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Atlantic Geology

Application of Airborne Gamma Ray Spectrometric Surveys Meguma Terrane, Nova Scotia

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Volume 22, Number 1, April 1986

URI: https://id.erudit.org/iderudit/ageo22_1art08

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Publisher(s)

Atlantic Geoscience Society

ISSN

0843-5561 (print)
1718-7885 (digital)

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Cite this article

Ford, K. L. & Carson, J. M. (1986). Application of Airborne Gamma Ray Spectrometric Surveys Meguma Terrane, Nova Scotia. *Atlantic Geology*, *22*(1), 117–135.

Article abstract

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Within a cogenetic suite of Devonian-Carboniferous peraluminous granitic rocks uranium concentrations are shown to increase progressively with increasing differentiation while thorium concentrations reflect two contrasting trends- The most prevalent trend, shown by the granitic rocks of the eastern part of the South Mountain Batholith (New Ross area) and Eastern Meguma Terrane, is one of decreasing thorium concentrations with increasing differentiation. A second, less prominent trend exhibited by the granitic rocks of the western part of the South Mountain Batholith shows increasing thorium concentrations with increasing differentiation. The more prevalent inverse relationship between uranium and thorium results in high eU/eTh ratios associated with the more differentiated phases of the granitic suite. In addition, certain slate units of the Meguma Group are shown to have distinctly higher radioelement contents, in particular thorium, compared to the other slate units and the remainder of the Meguma Group.

Follow-up investigations of these airborne gamma-ray spectrometric surveys have confirmed the relationships between uranium and thorium. Limited lithogeochemical sampling has shown that those phases of the granitic suite which exhibit a high eU/eTh ratio also exhibit increased levels of other lithophlle elements, Sn and Be and occasionally Li and F.

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Maritime Sediments and Atlantic Geology

Vol. 22 April, 1986 No. 1

Application of Airborne Gamma Ray Spectrometric Surveys Meguma Terrane, Nova Scotia

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Between 1976 and 1983 a series of airborne gamma-ray spectrometric surveys with flight lines spaced at one kilometre intervals were carried out in the Province of Nova Scotia. These surveys covered most of the Meguma Terrane and have yielded radioelement distribution patterns that have proven useful in delineating various aspects of the region's geology.
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Follow-up investigations of these airborne gamma-ray spectrometric surveys have confirmed the relationships between uranium and thorium. Limited lithogeochemical sampling has shown that those phases of the granitic suite which exhibit a high eU/eTh ratio also exhibit increased levels of other lithophile elements, Sn and Be and occasionally Li and F.

Entre 1976 et 1983 une série de levées de terrains spectométrique aérien de rayons gamma, avec des lignes de vols éspacées à intervals d'un kilomètre, ont été effectuées dans la province de la Nouvelle Ecosse. Ces levées s'étendent sur la pluspart du terrain Meguma et ont fourni des pattrons de distribution d'éléments radioactifs qui ont été utiles pour décrire divers aspects de la géologie de la region.
Dans une suite Dévoniène-Carbonifère cogénétique de roches granitiques per-alumineuse, il a été démonté que les concentrations d'uranium augmentent progressivement avec des hausses de différenciations alors que les concentrations de thorium montrent deux tendences contrastantes. La tendence la plus dominante, démontrée par les roches granitiques du batholithe de la "South Mountain", (région de New Ross) et du terrain "Eastern Meguma", est une baisse de concentration de thorium avec un accroissement de différenciation. Une autre tendance, moins accentuée, exposée par les roches granitiques de la partie de l'ouest du batholithe de la "South Mountain" montre une hausse des concentrations de thorium avec une hausse de différenciation. Les relations inverses les plus dominantes entre l'uranium et le thorium donnent des rapports eU/eTh, qui sont associés avec les phases plus différenciées de la suite granitique. De plus, certaines unités d'ardoise du groupe Meguma, ont des teneurs d'éléments radioactif qui sont nettement plus élevées, surtout pour le thorium, comparé aux autres unités d'ardoise dans le reste du groupe Meguma.
De plus amples investigations de ces levées spectrometriques à rayons gamma, ont confirmé les relations entre l'uranium et le thorium. Des prévèlements d'échantillons limité de géochimie, ont démontré ces phases de la suite granitique, qui exposent de hautes proportions de eU/eTh, comprennent aussi des niveaux élevés d'autres éléments, lithophiles, Sn, Be, et desfois Li et F.

MARITIME SEDIMENTS AND ATLANTIC GEOLOGY
22, 117-135 (1986)

0711-1150/86/010117-19$3.85/0

INTRODUCTION

The purpose of this paper is to illustrate the variety of airborne gamma ray spectrometric patterns over the granites and metasediments of the Meguma Terrane of Nova Scotia and to correlate these patterns with bedrock petrographic and elemental variations.

Since 1976, the Geological Survey of Canada has been systematically collecting high sensitivity airborne gamma ray spectrometric data in the Province of Nova Scotia. These surveys have proven useful in mapping the regional radioelement distribution patterns, in showing a variety of geological relationships, and in outlining areas of potential uranium and lithophile element enrichment and mineralization. The general principles of gamma ray surveying, including instrumentation, electronics, and operational procedures have been described by Bristow (1979), Grasty (1979) and Killeen (1979).

Between 1976 and 1978, approximately 11,000 line kilometres of reconnaissance (5 km line spacing) airborne gamma ray spectrometric data were collected covering the entire province of Nova Scotia (Geological Survey of Canada, Geophysical Series Maps 35411G, 35511G, 35611G, 36111G and 35821G, and Open File 429). As well, between 1976 and 1983 a substantial portion of southern and central Nova Scotia, covering most of the Meguma Terrane, was reflown with approximately 28,000 line kilometres of surveys with one kilometre line spacing (Fig. 1). This more detailed coverage has

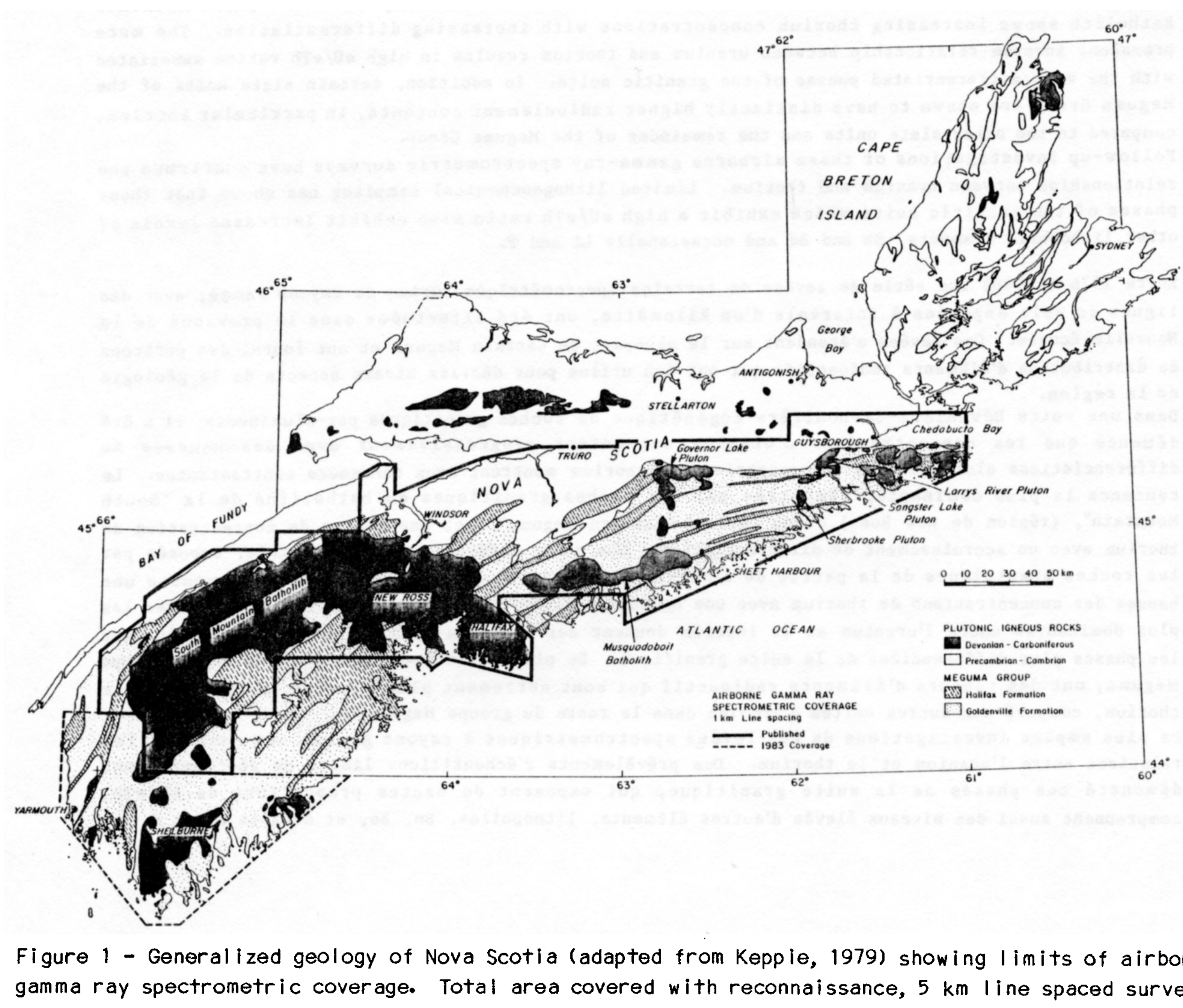

Figure 1 - Generalized geology of Nova Scotia (adapted from Keppie, 1979) showing limits of airborne gamma ray spectrometric coverage. Total area covered with reconnaissance, 5 km line spaced surveys.

provided increased resolution of the radioelement distribution patterns indicated by the reconnaissance surveys resulting in the delineation of several phases of the composite granitic intrusives.

