Point pluton of Wiebe (1975), Barr *et al.* (1982), and Barr & Pride (1986). Unit 2 consists mainly of medium- to coarse-grained granodiorite and monzogranite (Fig. 2b), and forms the eastern and western parts of the BBGS. Unit 3 consists mainly of medium-grained monzogranite (Fig. 2c), and forms a northeasterly trending belt through the central part of the pluton, as well as a belt along the southern margin. In addition to these three main units, aplite and pegmatite dykes of syenogranite to alkali feldspar granite composition occur throughout the BBGS and in adjacent country-rocks (except the McMillan Flowage Formation).

Units 1 and 2 of the BBGS are generally weakly foliated, whereas unit 3 is characterized by a strong foliation, especially near the southern margin of the pluton, where it has apparently been sheared by postcrystallization movement on the Eastern Highlands Shear Zone. Because unit 3 is characterized by the presence of a strong foliation more than by distinctive mineralogical composition, some foliated parts of units 1 and 2 may have been included with unit 3 in the distribution of units shown on Figure 2. Gradational variations in grain size, composition, and degree of foliation can in places be seen in a single outcrop within each unit. No sharp contacts between the three main units were observed, and their relationships may be gradational.

All three main units consist of plagioclase, quartz, microcline, biotite, and muscovite, with accessory (total <1 %) apatite, zircon, monazite, and ilmenite. The texture is typically hypidiomorphic granular, although in strongly foliated samples, especially those from the southern part of unit 3, shear foliation has been superimposed on

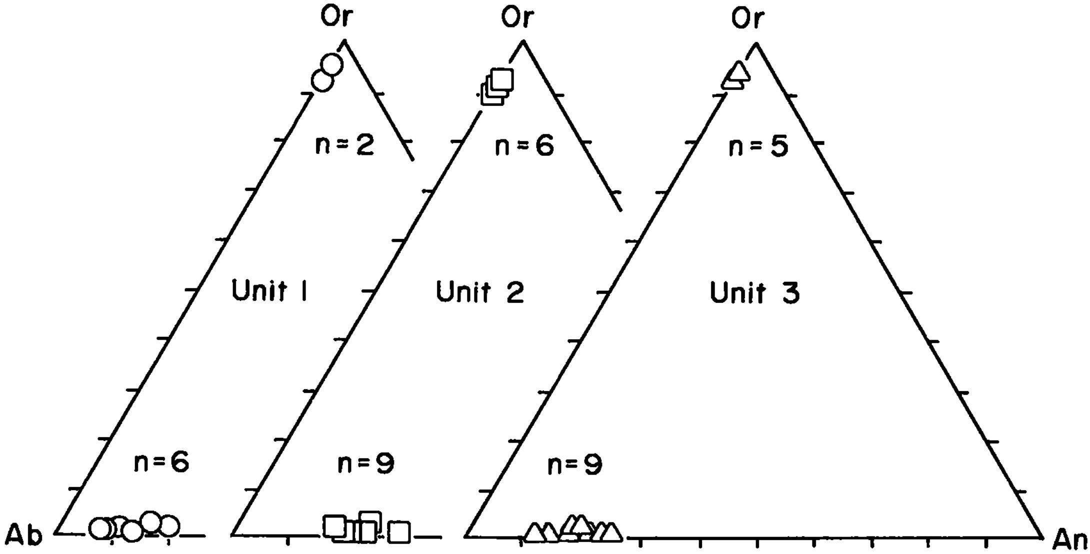

FIG. 3. Range of feldspar compositions in the Black Brook Granitic Suite in terms of orthoclase (Or), albite (Ab), and anorthite (An) components, based on data in Yaowanoiyothin (1988). Plagioclase data points are averages representing 12 analyses in two samples of unit 1, 62 analyses in five samples from unit 2, and 40 analyses in six samples from unit 3. K-feldspar data points represent 8 analyses in two samples from unit 1, 23 analyses in six samples from unit 2, and 22 analyses in five samples from unit 3.

and partially or completely destroyed the original igneous texture. Plagioclase is commonly subhedral, quartz generally has irregular anhedral grain boundaries, and microcline occupies irregular spaces interstitial to plagioclase and quartz. Myrmekitic intergrowths of quartz and plagioclase are common, and form bulbous shapes at the margin of plagioclase grains adjacent to microcline.

Plagioclase displays normal and oscillatory zoning; optical determinations and microprobe analyses indicate that it is of albite - oligoclase composition. Plagioclase in unit 2 is somewhat more calcic in average composition than that in unit 3, and unit 1 contains the least calcic plagioclase (Fig. 3). A narrow rim of albite is present on many plagioclase grains.

Microcline typically displays well-developed tartan twinning, and is perthitic. Compositions in all three units cluster around Or_{92} (Fig. 3). The larger grains have inclusions of plagioclase, quartz, and biotite, which indicates that microcline formed relatively late in the crystallization sequence.

Biotite ($\beta = \gamma$ = dark green; α = pale yellow) forms less than 5% of most samples, and is typically more abundant in granodiorite than in monzogranite. Microprobe analyses (Table 1) indicate that the biotite has an aluminum content typical of biotite unaccompanied by other ferromagnesian minerals or coexisting with muscovite in plutonic rocks (Fig. 4). The Fe/(Fe+Mg) ratio generally increases with increasing silica content in the host rocks, and hence unit 2 contains biotite with the lowest Fe/(Fe+Mg) ratio, and unit 1, the

TABLE 1. AVERAGE COMPOSITIONS OF BIOTITE, BLACK BROOK GRANITIC SUITE[1]

	Unit 1		Unit 2		Unit 3	
	1038	1089	4093	4046	3660	4036
SiO_2(wt.%)	72.60	73.86	69.61	71.72	70.82	72.17
	n=6	n=3	n=10	n=7	n=3	n=7
SiO_2(wt.%)	35.13	35.30	35.67	35.08	35.03	35.55
TiO_2	2.94	3.06	3.30	3.26	3.78	3.42
Al_2O_3	16.78	16.77	17.85	17.89	16.74	17.51
FeO[t]	23.16	23.28	20.07	21.54	21.60	21.15
MnO	0.57	0.94	0.49	0.45	0.44	0.55
MgO	6.50	5.39	8.51	8.09	7.44	7.87
CaO	0.04	0.00	0.00	0.01	0.12	0.00
Na_2O	0.14	0.07	0.14	0.10	0.13	0.11
K_2O	9.59	9.71	9.43	9.68	9.28	9.90
F	-	-	0.33	0.33	0.54	0.34
Sum	-	-	95.79	96.43	95.10	96.40
less O=F	-	-	0.14	0.14	0.23	0.14
Total	94.81	94.52	95.65	96.29	94.87	96.26
			Number of ions on the basis of 22(O)			
Si	5.51	5.57	5.43	5.36	5.43	5.43
^{IV}Al	2.49	2.43	2.57	2.64	2.57	2.57
^{VI}Al	0.62	0.69	0.64	0.58	0.48	0.58
Ti	0.35	0.36	0.38	0.37	0.44	0.39
Fe	3.04	3.07	2.56	2.75	2.80	2.70
Mn	0.08	0.13	0.06	0.06	0.06	0.07
Mg	1.52	1.27	1.93	1.84	1.72	1.79
Ca	0.01	0.00	0.00	0.00	0.02	0.00
Na	0.04	0.02	0.04	0.03	0.04	0.03
K	1.92	1.95	1.83	1.89	1.83	1.93
F	-	-	0.16	0.16	0.26	0.16

[1]Calculated from data tabulated in Yaowanoiyothin (1988). Analyses by JEOL 733 Superprobe at Dalhousie University, Halifax.