Previously reported ground follow-up investigations (Ford et al, 1981; Ford, 1982; and Ford and Ballantyne, 1983) and data presented in this report have confirmed the radioelement variations within and between the Devonian-Carboniferous granites of southern and central Nova Scotia. In many cases these variations relate to varying degrees of differentiation and possibly autometasomatic alteration within the granites (Chatterjee and Muecke, 1982).

This report will focus on previously defined regional radioelement distribution patterns from the eastern Meguma Terrane with examples from the Governor Lake, Sherbrooke and Sangster Lake Plutons (Fig. 1). Previously unreported results of ground follow-up investigations conducted in 1982 on the Governor Lake and Sherbrooke Plutons along with some earlier results from the Sherbrooke and Sangster Lake Plutons (Ford and Ballantyne, 1983) are included.

REGIONAL GEOLOGY

The geology of the eastern Meguma Terrane is dominated by the Cambro-Ordovician Meguma Group which is divisible into the older Goldenville Formation (predominantly greywacke), and the younger Halifax Formation (predominantly slate) (Fig. 1). These metasedimentary units have been folded into a series of open to tight folds with east-west striking, steeply dipping axial planes. These major Acadian fold structures predate the intrusion into the Meguma Group of a series of Devonian-Carboniferous (c. 370 Ma) granitoid plutons (Smith, 1981; Keppie, 1979). The granitoids range in composition from granodiorite to monzogranite with minor amounts of muscovite-bearing leucogranite and associated aplitic and pegmatitic dyke rocks. Metamorphic grade within the eastern Meguma Terrane ranges from lower greenschist-chlorite grade to middle amphibolite-staurolite grade (Henderson, 1983).

Although not indicated on Figure 1, the geology to the north of the Meguma Terrane is dominated by Lower Carboniferous continental and marine sediments of the Horton and Windsor Groups, respectively. These groups, in part, onlap the Meguma Group (Shubenacadie and Musquodoboit Basins; Boehner, 1980) or are bounded by the West River - St. Mary's Fault.

AIRBORNE GAMMA RAY SPECTROMETRIC RESULTS

Airborne gamma ray spectrometric data acquired over the eastern Meguma Terrane with a line spacing of 1 kilometre are shown on Figures 2,3 and 4. The airborne patterns over the Governor Lake, Sherbrooke and Sangster Lake Plutons (Fig. 1) illustrate the variations generally observed over other granites of the Meguma Terrane. Figure 2 shows that the Sangster Lake Pluton has the highest equivalent uranium (eU) concentrations at slightly greater than 6 ppm while maximum values for the Sherbrooke and Governor Lake Plutons are slightly greater than 3 ppm. These differences may reflect variations in exposure as the Sangster Lake Pluton is well exposed relative to the Sherbrooke and Governor Lake Plutons.

The term equivalent, as reported by the International Atomic Energy Agency (IAEA, 1976) is used for reporting uranium concentration, measured by gamma ray spectrometry where, assuming the sample material is in radioactive equilibrium and appropriate corrections have been made, it is a correct measure of uranium concentration.

The effect of variation in bedrock exposure is further illustrated by comparing the average radioelement

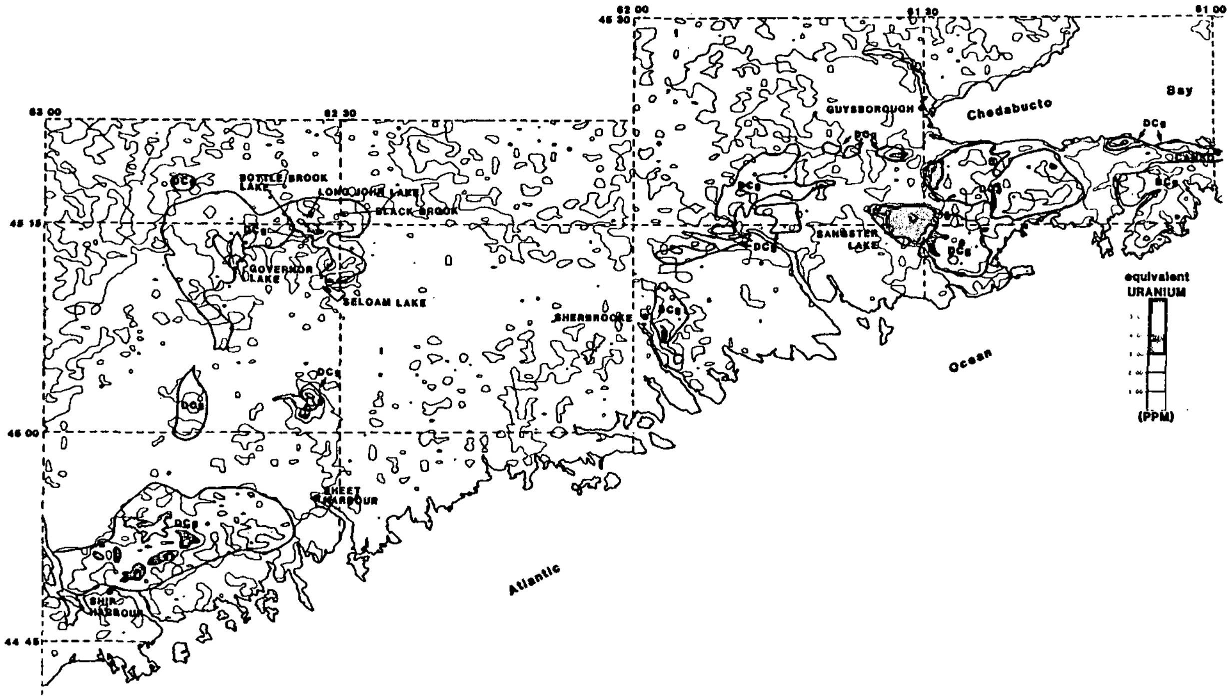

Figure 2 - Equivalent uranium (ppm) map for the eastern Meguma Terrane compiled from 1 km line spaced airborne gamma ray spectrometric surveys. Scale 1 cm = 6.8 km.

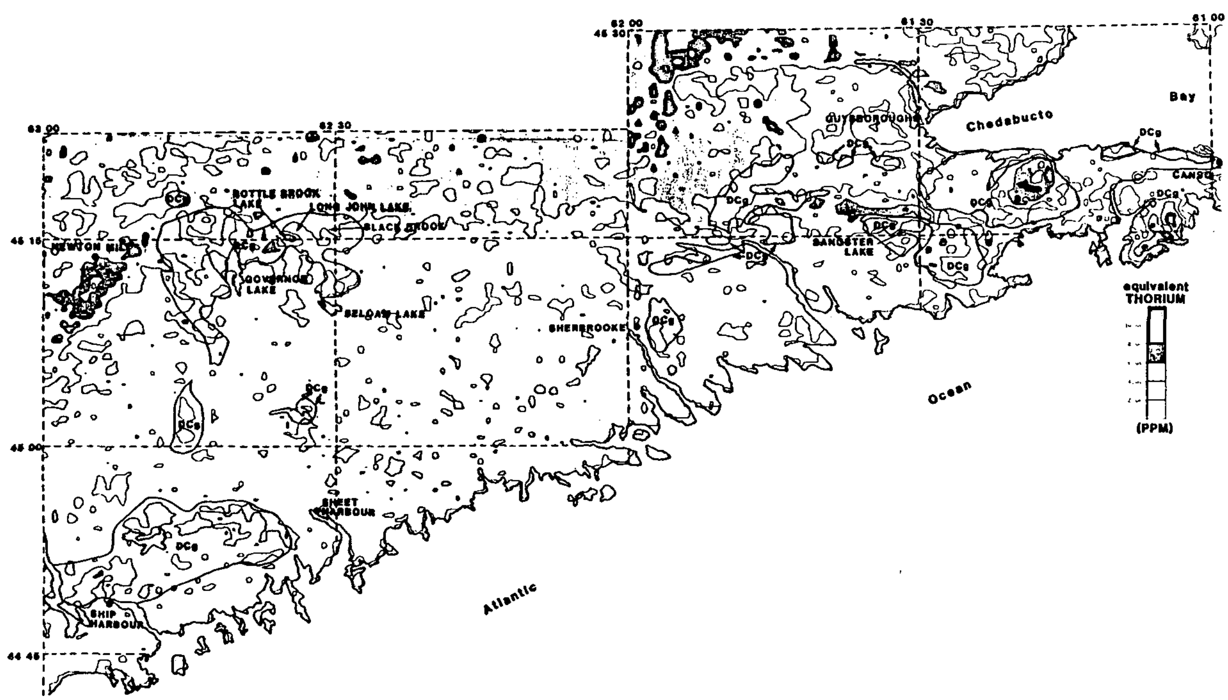

Figure 3 - Equivalent thorium (ppm) map for the eastern Meguma Terrane compiled from 1 km line space airborne gamma ray spectrometric surveys. Scale 1 cm = 6.8 km.