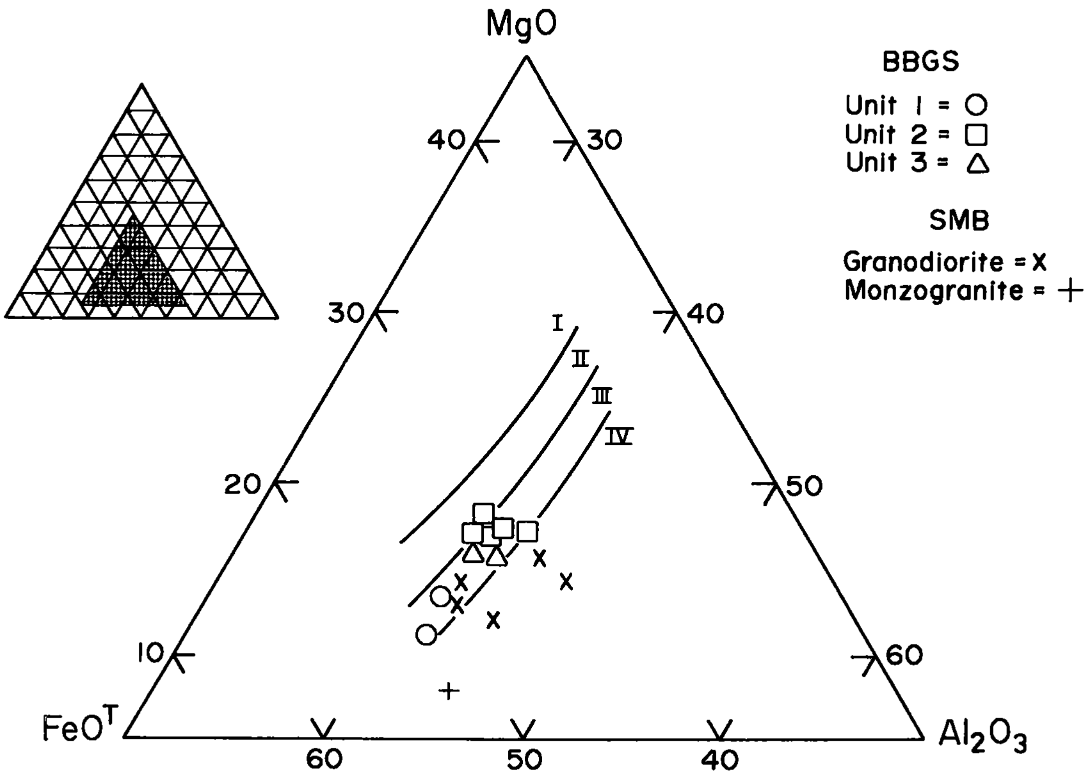

FIG. 4. Biotite compositions from the Black Brook Granitic Suite (BBGS) and South Mountain Batholith (SMB) plotted on an Al_2O_3–FeO^t–MgO diagram, with biotite compositional fields from de Albuquerque (1973). I, biotite coexisting with amphibole; II, biotite unaccompanied by other ferromagnesian minerals; III, biotite coexisting with muscovite; IV, biotite coexisting with aluminosilicate minerals. Black Brook data are average compositions for samples from units 1, 2 and 3 from Yaowanoiyothin (1988) and Table 1. South Mountain Batholith (SMB) biotite compositions from granodiorite and monzogranite samples are from Allan & Clarke (1981).

highest (Fig. 5a). Titanium contents also are lowest in biotite of unit 1 (Fig. 5a), and show a negative correlation with octahedrally coordinated Al (Fig. 5b). The biotite compositions in the BBGS are consistent with the observations of de Albuquerque (1973), who showed that Ti content in biotite generally decreases whereas Al increases in more felsic granitic rocks because of decrease in temperature and increase in aluminum activity.

Muscovite in the BBGS occurs in four forms distinguished on the basis of texture: single flakes, clusters of flakes, flakes intergrown with biotite, and sericitic muscovite (in plagioclase). The first three forms are considered to be primary (igneous) in origin. Although a detailed comparison of the compositions of the different textural types was not undertaken, available data suggest that the primary muscovite has higher content of Ti and lower Mg compared to the sericitic (secondary) muscovite (Fig. 6). No consistent differences among muscovite compositions in units 1, 2, and 3 were noted (Table 2).

Accessory zircon and rare monazite occur mainly as inclusions in biotite in the BBGS, whereas apatite occurs both as inclusions and as larger discrete grains. Ilmenite is typically tabular and occurs in very minor amounts in association with biotite.

GEOCHEMISTRY

Chemical variations

Eighty-one samples were analyzed from units 1, 2, and 3 of the BBGS (Fig. 2); means and standard deviations for the chemical composition of each unit are given in Table 3, and the original data are tabulated in Yaowanoiyothin (1988). Each unit displays a range in chemical composition, consistent with its range in modal mineralogy, and considerable compositional overlap occurs among the three units, as illustrated by selected variation diagrams in Figure 7. However, unit 1 shows chemical differences compared to units 2 and 3 that

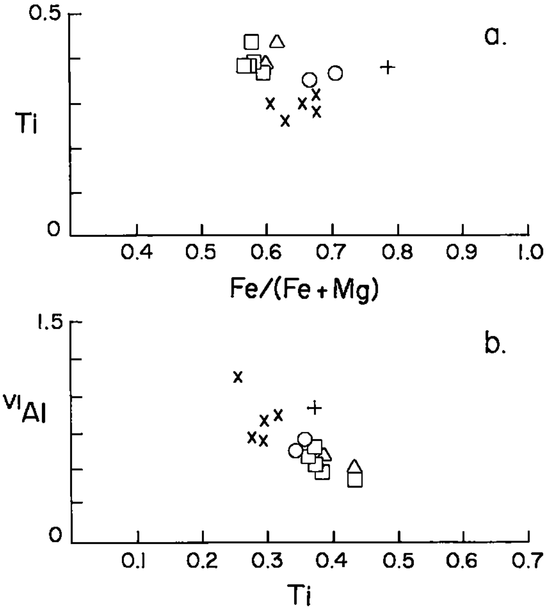

FIG. 5. Biotite compositions (atomic proportions) from Black Brook Granitic Suite and South Mountain Batholith. Black Brook data are average compositions for samples from units 1 (circles), 2 (squares), and 3 (triangles) of BBGS from Yaowanoiyothin (1988) and Table 1. South Mountain Batholith data are from Allan & Clarke (1981); x, granodiorite; +, monzogranite.