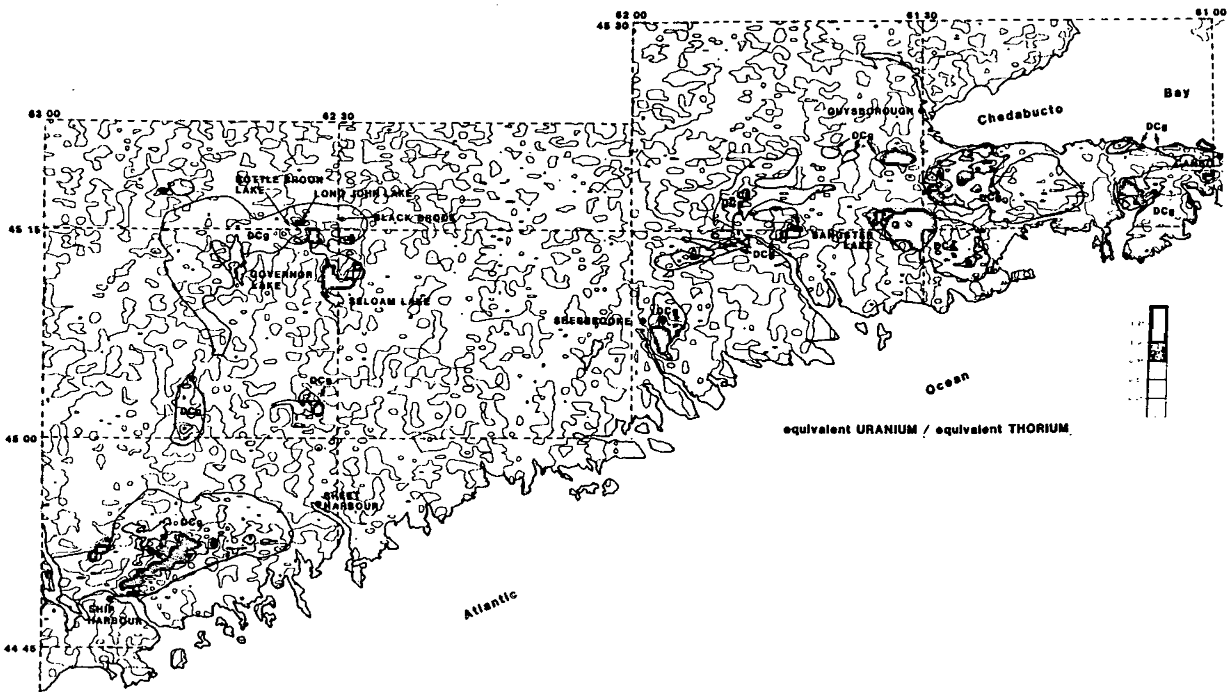

Figure 4 - Equivalent uranium/equivalent thorium ratio map for the eastern Meguma Terrane compiled from 1 km line spaced airborne gamma ray spectrometric surveys. Scale 1 cm = 6.8 km.

concentrations measured by in-situ gamma ray spectrometry for these three plutons (Table 1) with the airborne measurements. The extreme eastern portion of the Sangster Lake Pluton has a mean surface concentration of slightly greater than 6 ppm eU determined by airborne spectrometry and an average bedrock eU concentration of 12.3 ppm based on 19 in-situ gamma ray spectrometric measurements. Compare this with the southwestern portion of the Sherbrooke Pluton which has a mean surface concentration of just slightly greater than 3 ppm eU and an average bedrock concentration of 16.5 ppm eU based on 14 in-situ measurements. Usually airborne determinations of radioelement concentrations will be less than bedrock concentrations, due to the shielding effects of overburden, wetness, and vegetation, however the two measurements will be proportional (Charbonneau et al, 1976).

Figure 2 illustrates the variability of the eU concentrations within each pluton. The Sangster Lake Pluton shows concentrations ranging from 1 ppm near the western margin to greater than 6 ppm in the eastern part of the pluton. In the Sherbrooke Pluton, concentrations range from less than 1 ppm to greater than 3 ppm with maximum concentrations occurring towards the southwest margin. In the Governor Lake Pluton eU concentrations range from less than 1 ppm to greater than 3 ppm with the higher concentrations restricted to the eastern part of the pluton (Bottle Brook Lake - Long John Lake area) and the marginal parts of the pluton in the Seloam Lake area.

In contrast to the eU distribution patterns, those areas of the three plutons which have elevated concentrations of eU generally have the lowest concentrations of equivalent thorium (eTh) (Fig. 3). For example, the southwestern margin of the Sherbrooke Pluton which has eU concentrations of greater than 3 ppm, has eTh concentrations of less than 2 ppm compared with eTh levels for the northeastern portion of the pluton that reach 4 ppm. In the Governor Lake Pluton eTh levels range from less than

Table 1

Radioelement content of various granitic and metasedimentary rock of the eastern Meguma Terrane, Nova Scotia

Location	No. of Values	Arithmetic Mean and Range			Rock Type
		K (%)	eU (ppm)	eTh (ppm)	
GOVERNOR LAKE PLUTON					
- Bottle Brook Lake	15	4.43 (3.89-5.53)	7.9 (5.8-10.8)	30.4 (18.6-38.3)	Fine Grained, Biotite Monzogranite
- Black Brook	17	4.52 (3.69-5.87)	7.4 (4.3-10.2)	11.3 (8.5-13.3)	Coarse Grained, Biotite (±Musc.) Monzogranite
- Long John Lake	24	3.96 (2.52-5.12)	6.8 (3.5-10.5)	4.4 (1.8-7.4)	Medium Grained, Muscovite (±Bio.) Leuco-Monzogranite
- Seloam Lake	14	3.52 (2.84-4.56)	10.9 (6.6-16.3)	4.1 (2.7-7.1)	Medium Grained, Muscovite (±Bio.) Leuco-Monzogranite
SHERBROOKE PLUTON					
- Northeast	4	4.64 (4.30-5.03)	7.9 (7.23-9.16)	10.7 (9.7-11.4)	Medium Grained, Biotite-Muscovite Monzogranite
- Southwest	14	4.13 (3.31-4.99)	16.6 (7.16-31.8)	5.3 (3.2-9.1)	Medium Grained, Muscovite-Biotite Monzogranite
SANGSTER LAKE PLUTON					
- Western	8	3.99 (3.55-4.47)	3.2 (1.9-5.5)	5.1 (4.3-6.4)	Coarse Grained, Biotite-Muscovite Monzogranite
- Central	32	3.57 (2.83-4.68)	9.1 (5.5-13.7)	5.2 (3.4-7.0)	Medium Grained, Biotite-Muscovite Monzogranite
- Eastern	19	3.62 (3.11-4.17)	12.3 (8.6-17.5)	5.0 (4.1-6.1)	Fine-Medium Grained, Muscovite (±Bio.) Leucogranite
MEGUMA GROUP					
- Halifax Form.	31	3.51 (2.17-5.33)	4.9 (1.7-11.4)	17.4 (9.6-25.8)	Andalusite-Bearing Slate, Minor Pyrite
- Goldenville Form.	19	2.33 (1.21-3.66)	1.8 (0.4-4.0)	9.2 (4.9-15.9)	Metaquartzite and Metagreywacke
SOUTH MOUNTAIN BATHOLITH *					
- Granodiorite	31	3.6 (3.0-4.5)	3.6 (1.8-5.4)	12.9 (8.7-15.4)	
- 2 - Mica Monzogranite (New Ross)	54	4.3 (1.8-5.5)	6.9 (2.7-21.7)	10.9 (2.1-20.9)	
- Dike Rocks and minor Intrusives (New Ross)	20	4.1 (3.1-7.0)	8.5 (2.5-21.7)	6.4 (2.3-10.9)	
Average Granodiorite (Taylor, 1965)			3.0	10	
Average Granite (Taylor, 1965)			4.8	17	

Radioelement content of Nova Scotia lithologies measured by in-situ gamma ray spectrometry

2 ppm to greater than 7 ppm. Again, as with the Sherbrooke Pluton, areas of highest eU levels (Bottle Brook Lake - Long John Lake and Seloam Lake) generally have the lowest eTh levels. In the case of the Bottle Brook Lake - Long John Lake area however, eTh levels are somewhat higher at Bottle Brook Lake (7 ppm) than they are at Long John Lake (3 ppm). In-situ gamma ray spectrometric data (Table 1) confirms this relative variation determined by airborne measurements. The fine grained biotite monzogranite of the Bottle Brook Lake area contains on average, 7.9 ppm eU and 30.4 ppm eTh compared with 6.8 ppm eU and 4.4 ppm eTh for the medium grained muscovite leuco-monzogranite of the Long John Lake area. Airborne eTh determinations over the Sangster Lake Pluton show no apparent zonation and range between 2 to 4 ppm compared with an average bedrock concentration of 5 ppm.

In Figure 4 the high eU/eTh ratios are restricted to those granitic areas which are characterized by either elevated concentrations of uranium and/or depleted concentrations of thorium. In the Sherbrooke Pluton, the high eU/eTh ratio developed along the southwestern margin is the result of increasing eU levels (1-2 ppm for the northeastern margin to greater than 3 ppm for the southwestern edge) superimposed on decreasing eTh levels (4 ppm to less than 2 ppm). In contrast to the Sherbrooke Pluton, the high eU/eTh ratio associated with the central and eastern portions of the Sangster Lake Pluton is the result of sharply increased eU levels (1 ppm in the west to greater than 6 ppm in the east) superimposed on relatively constant eTh levels. In still a third situation, the high eU/eTh ratio associated with the Long John Lake area of the Governor Lake Pluton appears to be the result of decreasing eTh levels superimposed on a relatively constant eU level.