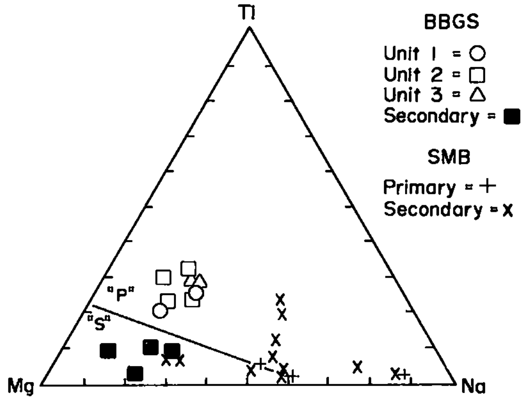

FIG. 6. Triangular plot of Ti–Na–Mg (atomic proportions) for muscovite from Black Brook Granitic Suite (BBGS) and South Mountain Batholith (SMB). Black Brook data are from Yaowanoiyothin (1988) and Table 2. Average compositions of primary and secondary muscovites from South Mountain Batholith are from Ham & Kontak (1988). Dashed line separates compositions of most examples of muscovite inferred to be primary from those inferred to be secondary on the basis of textural criteria (from Miller *et al.* 1981).

are consistent with its more felsic average composition; the average SiO_2 content of unit 1 (73.5%) is higher than that of units 2 (70.9%) or 3 (72.2%), and average TiO_2, MgO, and FeO^t, for example, are lower (Table 3). Unit 3 has average chemical compositions intermediate between the other two units.

In the suite as a whole, TiO_2, Al_2O_3, FeO^t, MnO, MgO, CaO, P_2O_5, Ba, Sr, V, and Zr show strong to moderate negative correlations with SiO_2, and K_2O, Pb, Rb, and Y, strong to moderate positive correlations with SiO_2 (Pearson Correlation Coefficients greater than −0.5 or +0.5, respectively; Yaowanoiyothin 1988). Other elements do not show significant correlations with SiO_2.

The chemical elements that show systematic variations in the BBGS are generally those that are major or minor constituents of the major minerals in the suite, and their variations correlate with variations in modal abundance of plagioclase, biotite, and microcline in the samples, both within each unit and among the three units. Because zircon and apatite occur mainly as inclusions in biotite, their modal abundance correlates with modal abundance of biotite, and hence Zr and P_2O_5 tend to correlate positively with elements that are present in biotite. Hence, we suggest that the chemical variations in the BBGS are mainly the result of fractionation and accumulation of plagioclase, K-feldspar, and biotite (with included zircon and apatite) during crystallization, which resulted in inhomogeneous distribution of these

TABLE 2. AVERAGE COMPOSITIONS OF MUSCOVITE, BLACK BROOK GRANITIC SUITE[1]

	Unit 1		Unit 2		Unit 3	
	1038	1089	4073	4046	3660	3171
SiO_2(wt.%)	72.50	73.86	69.97	71.72	70.82	72.91
	n=4	n=6	n=15	n=7	n=3	n=4
SiO_2(wt.%)	45.89	47.61	46.22	46.16	45.48	47.02
TiO_2	1.04	0.93	1.02	1.27	1.39	1.20
Al_2O_3	31.30	30.45	30.73	32.64	31.27	31.15
FeO^t	4.62	5.20	5.08	4.94	4.99	4.89
MnO	0.01	0.06	0.02	0.00	0.02	0.00
MgO	1.05	1.24	1.19	0.97	1.11	1.02
CaO	0.00	0.00	0.04	0.00	0.10	0.02
Na_2O	0.40	0.29	0.30	0.33	0.38	0.39
K_2O	10.59	10.44	10.80	10.52	10.17	10.21
F	0.41	-	0.14	0.35	0.00	0.00
Sum	95.41	-	95.54	97.18	94.91	96.00
less O=F	0.17	-	0.06	0.15	0.00	0.00
Total	95.24	96.22	95.48	97.03	94.91	96.00
Number of ions on the basis of 22(O)						
Si	6.24	6.40	6.28	6.15	6.21	6.72
^{IV}Al	1.76	1.60	1.72	1.85	1.79	1.67
^{VI}Al	3.25	3.23	3.21	3.28	3.24	3.26
Ti	0.11	0.09	0.10	0.13	0.14	0.12
Fe	0.52	0.58	0.58	0.55	0.57	0.56
Mn	0.00	0.01	0.00	0.00	0.00	0.00
Mg	0.21	0.25	0.24	0.19	0.22	0.20
Ca	0.00	0.00	0.00	0.00	0.01	0.00
Na	0.10	0.08	0.08	0.08	0.10	0.10
K	1.83	1.79	1.87	1.79	1.77	1.75
F	0.18	-	0.06	0.15	0.00	0.00

[1]Calculated from data tabulated in Yaowanoiyothin (1988). Analyses by JEOL 733 Superprobe at Dalhousie University, Halifax.

TABLE 3. AVERAGE COMPOSITIONS (WITH STANDARD DEVIATION) OF UNITS 1, 2, AND 3 OF BLACK BROOK GRANITIC SUITE[1], AVERAGE S-TYPE AND AVERAGE FELSIC S-TYPE GRANITE[2], AND SELECTED UNITS OF SOUTH MOUNTAIN BATHOLITH[3]

	Unit 1 (n=18)		Unit 2 (n=32)		Unit 3 (n=31)		S-Type	Felsic S-Type	SMB gd (n=57)	SMB mg (n=88)	SMB mbmg (n=44)	SMB clmg (n=64)	SMB flmg (n=100)
SiO_2	74.56	± 0.88	70.86	± 1.48	72.17	± 0.92	70.27	73.39	67.10	69.51	71.46	73.22	73.90
TiO_2	0.12	0.04	0.28	0.08	0.20	0.07	0.48	0.28	0.67	0.48	0.34	0.19	0.13
Al_2O_3	14.08	0.40	15.37	0.61	14.90	0.60	14.10	13.45	15.51	14.82	14.62	14.23	14.27
FeO^t	1.24	0.28	1.82	0.48	1.37	0.35	3.49	2.13	4.09	3.16	2.26	1.70	1.31
MnO	0.01	0.00	0.04	0.01	0.03	0.01	0.06	0.04	0.09	0.08	0.05	0.05	0.04
MgO	0.22	0.10	1.13	0.36	0.82	0.59	1.42	0.58	1.83	1.46	1.17	0.91	0.84
CaO	1.43	0.29	1.63	0.39	1.48	0.39	2.03	1.28	1.94	1.31	0.88	0.59	0.41
Na_2O	3.86	0.33	3.68	0.66	3.63	0.72	2.41	2.81	3.48	3.41	3.52	3.41	3.51
K_2O	4.67	0.43	3.85	0.62	4.17	0.66	3.96	4.56	3.69	4.26	4.63	4.68	4.48
P_2O_5	0.08	0.03	0.09	0.03	0.08	0.02	0.15	0.14	0.21	0.20	0.25	0.23	0.27
Ba	466	233	840	245	630	259	468	388	667	491	351	196	146
Cu	4	1	7	6	5	4	11	4	7	5	2		3
Ga	20	2	18	3	18	3	17	17	21	7	10	13	19
Nb	12	3	10	3	11	4	12	13	12	11	13	12	12
Ni	6	2	6	2	5	2	13	4					
Pb	43	20	23	9	32	10	27	28	17	20	22	19	20
Rb	233	39	190	41	208	55	217	277	149	184	255	301	338
Sr	162	75	362	191	287	188	120	81	171	118	80	48	31
Th	16	6	15	9	16	8	18	18	13	12	13	9	6
V	8	6	23	11	16	6	56	23	55	35	20	9	5
Y	21	4	16	5	17	5	32	33	32	32	24	24	21
Zn	44	11	48	12	42	8	62	44	78	66	60	51	45
Zr	94	33	175	66	125	46	165	136	193	159	123	82	60
A/CNK	1.01	0.03	1.17	0.09	1.14	0.14	1.18	1.13	1.17	1.18	1.18	1.21	1.25