These associations between uranium and thorium and the resulting high eU/eTh ratio are an unusual characteristic of most, but not all, granitoids of the Meguma Terrane.

An interesting additional feature of the airborne gamma ray spectrometric data is the distinction between the Halifax Formation and the Goldenville Formation. The primary difference is illustrated on Figure 3 in the Newton Mills area and along the northern margin of the Sangster Lake Pluton where some slate units of the Halifax Formation are shown to have higher eTh levels than the Goldenville Formation. Variation within and between different slate units may reflect differences in bedrock exposure or overburden variations. Differences in the radioelement concentrations of the Halifax and Goldenville Formations, based on in-situ gamma ray spectrometry are shown in Table 1. Measurements on roadside outcrops of the Halifax Formation southeast of Newton Mills (Fig. 3) reveal eTh concentrations as high as 62 ppm. This high thorium concentration was found to be associated with a narrow (10 cm) quartzitic unit within the slate. Chemical analysis of a sample from this unit (Table 2) shows high Zr with elevated concentrations of TiO_2, Ce, La and Th. Petrographic and microprobe analysis reveal a relatively abundant, apparently detrital, accessory mineral suite composed of zircon-rutile-tourmaline-garnet and thorite.

GROUND FOLLOW-UP INVESTIGATIONS

Bedrock Radioelement Contents

One hundred and fifty seven in-situ gamma ray spectrometric measurements were made on bedrock exposures of the granites and metasediments of the eastern Meguma Terrane of Nova Scotia using a portable Disa 400 (Exploranium) gamma ray spectrometer. Since the airborne measurements represent an average surface concentration which is dependent on the percentage of outcrop and overburden, the relationship between the bedrock and overburden radioelement contents, the percentage

Table 2

Major, Minor and Selected Traces Element Analysis of the Halifax Formation
From The Newton Mills Area, Nova Scotia

Sample	FIA-82-132	FIA-82-133	FIA-82-135		FIA-82-132	FIA-82-133	FIA-82-135
	Black, Pyritic Slate	Grey-Green Non-Pyritic Slate	Fine Grained Grey-Green Quartzitic Unit				
Weight%				PPM			
SiO_2	63.4	61.2	82.0	Sr	110	100	52
TiO_2	.91	.96	1.47	Ba	860	850	170
Al_2O_3	19.9	21.0	7.7	Rb	130	210	40
Fe_2O_3	2.3	.9	.9	Zr	210	130	3470
FeO	2.5	4.8	2.1	Cu	12	13	10
MnO	.03	.40	.32	Pb	8	—	--
MgO	1.42	1.29	.66	Zn	68	90	27
CaO	.06	.16	.47	Li	80	81	44
Na_2O	1.2	.8	1.0	B	47	57	84
K_2O	3.27	4.60	.79	Ce	34	114	230
H_2O	4.2	4.1	1.3	La	16	54	104
CO_2	0.0	0.0	.3	U	5.0	3.0	11.0
P_2O_5	.07	.13	.09	Th	8	16	70
S	.03	.00	.00				
L.O.I.	0.7	--	--				
TOTAL	100.2	100.8	99.6				

Analytical Methods: Major and minor oxides, Rb and Zr by x-ray influorescence except FeO by a modified Wilson's method and H_2O and CO_2 by infra-red spectrometry; Sr, Ba and B by optical emission spectrometry; Cu, Pb, Zn and Li by atomic absorption; Ce, La, U and Th by neutron activation analysis.

of surface water and soil moisture, and the density of vegetation (Charbonneau et al, 1976), the airborne determinations will usually be less than, although proportional to the corresponding bedrock concentrations.

Table 1 lists the average radioelement concentrations in the various phases of the three granites investigated along with the radioelement concentrations of the Halifax and Goldenville Formations of the Meguma Group. For comparison, the average radioelement concentrations of the South Mountain Batholith in the New Ross area are also included (Ford, 1982) along with the average uranium and thorium contents for granodiorite and granite as reported by Taylor (1965).

These averages reflect the generally low eTh concentrations and high eU/eTh ratios for some phases of the Nova Scotia granites. Few phases actually show an enrichment of thorium beyond Taylor's average of 17 ppm for granite. The 30.4 ppm average eTh concentration of the fine grained biotite monzogranite of the Bottle Brook Lake area is the second highest average eTh concentration found for granitoids in the Meguma Terrane of Nova Scotia. As previously reported (Ford, 1982) the highest average concentration of 36.6 ppm, is associated with biotite granite of the Wedgeport Pluton south of Yarmouth.

In Figure 5, the radioelement variation within and between individual plutons is shown to be considerable. Of the three plutons represented in Figure 5, the Governor Lake Pluton shows the greatest variability with individual eU determinations ranging from 3.5 to 16.3 ppm and eTh determinations ranging from 1.8 to 38.3 ppm.

As indicated by the airborne gamma ray spectrometric surveys and confirmed by the bedrock determinations presented in Figure 5 each pluton appears to show a slightly different relationship

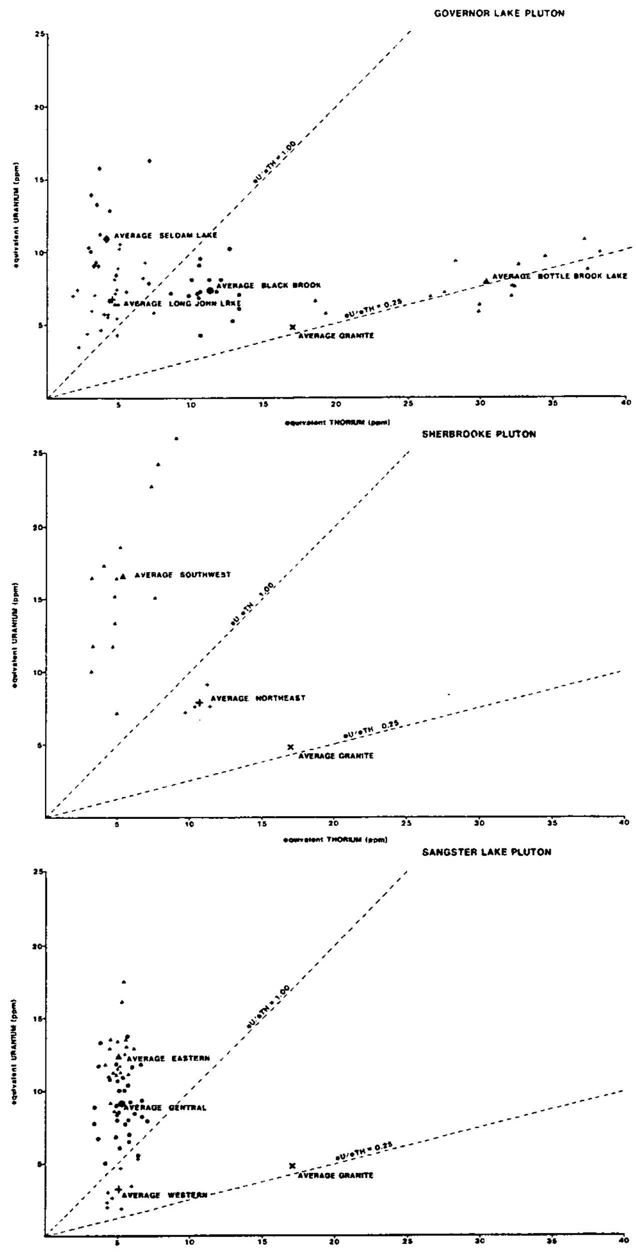

Figure 5 - Variation in equivalent uranium and equivalent thorium contents based on in situ gamma ray spectrometry for the Governor Lake, Sherbrooke and Sangster Lake Plutons. Also shown are the average uranium and thorium contents for granite from Taylor (1965).

between the two radioelements. In the Sherbrooke Pluton, average bedrock radioelement concentrations range from 7.9 ppm eU and 10.7 ppm eTh in the northeast to 16.6 ppm eU and 5.3 ppm eTh in the southwest. This inverse relationship is not accompanied by any obvious change in mineralogy or texture in the Sherbrooke granite except for an increase in the muscovite-biotite ratio with muscovite becoming the predominant micaceous phase in the high eU/eTh ratio portions of this pluton. It has been suggested (Plant et al, 1980) that such an increase in the muscovite-biotite ratio may reflect a high temperature water-rock interaction or autometasomatic alteration. As will be discussed in the next section on lithogeochemistry, the southwest portion of the pluton appears to be more evolved chemically than the northeast portion.

Figure 5 illustrates the restricted range of eTh concentrations for the Sangster Lake Pluton. For the 59 in-situ gamma ray spectrometric measurements, the eTh concentrations exhibit a narrow range from 3.4 to 7.0 ppm while the eU concentrations range from 1.9 to 17.5 ppm. These data and the corresponding averages reflect a sharp increase in the eU concentrations superimposed on a constant eTh concentration resulting in a high eU/eTh ratio for the eastern portion of the pluton. These variations do not correspond with any obvious mineralogical or textural variation in the pluton with the exception of a slight increase in the muscovite content associated with the high ratio portion of this two-mica monzogranite (O'Reilly, personal communication, 1983). A limited number of measurements taken on outcrop of a small leucogranite phase in the eastern portion of the Sangster Lake Pluton show eU concentrations as high as 51.7 ppm with a corresponding eTh concentration of 4.6 ppm. However, measurements considered to be more representative of this phase show eU concentrations of between 9.0 and 19.4 ppm with corresponding eTh concentrations between 1.2 and 3.5 ppm. These values suggest only slight differences between this more evolved (O'Reilly, 1983) leucogranite phase and the less evolved monzogranite, and may not be enough to distinguish these two separate phases on the airborne data.