[1] calculated from data tabulated in Yaowanoiyothin (1988). [2] from Whalen et al. (1987). [3] from MacDonald et al. (1989).

minerals. However, it is apparent that the efficiency of the separation was low, and resulted in gradational variations in mineral proportions that occur even on an outcrop scale, rather than well-defined layering.

There is no petrographic evidence that variations in restite abundance (*e.g.*, White & Chappell 1977, 1983) played a significant role in causing compositional variation in the BBGS. No clots of mafic minerals or strongly Ca-rich cores in plagioclase were observed. Contacts between xenoliths and granite host are sharp. If restite was present in the BBGS magma, it separated below the present level of exposure.

Systematic covariations of Ba, Rb, and Sr are consistent with a differentiation model and show trends typical of combined feldspar - biotite fractionation (Fig. 8). The data indicate a greater role for feldspar than biotite, at least at the present level of exposure, although *REE* data suggest the opposite (see below). The samples that contain higher Sr and lower Rb (such as 1061, Fig. 8) may have experienced plagioclase accumulation, as was also suggested by Barr & Pride (1986) on the basis of more rigorous modeling of fractionation processes within unit 1. The trend for unit 1 differs slightly from that of the other units, indicating that different proportions of minerals, particularly more K-feldspar, were fractionating in this unit compared to the other two units.

No direct field evidence was observed to indicate the relative ages of units 1, 2, and 3; their close compositional similarity and apparently gradational relationships suggest that they were essentially coeval. However, the elongate shape of unit 3, its apparent separation of unit 2 into two parts (Fig. 2), and its strongly developed foliation suggest that it may have been emplaced slightly later. The compositions of samples from unit 3 cover almost the same range as samples from units 1 and 2 combined (*e.g.*, Figs. 7, 8). We suggest that units 1 and 2 may represent the range of compositions generated within the parent magma by more extended differentiation, whereas in unit 3, perhaps emplaced slightly later in an active shear-zone, the compositions are more intermixed and cannot be separated into discrete mappable bodies.

Rare-earth elements

Five samples from unit 2 that range in SiO_2 content from 68.7 to 74.7% were analyzed for rare-earth elements (*REE*) (Table 4). Additional *REE* data from four samples (one from each of units 1, 2, and 3 and one sample from an aplite dyke) are taken from Barr & Pride (1986); two other samples from the study of Barr & Pride (1986) are omitted because they are now considered to represent orthogneissic xenoliths and are not part of BBGS. The data reported by Barr & Pride (1986) include only seven elements, and the analytical

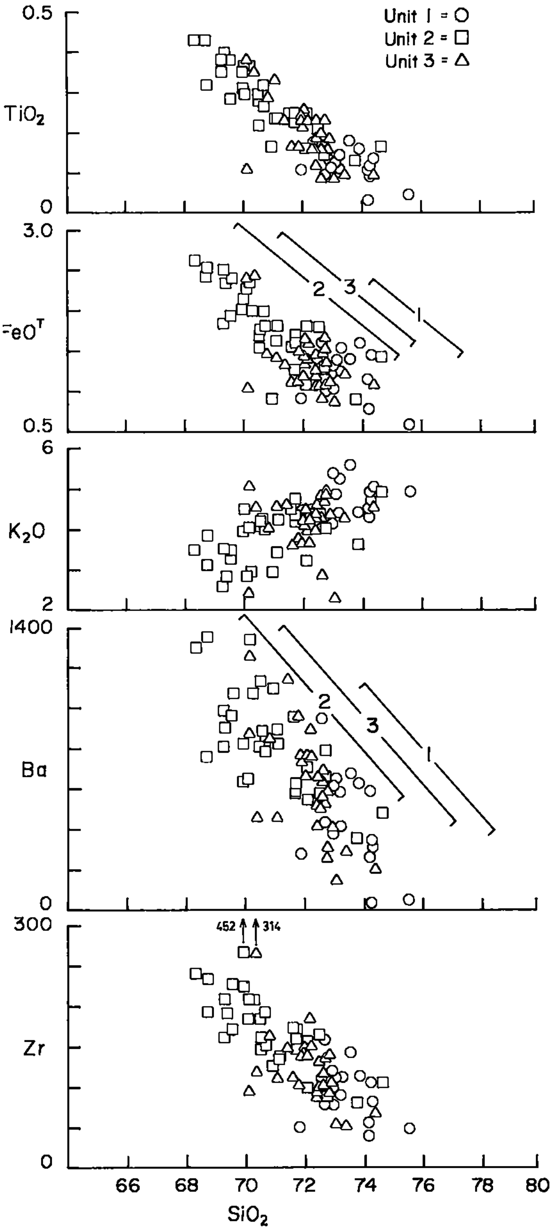

FIG. 7. Selected variation diagrams for analyzed samples from unit 1 (circles, n = 18), unit 2 (squares, n = 32), and unit 3 (triangles, n = 31) of the Black Brook Granitic Suite.