In the Governor Lake Pluton the radioelement variations shown in Figure 5 correspond with distinct petrographic variations. As will be shown in a discussion of the lithogeochemistry of these phases the low eTh and high eU/eTh ratio phases at Long John Lake and Seloam Lake are more evolved than the Black Brook and Bottle Brook Lake phases. In both the Long John Lake and Seloam Lake areas the predominant rock type is a medium grained, muscovite leuco-monzogranite with minor biotite, while at Black Brook and Bottle Brook Lake the predominant rock type is a biotite monzogranite with minor muscovite.

In the New Ross area of the South Mountain Batholith, Chatterjee and Muecke (1982) have noted similar variations in uranium and thorium concentrations which they have related to differentiation within a cogenetic suite of granitic rocks. Uranium concentrations were shown to increase and thorium concentrations decrease with progressive differentiatiion from a biotite granodiorite, through biotite-muscovite and leucocratic monzogranite to minor intrusions of aplite, pegmatite and porphyries. The range or rock types encountered in the South Mountain Batholith was not encountered in the plutons from the eastern Meguma Terrane reported here although granodioritic phases may be present in the western portion of the Governor Lake Pluton and have been recorded in other plutons of the Chedabucto Bay area (O'Reilly, 1983; Ham, 1983).

The variations in radioelement concentrations measured by in-situ gamma ray spectrometry clearly verify the relative variations observed in the regional airborne survey data and show a correlation with differentiation and possibly autometasomatic alteration.

Lithogeochemistry in Relation to Radioelement Variation

Based on a limited rock sampling program, Ford et al. (1981) showed that

Table 3
Means and ranges of major, minor and trace element analysis of the various phases of the Governor Lake Pluton, Nova Scotia

	GOVENOR LAKE PLUTON						
	Bottle Brook Lake (N=5)	Black Brook (N=6)	Long John Lake (N=6)	Seloam Lake (N=6)	Dyke Rocks (N=4)		
	Fine Grained Biotite Monzogranite	Coarse Grained Biotite (+Musc.) Monzogranite	Medium Grained Muscovite (+Bio.) Leuco-Monzogranite	Medium Grained Muscovite (+Bio.) Leuco-Monzo granite		Specialized or Stannigene Granites (Tischendorf, 1977) Group I	Normal Granites (Tischendorf, 1977) Group III
SiO_2	72.48	72.30	75.90	74.18	75.38	73.38	70.84
	(71.20-73.30)	(71.40-73.50)	(73.70-77.00)	(73.50-74.60)	(73.90-78.00)		
TiO_2	.35	.28	.07	.05	.02	.16	.34
	(0.33-0.37)	(0.18-0.37)	(0.03-0.10)	(0.02-0.09)	(0.01-0.03)		
Al_2O_3	14.28	14.72	14.05	15.25	15.30	13.97	14.33
	(13.90-15.30)	(14.20-15.30)	(13.00-15.30)	(14.80-15.90)	(13.50-16.10)		
Fe_2O_3	.74	.32	.18	.30	.22	.80	1.31
	(0.40-1.30)	(0.00-0.90)	(0.00-0.30)	(0.00-0.60)	(0.10-0.30)		
FeO	.90	1.23	.38	.22	.25	1.10	1.78
	(0.40-1.20)	(0.30-1.80)	(0.20-0.50)	(0.00-0.40)	(0.20-0.30)		
MnO	.03	.03	.02	.04	.04	.045	.064
	(0.02-0.03)	(0.02-0.04)	(0.01-0.02)	(0.01-0.17)	(0.01-0.06)		
MgO	.63	.62	.20	.16	.14	.47	.81
	(0.57-0.68)	(0.28-0.84)	(0.07-0.26)	(0.09-0.23)	(0.10-0.19)		
CaO	.69	.91	.43	.31	.51	.75	1.89
	(0.55-0.86)	(0.61-1.27)	(0.33-0.60)	(0.14-0.55)	(0.34-0.71)		
Na_2O	2.72	3.00	3.27	4.07	4.58	3.20	3.44
	(2.20-3.60)	(2.50-3.30)	(2.40-4.10)	(3.60-4.50)	3.20-5.70)		
K_2O	5.04	4.56	4.04	4.95	2.26	4.69	4.34
	(4.68-5.17)	(3.86-5.06)	(3.49-4.54)	(3.68-4.170	(0.73-3.15)		
H_2O	.96	.93	.85	.82	.82	—	—
	(0.80-1.20)	(0.90-1.00)	(0.60-1.10)	(0.70-0.90)	(0.40-1.30)		
CO_2	.26	.07	.20	.35	.08	—	—
	(0.00-0.70)	(0.00-0.10)	(0.10-0.60)	(0.10-0.50)	(0.00-0.10)		
P_2O_5	.28	.27	.32	.28	.46	—	—
	(0.25-0.31)	(0.19-0.36)	(0.26-0.37)	(0.19-0.37)	(0.29-0.54)		
Total	99.90	99.24	99.91	99.98	100.06	A	B
Sr	51	67	10	15	50	7	100
	(43-60)	(37-93)	(3-13)	(3-29)	(13-95)	(2-31)	
Ba	448	422	60	84	46	68	840
	(440-480)	(210-610)	(21-87)	(11-190)	(17-100)	(3-356)	
Rb	294	437	287	347	338	651	170
	(270-330)	(220-300)	(210-370)	(200-480)	(160-500)	(300-1,080)	
Zr	142	118	42	38	45	177	175
	(130-170)	(60-150)	(30-40)	(30-50)	(40-50)	(58-400)	
F	760	567	550	383	375	4330	850
	(400-900)	(400-700)	(300-700)	(200-500)	(100-500)	(2,200-6,000)	
Li	99	110	114	95	32	84	40
	(66-143)	(92-147)	(79-168)	(36-156)	(8-51)	(50-200)	
Be	3.2	4.1	4.0	5.7	156.2	14	3
	(1.0-4.9)	(2.0-5.8)	(2.3-6.3)	(3.8-10.0)	(26.0-410.0)	(2-50)	
Sn	7.2	11.0	13.5	28.7	50.0	22	3
	(4-12)	(5-16)	(9-19)	(12-43)	(42-65)	(2-114)	
Ce	60.0	39.0	9.0	5.3	5.5	111	57
	(54-66)	(24-50)	(6-14)	(2-10)	(2-8)	(47-293)	
La	22.0	16.0	3.0	2.2	1.8	99	55
	(20-25)	(9-22)	(2-5)	(1-4)	(1-3)	(24-550)	
U	6.9	4.8	5.4	4.8	14.0	—	4.7
	(5.0-8.0)	(3.5-6.5)	(2.5-10.0)	(3.5-8.0)	(2.0-25.0)		
Th	27.0	10.0	2.0	1.0	1.0	46	20
	(23-30)	(7-12)	(1-4)	(1-2)	(1-1)	(3-105)	
U/Th	0.26	0.48	2.70	4.80	14.00	—	0.24

A - Means and ranges of trace elements in stanniferous granites, Younger Granites, Northern Nigeria: Olade (1980)

B - Low-calcium granites: Turekian and Wedepohl (1961)

Analytical methods: Major and minor oxides, Rb, Zr and Sn by x-ray fluorescence except FeO by a modified Wilson's method and H_2O and CO_2 by infra-red spectrometry; Sr, Ba and Be by optical emission spectrometry; Ce, La, U and Th by neutron activation analysis; F by fusion and specific-ion electrode; Li by atomic absorption.

Table 4

Means and ranges of major, minor and trace element analysis of the various phases of the Sherbrooke and Sangster Lake Plutons, Nova Scotia

	SHERBROOKE PLUTON				SANGSTER LAKE PLUTON				
	Northeast (N=4)1	Southwest (N=4)2	Leucogranite Dykes (N=8)3	Albitized Dyke (N=3)	West (N=3)	East I (N=13)	East II (N=11)		
	Medium Grained Biotite-Muscovite Monzogranite	Medium Grained Muscovite-Biotite Monzogranite	Fine Grained Muscovite Leuco Monzogranite		Coarse Grained Biotite-Muscovite Monzogranite	Medium Grained Biotite-Muscovite Monzogranite	Fine-Medium Grained Muscovite (±Biotite) Leucogranite	Specialized or Stannigene Granites (Tischendorf, 1977) Group I	Normal Granites (Tischendorf, 1977) Group III
SiO_2	73.07 (71.80–75.00)	73.45 (72.60–74.20)	74.76 (73.30–76.60)	74.27 (74.00–74.50)	74.13 (73.10–75.50)	72.55 (69.40–76.30)	73.57 (67.90–75.30)	73.84	70.84
TiO_2	.17 (0.11–0.23)	.08 (0.04–0.13)	.06 (0.01–0.09)	.02 (0.01–0.03)	.17 (0.14–0.23)	.20 (0.11–0.27)	.06 (0.02–0.17)	.16	.34
Al_2O_3	14.17 (14.30–15.10)	14.78 (14.30–15.30)	14.60 (13.40–15.90)	15.36 (15.00–15.70)	14.30 (13.50–15.00)	15.49 (13.80–17.30)	15.61 (14.60–18.90)	13.97	14.33
Fe_2O_3	.21 (0.20–0.30)	.15 (0.00–0.20)	.22 (0.10–0.30)	.31 (0.30–0.31)	1.06 (0.91–1.38)	1.52 (0.84–2.12)	.69 (0.33–2.10)	.80	1.31
FeO	.94 (0.59–1.17)	.61 (0.40–0.80)	.31 (0.10–0.50)					1.10	1.78
MnO	.02 (0.02–0.03)	.03 (0.02–0.03)	.04 (0.01–0.08)	.03 (0.02–0.04)	.03 (0.02–0.04)	.05 (0.02–0.06)	.04 (0.01–0.23)	.045	.064
MgO	.35 (0.08–0.53)	.21 (0.16–0.27)	.07 (0.00–0.17)	.05 (0.02–0.09)	.33 (0.26–0.46)	.36 (0.20–0.48)	.13 (0.03–0.37)	.47	.81
CaO	.65 (0.53–0.78)	.52 (0.46–0.64)	.37 (0.23–0.64)	.39 (0.30–0.39)	.64 (0.60–0.69)	.38 (0.28–0.47)	.29 (0.14–0.49)	.75	1.89
Na_2O	3.54 (3.00–3.81)	4.06 (3.80–4.50)	4.84 (3.13–5.90)	6.96 (6.40–7.85)	3.66 (3.45–3.76)	3.88 (3.07–4.51)	4.49 (3.56–5.29)	3.20	3.44
K_2O	4.67 (4.23–5.11)	4.16 (3.93–4.55)	3.25 (2.02–4.53)	1.35 (0.89–2.20)	4.55 (4.37–4.70)	4.16 (3.49–4.98)	3.95 (3.16–4.69)	4.69	4.34
H_2O	.73 (0.40–0.90)	.70 (0.60–0.80)	.60 (0.40–0.80)	.43 (0.30–0.60)	.60 (0.60–0.60)	.70 (0.10–1.00)	.52 (0.30–1.00)	—	—
CO_2	.13 (0.00–0.20)	.30 (0.10–0.60)	.19 (0.10–0.30)	.07 (0.00–0.10)	—	—	—	—	—
P_2O_5	.22 (0.16–0.27)	.30 (0.25–0.37)	.29 (0.14–0.62)	.31 (0.30–0.34)	.29 (0.24–0.36)	.35 (0.23–0.48)	.38 (0.30–0.44)	—	—
Total	99.41	99.35	99.60	99.95	99.76	99.64	99.73	A	B
Sr	71 (54–97)	17 (3–36)	28 (12–75)	31 (10–50)	67 (30–100)	18 (3–50)	47 (3–120)	7 (2–31)	100
Ba	310 (110–430)	23 (10–55)	24 (10–71)	26 (13–40)	263 (120–360)	80 (50–130)	94 (20–320)	68 (3–356)	840
Rb	224 (199–242)	294 (210–350)	387 (257–610)	497 (390–690)	207 (160–280)	335 (240–510)	412 (280–600)	651 (300–1,080)	170
Zr	90*	40** (40–40)	53*** (30–70)	37 (10–70)	27 (10–40)	45 (20–60)	11 (10–40)	177 (58–400)	175
F	452 (290–600)	587 (460–690)	465 (280–900)	595 (200–850)	342 (270–400)	800 (600–1050)	538 (390–710)	4330 (2,200–6,000)	850
Li	115 (61–187)	166 (103–263)	51 (28–80)	6 (4–8)	52 (4–8)	180 (27–362)	64 (21–168)	84 (50–200)	40
Be	6.9 (2.6–11.0)	11.3 (2.7–26.0)	53.5 (7.9–140.0)	128.0 (100.0–182.0)	3.8 (3.5–4.0)	10.5 (3.5–28.0)	25.3 (3.0–61.0)	14 (2–50)	3
Sn	9.6 (6.5–14.0)	19.8 (8.0–35.0)	39.1 (12–72)	248.0 (126.0–400.0)	8 (4–10)	21 (1–33)	32 (16–48)	22 (2–114)	3
Ce	34*	9.0** (8–10)	7.0*** (4–16)	6*	—	—	—	111 (47–293)	57
La	13*	2.5** (2–3)	2.5*** (1–6)	3*	—	—	—	99 (24–560)	55
U	2.7 (1.6–3.6)	9.0 (2.9–17.5)	8.7 (1.9–16.5)	8.8 (7.0–12.0)	3.7 (2.5–5.0)	9.5 (5.5–16.7)	9.8 (2.5–21.0)	—	4.7
Th	4.8 (2–8)	2.2 (1–4)	1.0 (1–2)	1.0 (1–1)	3.0 (2–4)	4.1 (1–7)	1.7 (1–6)	46 (3–105)	20
U/Th	0.56	4.09	8.70	8.80	1.23	2.32	5.76	—	0.24

* - One analysis only; ** - Two analyses only; *** - Four analyses only

1 - Three analyses supplied by P.K. Smith, Nova Scotia Dept. of Mines and Energy
2 - Two analyses supplied by P.K. Smith, Nova Scotia Dept. of Mines and Energy
3 - Four analyses supplied by P.K. Smith, Nova Scotia Dept. of Mines and Energy

A - Means and ranges of trace elements in stanniferous granites, Younger Granites, Northern Nigeria; Olade (1980)
B - Low-calcium granites: Turekian and Wedepohl (1961)

Analytical methods: Sherbrooke Pluton - Major and minor oxides, Rb, Zn and Sn by x-ray fluorescence, except FeO by a modified Wilson's method and H_2O and CO_2 by infra-red spectrometry; Sr, Ba and Be by optical emission spectrometry; Ce, La, U and Th by neutron activation analysis; F by fusion and specific-ion electrode; Li by atmoic absorption. Sangster Lake Pluton - Major and minor oxides, Sr, Ba, Rb, Zr and Sn by x-ray fluorescence, Be and Li by atomic absorption; F by fusion and specific-ion electrode; U and Th by neutron activation analysis.

the Sangster Lake Pluton was enriched in U, Sn, Rb, Li and Cs and depleted in Sr, Ba, Zr and Th compared to the average abundances of these elements for low-Ca granites as given by Turekian and Wedepohl (1961). Additional work by Ford and Ballantyne (1983) on the Sangster Lake Pluton correlated these enrichment and depletion trends with variation in the radioelement concentrations and showed that in general the high U/Th ratio phases exhibited the characteristics of increased differentiation and possible autometasomatic alteration.

Table 3 and 4 provide a summary of the major, minor and selected trace element analyses for the Governor Lake, Sherbrooke and Sangster Lake Plutons along with major and minor element data from Tischendorf (1977) and trace element data from Olade (1980) and Turekian and Wedepohl (1961) for comparison. These analyses do not represent all of the phases, styles of alteration or mineralization which may be present in these granites.

Compared to the "Normal Granite" group of Tischendorf (1977) the various phases of the three plutons presented in Tables 3 and 4 generally show elevated concentrations of SiO_2, Al_2O_3 and Na_2O, and depleted concentrations of TiO_2, Fe (Total), MnO, MgO and CaO. Many of these elemental abundances compare closely with Tischendorf's "Specialized or Stannigene granite" group. The selected trace element data show enrichment in Rb, Li, Be, Sn and U, and depletion in Sr, Ba, Zr, F and Th compared to Turekian and Wedepohl's average abundances for low-Ca granites.

Variations in elemental concentrations between the various phases sampled from each pluton can generally be correlated with the radioelement variations. In particular, certain elements are shown to increase and others to decrease with an increasing U/Th ratio (Figs. 6, 7 and 8). With an increasing U/Th ratio, the major and minor element variations reflect increasing differentiation and possible autometasomatic alteration in the form of pervasive albitization. This albitization trend, while not obvious petrographically is obvious chemically. Figures 6, 7 and 8 all show that with an increasing U/Th ratio, the K_2O concentrations decrease progressively while the Na_2O concentrations increase. This albitization trend and the associated radioelement variations may reflect the cumulative effects of increasing igneous differentiation and autometasomatic alteration. Albitization trends have been described elsewhere, as in the Nigerian Younger Granite Province by Olade (1980) and in the Tin Granites of the Seward Peninsula, Alaska by Hudson and Arth (1983).

This albitization trend and the associated U/Th ratio increases are both accompanied by enrichment and depletion of other elements. For example, CaO, Fe (Total), MgO and TiO_2 all show a general reduction in concentration with increasing U/Th ratio. These variations reflect the generally increasing leucocratic appearance of each successive phase. Selected trace element variations show similar enrichment and depletion trends associated with the increasing U/Th ratio although in each example their relative variations may be slightly different. For example, Rb generally shows a progressive enrichment with increasing U/Th although in the Governor Lake Pluton, Rb concentrations appear relatively constant in all phases sampled. Barium concentrations generally decrease and in some situations quite sharply (i.e. Governor Lake and Sherbrooke Plutons). Lithium concentrations appear to increase initially but then decrease sharply in the more evolved phases. Tin and beryllium both show progressive enrichment with increasing U/Th ratio although in the Governor Lake Pluton, Be enrichment is only slight until the final phases are encountered. Uranium and thorium concentrations follow the same relative variations as indicated