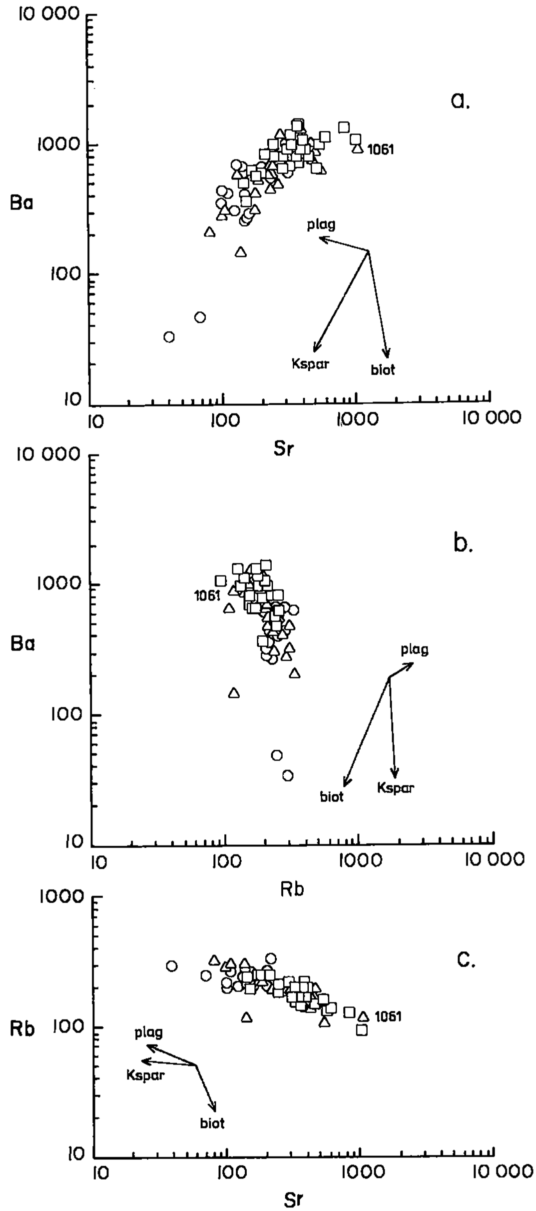

FIG. 8. Log-log plots of Ba-Sr, Ba-Rb, and Rb-Sr. Circles, unit 1; squares, unit 2; triangles, unit 3. Vectors show trends for Rayleigh crystal fractionation of 30% plagioclase (plag), 30% K-feldspar (Kspar), and 30% biotite (biot), calculated using the following partition coefficients for plagioclase, K-feldspar, and biotite, respectively: Ba: 0.4, 6, 6.36; Rb: 0.04, 0.8, 3.26; Sr: 3.35, 3.6, 0.12 (from McCarthy & Hasty 1976, Tindle & Pearce 1981).

method differed from that used in the present study (Table 4). Hence some caution is necessary in comparing the two sets of data.

The BBGS is characterized by enrichment in the *LREE* relative to the *HREE* (Fig. 9a). Total *REE* abundance decreases with increasing SiO_2 content (excluding sample 1061), and generally increases with increasing levels of P_2O_5 and Zr (Figs. 10a, b,

TABLE 4. RARE-EARTH-ELEMENT DATA[1] (PPM) FROM BLACK BROOK GRANITIC SUITE

	Unit 1	Unit 2						Unit 3	Aplite
	1098	3090	3587	4046	4119	4141	1026	1061	1035
La	18.02	50.36	29.05	37.52	61.75	34.58	38.35	5.76	10.57
Ce	32.63	85.08	69.54	70.14	108.81	60.62	63.83	9.86	21.15
Pr		8.14	6.00	7.47	10.64	6.40			
Nd	16.00	25.18	19.57	24.15	32.42	20.03	28.01	5.26	11.09
Sm	4.55	3.60	3.01	4.14	4.24	3.01	5.87	1.27	4.85
Eu	0.59	0.60	0.55	0.68	0.57	0.48	0.96	0.36	0.18
Gd		2.94	2.18	3.40	3.00	2.12			
Tb	0.66	0.35	0.25	0.41	0.33	0.30	0.71	0.16	0.89
Dy		2.02	1.26	1.89	1.88	1.53			
Ho		0.39	0.22	0.30	0.34	0.26			
Er		1.18	0.61	0.80	1.03	0.71			
Tm		0.19	0.08	0.10	0.16	0.10			
Yb	1.95	1.23	0.55	0.70	1.05	0.66	2.38	0.60	3.40
Lu		0.18	0.08	0.10	0.15	0.10			

[1] Data for samples 3090, 3587, 4046, 4119 and 4141 were obtained by ICP-MS at Memorial University of Newfoundland as described by Yaowanoiyothin (1988). Data for the other samples was obtained by instrumental neutron activation analysis as described by Barr & Pride (1986). Data differ from those presented by Barr & Pride (1986) in their Table 3 because that table inadvertently contained chondrite-normalized data for these samples.

c). Within unit 2, the three samples lowest in silica (1026, 3090, and 4119) have the highest total *REE* content, and flat *HREE* patterns compared to the three samples with higher silica contents. With the exception of sample 1061, the sample from an aplite dyke (1035) has the lowest total *REE*. It also has the largest negative Eu anomaly and the highest abundance of *HREE*. The low total *REE* in sample 1061 can be related to high plagioclase content relative to mica (and hence accessory phases), also reflected in low Zr and P_2O_5 (Fig. 10) and high Sr and Ba (Fig. 8). As suggested by Barr & Pride (1986), this sample and others of similar character may represent feldspar-enriched cumulates. The lack of a positive Eu anomaly may be the result of the existence of an initial negative Eu anomaly in the parental magma (*e.g.*, Fig. 9b) that was balanced by subsequent accumulation of feldspar.

As discussed previously, mineralogical and major- and trace-element variations in the BBGS suggest that feldspar and biotite were the major fractionating phases. The lack of a strong negative Eu anomaly suggests that biotite may have played a more important role than feldspar, although apatite fractionation may also have tended to offset the development of a negative Eu anomaly. Except for Eu in feldspar, both feldspars and micas have low K_d values for *REE*, and hence variations in feldspar and biotite abundance probably have little effect on *REE* patterns other than Eu (*e.g.*, Hanson 1980). In contrast, accessory phases (zircon, apatite, and monazite) have high K_d values for the *REE*; K_d values for both the *LREE* and *HREE* are high in apatite, high for the *LREE* in monazite, and high for the *HREE* in zircon (Hanson 1980, Mittlefehldt & Miller 1983). These minerals are considered to be the main reason for variation in *REE* in the BBGS. Samples with higher abundances of these minerals (*i.e.*, the lower-SiO_2 granodioritic samples, with higher biotite content and hence accessory mineral content) generally have higher total *REE*, as demonstrated by a negative correlation between total *REE* and SiO_2, but a positive correlation with P_2O_5 and Zr (Fig. 10). Plagioclase-rich sample 1061 is an exception to this generalization. Lack of positive correlation between total *REE* and Th content (Fig. 10d) does not support a major role for monazite in influencing *REE* behavior in the BBGS. The presence of garnet in aplite sample 1035 is consistent with the high abundance of the *HREE* in that sample.

The *REE* patterns for samples of the BBGS are similar to calculated patterns for melt and melt plus residue mixtures derived from a greywacke source (Fig. 9b). Because of the lack of petrographic evidence for restite phases in BBGS, variation in *REE* patterns is interpreted to represent the development of heterogeneities in the melt by varying amounts of crystal accumulation and fractionation, rather than by varying proportions of restite and melt. The less-well-developed negative Eu anomaly, compared to that in the South Mountain Batholith (Fig. 9b), may indicate that feldspar fractionation was less important in the BBGS than in the SMB (Muecke & Clarke 1981).