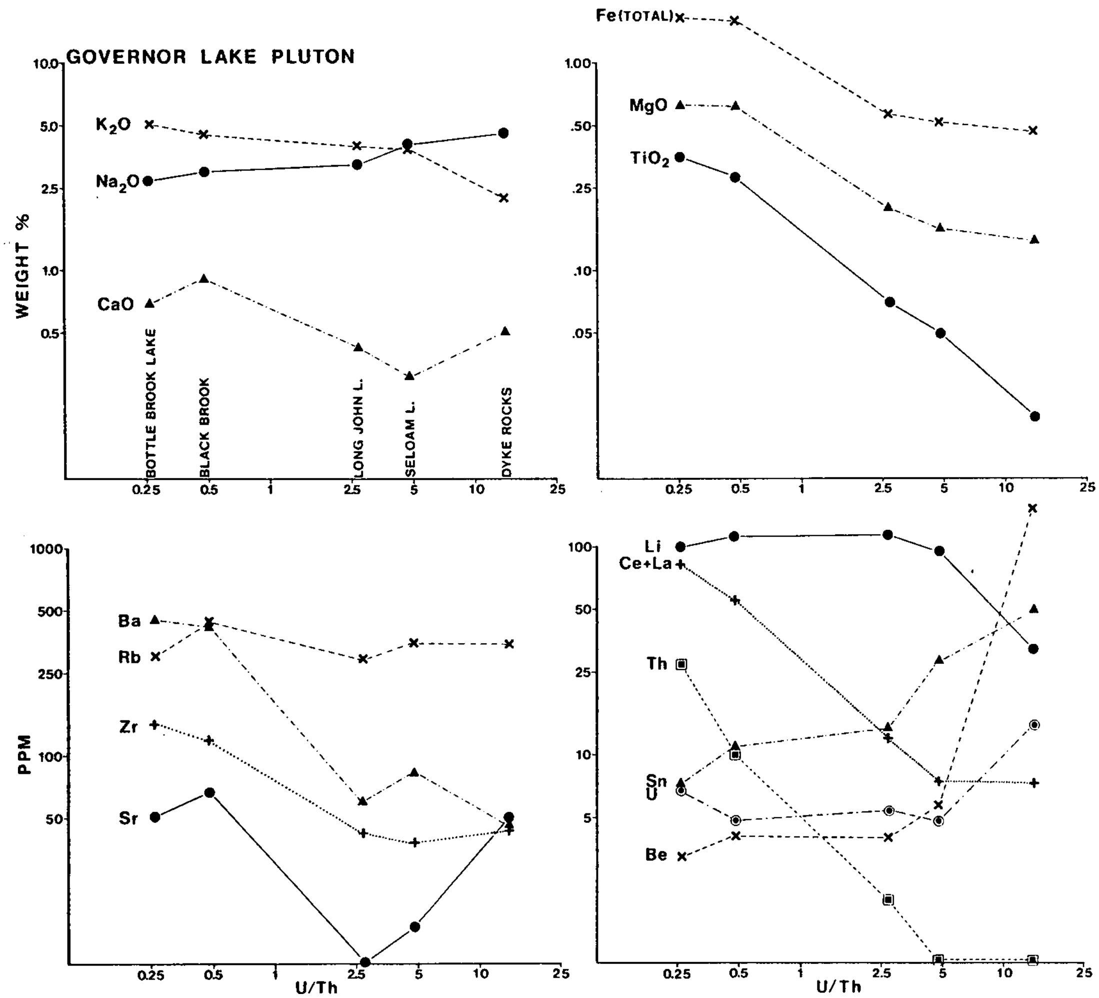

Figure 6 - Variation in selected major and minor oxides, and trace elements as a function of increasing U/Th ratio for the various phases of the Governor Lake Pluton. Uranium and thorium analysis by delayed neutron counting and neutron activation analysis, respectively.

by the airborne and ground gamma ray spectrometric surveys. Uranium concentrations either increase or remain relatively constant while thorium concentrations generally decrease, although in the Sangster Lake Pluton they remain relatively constant.

A relationship between the albitization trend and possible mineralization processes is suggested by comparison of the chemical analyses from the various phases for the Sherbrooke Pluton. Figure 7 illustrates the progressive increase in Na_2O, Rb, Sn and Be and decrease in K_2O, CaO, Fe (Total), MgO, TiO_2 and Ba with increasing U/Th ratio from the northeastern portion of the pluton to the southwestern portion and into the leucogranite dyke rocks. However, samples from an albitized dyke situated near the western margin of the pluton show extreme enrichments and depletions. Tin and beryllium concentrations reach maximums of 400 and 180 ppm respectively with associated Na_2O concentrations reaching a high of 7.8 wt. % while K_2O concentrations are depleted to a low of 0.9 wt. %. Ford and Ballantyne (1983) report the presence of cassiterite in samples from this albitized dyke but could not identify discrete Be-bearing mineral phases. Muscovite separates from this dyke were found to contain Be concentrations of 700 ppm. This is considerably higher than Be concentrations of muscovite reported by Beus (1965) which ranged from 30-140

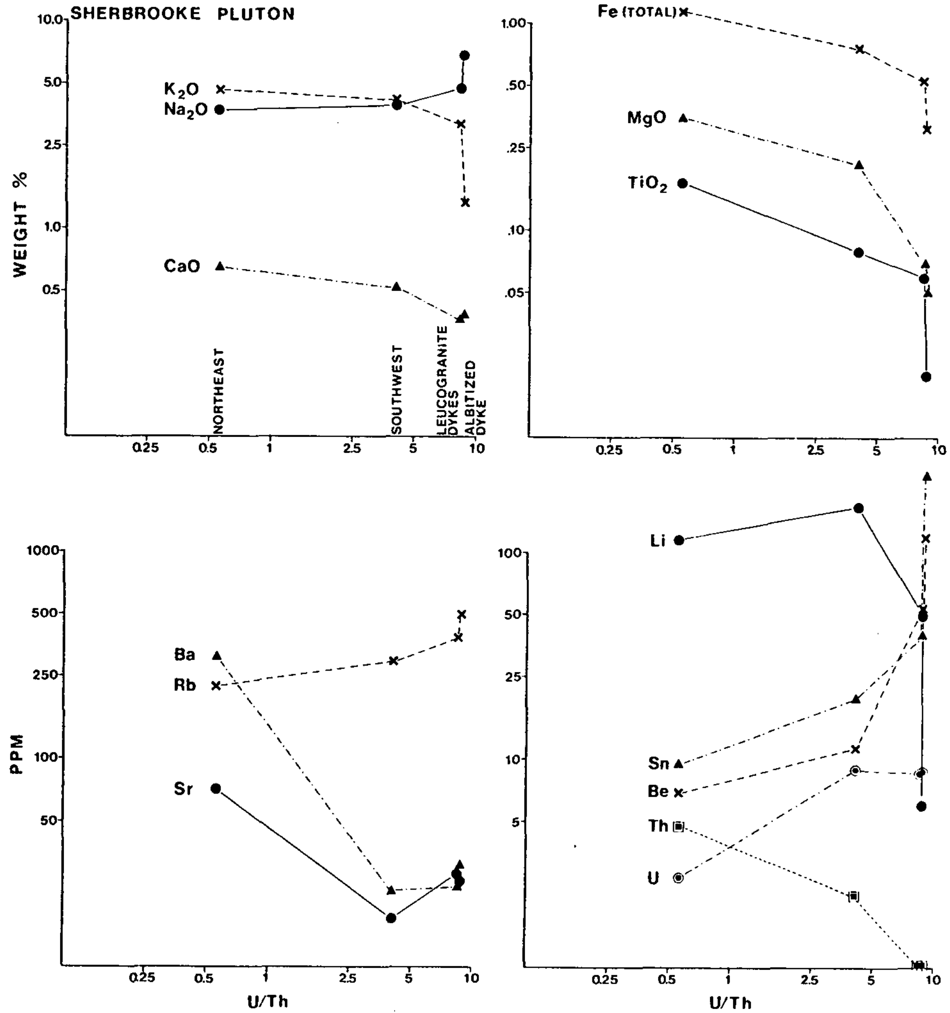

Figure 7 - Variation in selected major and minor oxides, and trace elements as a function of increasing U/Th ratio for the various phases of the Sherbrooke Pluton. Uranium and thorium analysis by delayed neutron counting and neutron activation analysis, respectively.

ppm. Beryl was identified in boulder samples of leucogranite dykes collected along the eastern margin of the Seloam Lake portion of the Governor Lake Pluton. Beryllium concentrations reached highs of 410 ppm in these samples.

Ford and Ballantyne (1983) reported the presence of the mineral phases, ixiolite, $(Ta, Nb, Fe, Mn, Sn)_4O_8$ and tapiolite, $(Fe^{+2}(Ta, Nb)_2O_6)$ in samples of the Sangster Lake Pluton which contained relatively high concentrations of Sn, Be, Nb and Ta. The presence of such mineral phases may explain the anomalous Sn concentrations in other phases of the granites of the eastern Meguma Terrane. It has also been reported (Imeokparia, 1982) that biotites from stanniferous granites of the Amo Younger Granite in Nigeria contain anomalous levels of Sn however those phases of the eastern Meguma Terrane granites reported here that have the highest Sn concentrations are often depleted in biotite.