CLASSIFICATION

The BBGS has many of the features of S-type granites, as described by Chappell & White (1974) and White & Chappell (1983). However, it lacks modal cordierite and was probably emplaced at a

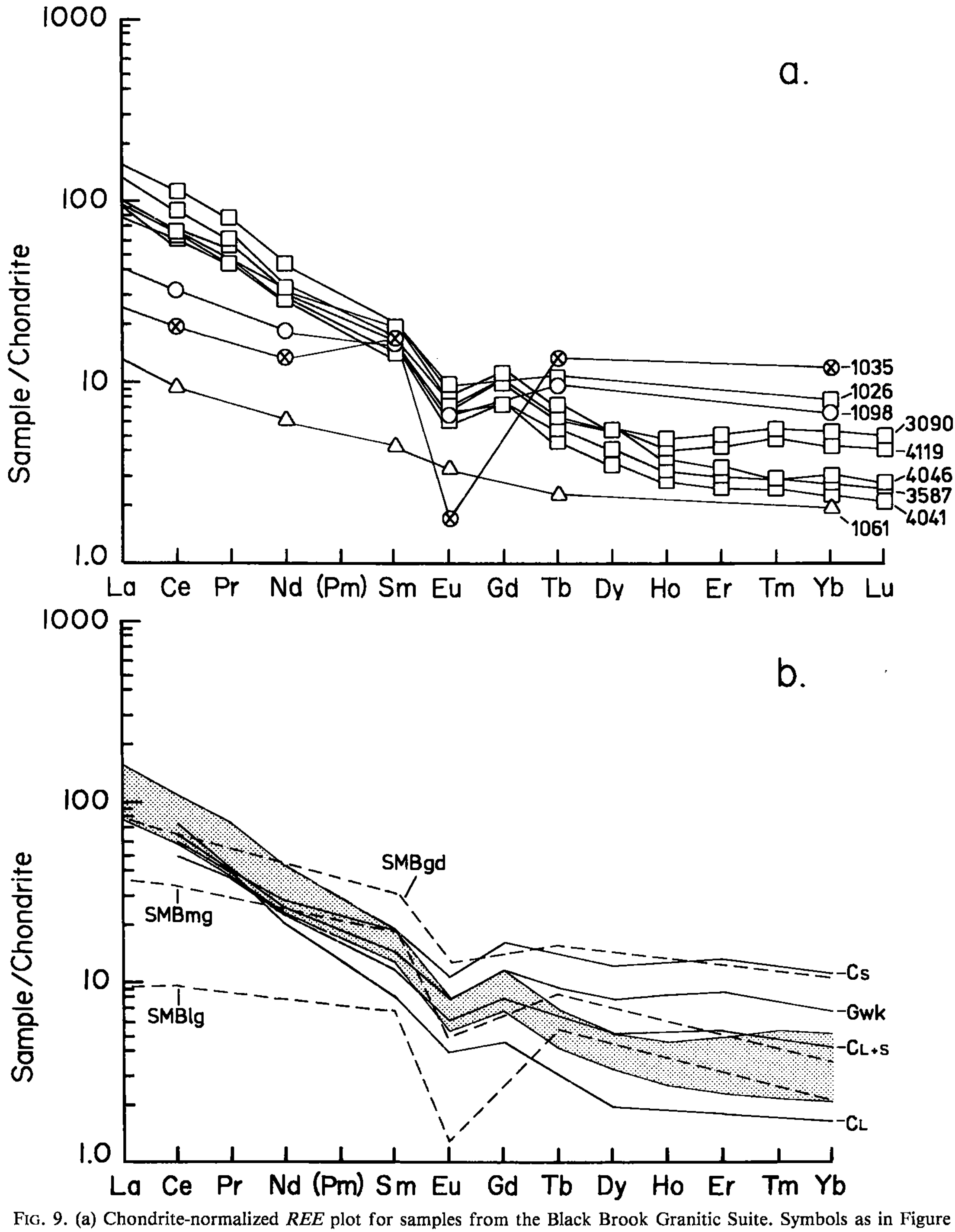

FIG. 9. (a) Chondrite-normalized *REE* plot for samples from the Black Brook Granitic Suite. Symbols as in Figure 2. Sample locations are shown on Figure 2. (b) Chondrite-normalized *REE* plot. Shaded field encloses samples from unit 2 of BBGS. Solid lines are after Hanson (1980) and indicate *REE* patterns for average greywacke (Gwk), melt derived by 30% partial melting of greywacke (CL), residual solid after partial melting (CS), and a mixture of 70% liquid and 30% residual solid (CL + S). Dashed lines refer to data for units of the South Mountain Batholith: SMBgd granodiorite, SMBmg monzogranite, and SMBlg leucogranite (data from Muecke & Clarke 1981). Chondrite-normalizing values from Evensen et al. (1978).

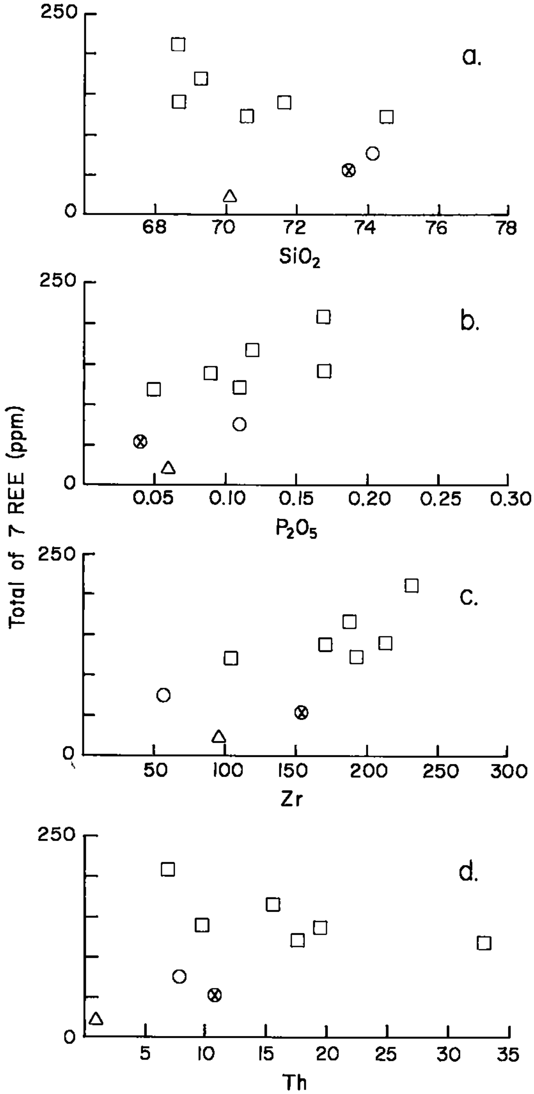

FIG. 10. Plots of total of 7 *REE* (La + Ce + Nd + Sm + Eu + Tb + Yb) against (a) SiO_2%, (b) Zr (ppm), (c) P_2O_5%, and (d) Th (ppm) for samples from the BBGS. Data from Table 4. Circle, unit 1; squares, unit 2; triangle, unit 3 (sample 1061); circle with x, aplite dyke.

deeper crustal level than the classic high-level (or "contact-aureole") S-type intrusive bodies of the Lachlan Fold Belt (White & Chappell 1983). Unit 2 of BBGS has average SiO_2 content (70.9%) similar to that in the average S-type granitic rock (70.3%), as compiled by Whalen *et al.* (1987). However, it has higher Al_2O_3, Na_2O, Ba and Sr, but lower Pb, Zn, Nb, Y, P_2O_5, TiO_2, V, and CaO compared to the average S-type granite (Table 3), as illustrated by a multi-element plot (Fig. 11a). Unit 1 of the BBGS has average SiO_2 content (73.5%) similar to that in the average felsic S-type granite (73.4%), but unit 1 is higher in Al_2O_3, Na_2O, Ba, Pb, and Sr, and lower in TiO_2, FeO^t, MgO, MnO, MgO, P_2O_5, Rb, V, Y, and Zr (Table 3, Fig. 11a). Many of these differences may be attributed to lower abundance of mafic minerals (biotite) in the BBGS, which suggests that fractional crystallization of biotite may have occurred during magma ascent (below the presently exposed level of the intrusive body), or that the BBGS (at least at the present level of exposure) contains a less restitic component than many S-type granites. The latter is supported by the lack of petrographic evidence for the presence of any restite in the BBGS, whereas it is apparently a feature of at least some S-type complexes (White & Chappell 1983).

The chemical characteristics of the BBGS are consistent with an origin in a syncollisional tectonic setting (Fig. 12). This tectonic setting is in agreement with the interpretation that the BBGS was emplaced during terrane juxtaposition. Petrographic features of the BBGS, such as its equigranular, nonporphyritic texture and the ubiquitous presence of microcline, indicate that the pluton crystallized at a relatively deep level. This interpretation is consistent with the abundance of associated pegmatite, the local development of high-grade ultramylonite in the BBGS, and the high regional metamorphic grade of its host rocks. The Cheticamp Lake Gneiss was at peak regional amphibolite-facies metamorphic conditions in bathozone 5 at 396±2 Ma, only about 20 million years before closure of the U–Pb system in monazite in the BBGS (Dunning *et al.* 1990, R. Raeside, pers. comm. 1991). However, emplacement and crystallization were followed, or more likely accompanied, by rapid uplift, as indicated by muscovite cooling ages of *ca.* 360 Ma, only 15 Ma younger than the age of intrusion (Reynolds *et al.* 1989), and by the presence of Early Carboniferous sedimentary rocks overlying the pluton. It seems likely that the BBGS was emplaced in a major fault-zone and that movement continued during emplacement and subsequent uplift, during which time the style of deformation changed from ductile to brittle.

The mechanism of magma genesis remains conjectural. Melting may have resulted from crustal thickening associated with juxtaposition of the Bras d'Or and Aspy terranes. The association of the BBGS with the terrane boundary along which high-grade mylonitization was occurring (Lin & Williams 1990) suggests that frictional heating may have played a role (*e.g.*, Strong & Hanmer 1981). Underplating of the crust by mafic magmas

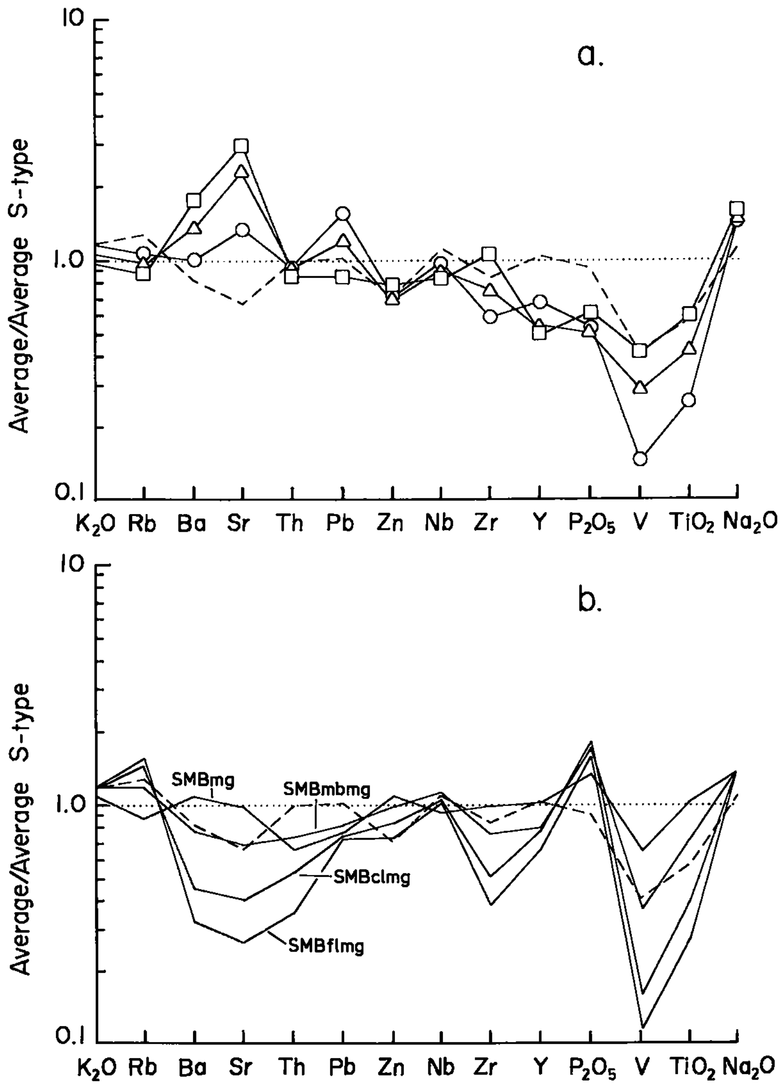

FIG. 11. Multielement diagrams for (a) average composition of units 1 (circle), 2 (square), and 3 (triangle) of the BBGS, and (b) average compositions of granitic units of South Mountain Batholith from MacDonald *et al.* (1989). Unit abbreviations: SMBmg biotite monzogranite, SMBmbmg muscovite-biotite monzogranite, SMBclmg coarse-grained leucomonzogranite, and SMBflmg fine-grained leucomonzogranite. Data are normalized to the average S-type granite of Whalen *et al.* (1987). The dashed line on both diagrams is the average felsic S-type granite of Whalen *et al.* (1987) for comparison.

(Huppert & Sparks 1988) also may have contributed, as Late Devonian mafic magmatism occurred widely in northern Cape Breton Island (Blanchard *et al.* 1984). Numerous mafic dykes in the BBGS (Yaowanoiyothin 1988) provide evidence for the presence of such magmas in the Black Brook area. Although the age of these dykes is not known, their apparent absence in the overlying Carboniferous units may be evidence that they are Late Devonian and hence only slightly younger than BBGS.

COMPARISON WITH THE SOUTH MOUNTAIN BATHOLITH

The similar ages and peraluminous compositions of the BBGS and the well-known South Mountain Batholith might lead to the assumption that the two