Fission track and scanning electron microprobe studies on samples from the uranium-enriched phases of the Sangster Lake Pluton indicate that the most abundant uranium-bearing phases include Fe-oxide, principally coating fractures and a variety of phosphate-rich phases which include Fe, rare-earth and chlorine-bearing varieties (Figures 9A and 9B). In addition, apatite (Figures

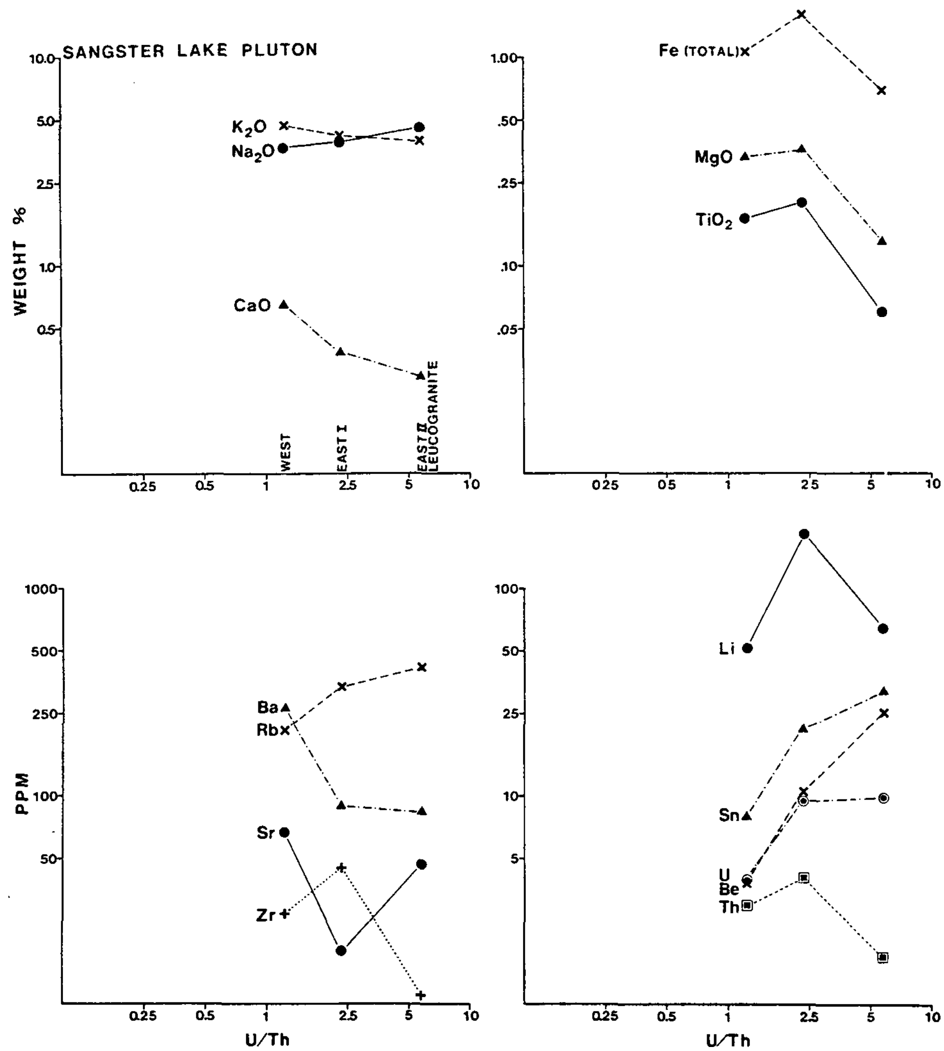

Figure 8 - Variation in selected major and minor oxides, and trace elements as a function of increasing U/Th ratio for the various phases of the Sangster Lake Pluton. Uranium and thorium analysis by delayed neutron counting and neutron activation analysis, respectively.

9C and 9D) with or without monazite and zircon inclusions show particularly strong fission track responses. In addition, minute monazite and zircon grains as inclusions in biotite show particularly strong fission track responses.

SUMMARY

Ground follow-up investigations not only confirm the relative variations in radioelement concentrations that are indicated by the airborne gamma ray spectrometric surveys, but they also illustrate the capability of the airborne results to delineate those granites or phases of larger composite granitic plutons that exhibit the characteristics of increased differentiation and/or autometasomatic alteration. In the eastern Meguma Terrane, the more evolved or differentiated granites generally show higher eU/eTh ratios than those less evolved phases. The high ratios are usually the result of an inverse relationship between the radioelements with U concentrations generally increasing and Th concentrations decreasing with increasing differentiation. The reasons for the unusually high eU/eTh ratios is not clearly understood but may be related to the cumulative effects of igneous

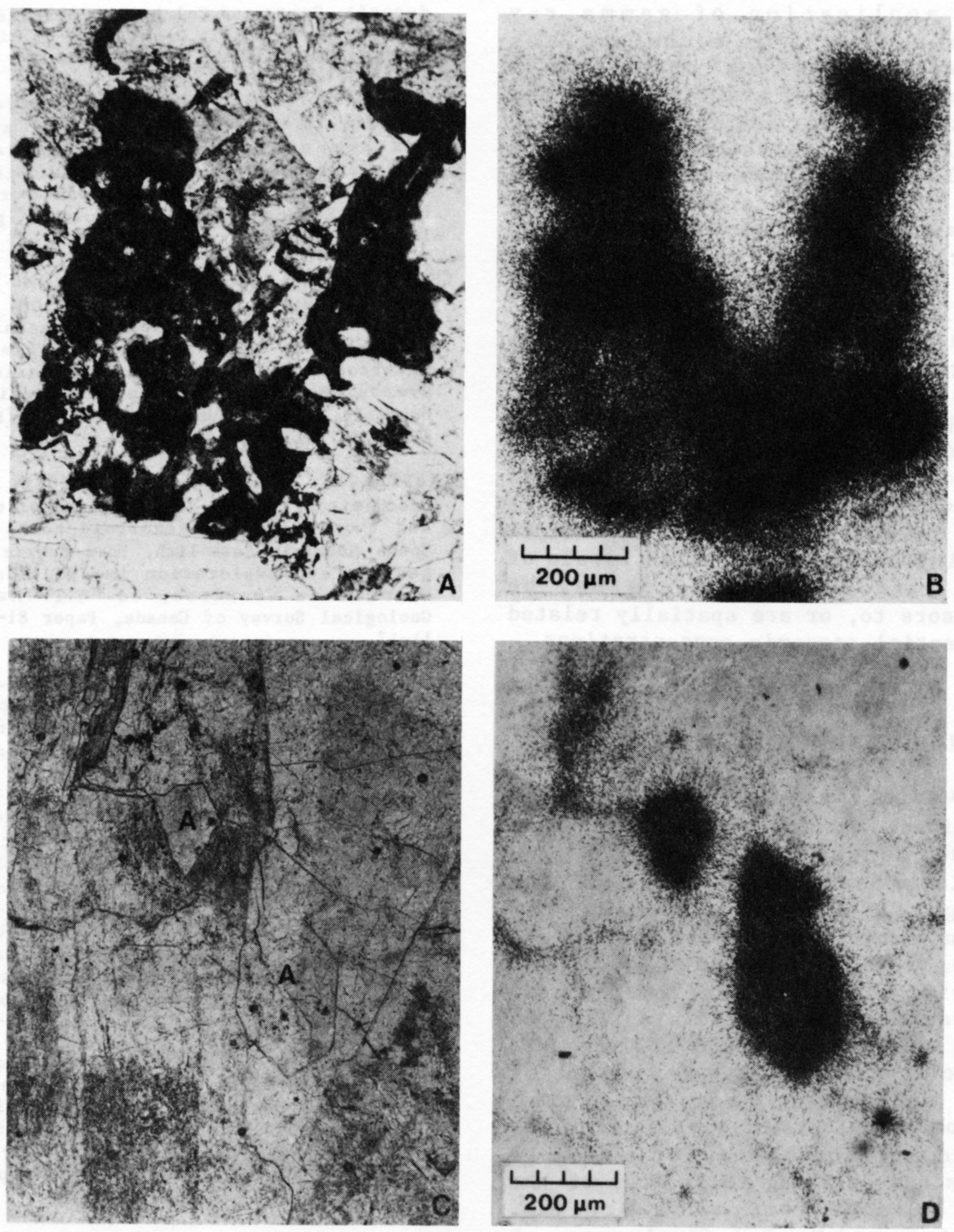

Figure 9 - Photomicrographs of Fe-bearing phosphate phase - 9A and apatite (A) -9C along with their associated fission track responses - 9B and 9D, respectively.

differentiation and some degree of late-stage autometasomatism. This is suggested by the correlation between the increasing U/Th ratios and the "albitization" trend. Associated with the increasing U/Th ratios and the albitization trend are enrichments and depletions in other elements. Of particular significance in the eastern Meguma Terrane is the enrichment of Sn and Be in the more evolved, high U/Th ratio phases.

The application of gamma ray spectrometry as a technique for delineating various phases of a composite suite of granitic rocks and for exploring for lithophile element mineralization in granitic environments has also been suggested by Yeates et al. (1982). It has been shown here that airborne and ground gamma ray spectrometric surveys are not only useful in delineating various phases of composite granite plutons but that they are also useful as a potential exploration technique in the regional exploration for granite-related lithophile elements. Those phases that are delineated by gamma ray spectrometry as having characteristics of increased differentiation (high eU/eTh ratios) and confirmed by bedrock sampling as having elevated levels of other lithophile elements may be precursors to, or are spatially related to potential economic concentrations.

ACKNOWLEDGEMENTS

We would like to thank Mrs. G.M. LeCheminant and Mr. G.R. LaChance, both of the Central Laboratories and Technical Services Division of the Geological Survey of Canada for carrying out mineral identification and microprobe analyses, and for supervising the chemical analysis of rock samples. We would also like to extend our appreciation to Mr. P.K. Smith of the Nova Scotia Department of Mines and Energy for providing additional analysis of samples from the Sherbrooke Pluton and for valuable discussions relating to geology of the area. Discussions with Mr. S.B. Ballantyne and Mr. B.W. Charbonneau of the Geological Survey of Canada were invaluable as were their critical reviews of this paper.

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