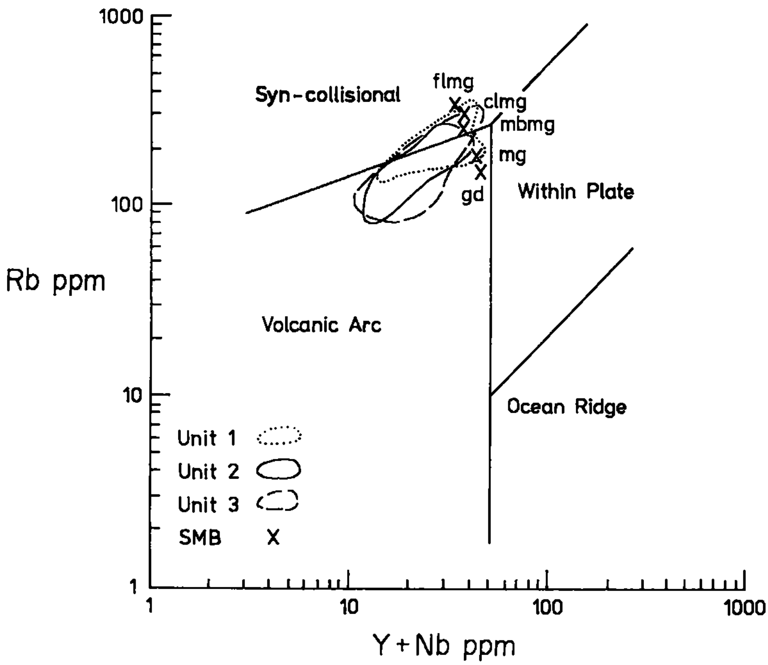

FIG. 12. Fields for data from units 1, 2, and 3 of the Black Brook Granitic Suite and average compositions of units from the South Mountain Batholith (SMB) plotted on the discrimination diagram of Pearce *et al.* (1984). Data for SMB units are from MacDonald *et al.* (1989: gd granodiorite, mg monzogranite, mbmg muscovite–biotite monzogranite, clmg coarse-grained leucomonzogranite, flmg fine-grained leucomonzogranite.

plutons are genetically related. Like the SMB (McKenzie & Clarke 1975, Clarke & Muecke 1985, MacDonald *et al.* 1989), the BBGS ranges in composition from granodiorite to monzogranite, lacks hornblende, and contains biotite as the major mafic mineral. Muscovite of probable igneous origin is present in most units of both plutons (Ham & Kontak 1988). However, the SMB commonly also contains cordierite (Maillet & Clarke 1985) and other highly aluminous minerals, which are absent from BBGS, and muscovite and biotite compositions are distinctly different in the two bodies (Figs. 5, 6). Biotite in the SMB is more aluminous (Fig. 4), consistent with the common occurrence of aluminosilicate phases. Biotite in granodiorite of the SMB contains less Ti than biotite in the BBGS, but biotite in monzogranite of the SMB may have comparable Ti content (Fig. 5a), although it is much more aluminous (Figs. 4, 5b). The lower Ti in biotite in the SMB is consistent with the higher Al content, as demonstrated by the linear correlation in biotite compositions in both SMB and BBGS (Fig. 5b) and explained by de Albuquerque (1973).

Like biotite, primary muscovite in the BBGS has higher Ti content than primary muscovite in the South Mountain Batholith (Fig. 6). The composition of both primary and secondary muscovite in the BBGS also tends to have lower Na content than in the SMB (Fig. 6).

In contrast to the BBGS, which displays a pervasive foliation consistent with syntectonic crystallization, the SMB is post-tectonic and generally unfoliated, except locally, near margins, where flow foliations are developed (Horne *et al.* 1988).

The range of chemical composition in the SMB (Table 3) is greater than in the BBGS because the granodiorite and biotite monzogranite units of the SMB are lower in SiO_2 (average 67.1 and 69.5%, respectively) than granodioritic unit 2 of the BBGS (70.9%). In units of comparable SiO_2 content (*e.g.*, unit 1 of BBGS and the coarse- and fine-grained monzogranite units of SMB; Table 3), the BBGS has lower FeO^t, MgO, and TiO_2, consistent with the lower abundance of modal biotite; modal biotite content averages only 1.6% in unit 1 of the BBGS (Yaowanoiyothin 1988), whereas monzogranitic units of the SMB units average about 6% biotite (McKenzie & Clarke 1975). Because the BBGS has lower whole-rock Ti content than the SMB, and higher Ti content in biotite, it seems likely that the SMB contains more ilmenite than the BBGS, although studies of the opaque phases in the SMB have not been reported to confirm this.

Both the BBGS and SMB have higher Na_2O and lower CaO and V than the average S-type granite (Table 3, Fig. 11). The SMB has higher P_2O_5 than the average S-type granite, whereas BBGS has lower P_2O_5, as well as lower Y and higher Ba and Sr. With increasing silica content in S-type granites, Ba, Sr, Zn, V, and TiO_2 decrease, as illustrated by comparison of lines for the average S-type and average felsic S-type granites in Figure 11a. Both the BBGS and SMB show similar trends in these elements, and in addition Zr also decreases, as does Th in the SMB, presumably because zircon (in the BBGS) and zircon plus monazite (in the SMB) were removed with the fractionating biotite. In the SMB, the more felsic units become more peraluminous, as shown by the increase in the A/CNK ratio (Table 3), whereas those in the BBGS become less peraluminous. The latter is a more characteristic feature of S-type granites, attributed to increasing removal of aluminosilicates phases in the restite (Clarke & Muecke 1985). However, in the case of the BBGS, it may have resulted from fractional crystallization of biotite.

On the Rb *versus* Y + Nb diagram (Fig. 12), both the BBGS and SMB plot on the boundary between the volcanic arc and syncollisional fields. However, with increasing silica content, the SMB shows a trend of increasing Rb with little change in Y + Nb, in contrast to the greater increase in Y + Nb in the BBGS. The lack of significant increase in Rb in the BBGS can be explained by the fractionation of more biotite or the accumulation of more plagioclase than in the SMB.

REE patterns in the BBGS and SMB are similar in shape, but the BBGS is relatively enriched in the *LREE* (Fig. 9b). In the SMB, as in the BBGS, the total *REE* content decreases with increasing silica, whereas the negative Eu anomaly increases; these features have been attributed to fractionation of plagioclase, biotite and zircon (Muecke & Clarke 1981). Hence, the evolution of magmas in the two cases appears to have been similar, although a greater role for biotite and accessory phases is required in the BBGS.

Although both the BBGS and SMB are S-type according to most criteria of White & Chappell (1977), neither case seems to offer an example of the restite model for the evolution of granitic magmas proposed by Chappell & White (1974) and White & Chappell (1983). Crustal protoliths are indicated by relatively high initial $^{87}Sr/^{86}Sr$ ratios of 0.708 - 0.709 in the SMB (Clarke & Halliday 1980), and *ca.* 0.709 in the BBGS (R.F. Cormier, written comm. 1988, data presented in Yaowanoiyothin 1988).

In summary, it seems likely that the SMB was derived from a more aluminous source than the BBGS. The protolith for the SMB may have experienced more partial melting to produce less felsic magma, and the resulting magma underwent more extensive fractional crystallization than the magma for the BBGS.

Conclusions

At the present level of exposure, the Black Brook Granitic Suite shows systematic petrographic and chemical variations that permit subdivision of the pluton into three units. However, these units appear to be essentially cogenetic, and variations within and among units generally can be explained by fractional crystallization of feldspar, biotite, zircon and apatite. The BBGS formed from a melt derived from metasedimentary source-rocks in a collisional tectonic setting. Emplacement and crystallization were syntectonic, and accompanied shearing along a terrane boundary. Crustal thickening, frictional heating, and mafic magma underplating all may have played a role in magma genesis. Studies of isotopic systems now in progress for the Black Brook Granitic Suite and other granitic units in the Aspy and Bras d'Or terranes may result in a better understanding of the nature of the source rocks of the BBGS, compared to other granites in Cape Breton Island.

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