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Résumé de l'article

Une nouvelle cartographie, pétrographie et géochimie, comprenant des analyses Rb/L, indiquent une région plus étendue de granite de muscovite-biotite et moins de diorite d'alaskite qu'on ne le pensait auparavant, dans la région de Halifax-St. Margarets Bay. Les roches de cette région ont été formées par la cristallisation fractionnée de quartz, de plagioclase, de biotite, de zircon, d'ilmenite, d'apatite, et de la monazite. La présence de monazite dans l'assemblage de cristallisation fractionnée est essentielle pour expliquer le fort enrichissement du contenu d'élément terre-rare, et le fractionnement des éléments légers terre rare, qui ont été relevés dans ces roches. Elles ont été affectées par la recristallisation hydrothermale perméable et par des développements locaux de druses pegmatitiques et par un complexe stratifié de veines à bordures greisen. Un complexe de veines stratifiées, à bordures greisen s'est formé dans une partie du granite muscovite-biotite, au sud de Sandwich Point, et même si cette zone montre tous les traits caractéristiques de la minéralisation d'autres parties du batholithe, elle est stérile.

A Re-Appraisal of the Alaskite/Muscovite-Biotite Granite Suite of Halifax County, Nova Scotia

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New mapping, petrography and geochemistry, including REE analyses, indicate that a much larger area of muscovite-biotite granite and fewer alaskite dykes occur in the Halifax - St. Margarets Bay area than was originally thought. The rocks of this area were formed by fractional crystallization of quartz, plagioclase, biotite, zircon, ilmenite, apatite, and monazite. The presence of monazite in the fractional crystallization assemblage is essential to account for the strong depletion of the rare earth element contents and fractionation of the light rare earth elements noted in these rocks. They have been affected by a pervasive hydrothermal recrystallization and by localized development of pegmatitic vugs and a greisen-bordered sheeted vein complex. A greisen-bordered sheeted vein complex has developed in part of the muscovite-biotite granite south of Sandwich Point, and although this zone shows all of the features characteristic of the mineralization elsewhere in the batholith, it is barren.

Une nouvelle cartographie, pétrographie et géochimie, comprenant des analyses REE, indiquent une région plus étendue de granite de muscovite-biotite et moins de diques d'alaskite qu'on ne le pensait auparavant, dans la région de Halifax-St. Margarets Bay. Les roches de cette région ont été formées par la cristallisation fractionnée de quartz, de plagioclase, de biotite, de zircon, d'ilmenite, d'apatite, et de la monazite. La présence de monazite dans l'assemblage de cristallisation fractionnée est essentielle pour expliquer le fort épuisement du contenu d'élément terre-rare, et le fractionnement des éléments légers terre rare, qui ont été relevés dans ces roches. Elles ont été affectées par la recristallisation hydrothermale perméable et par des développements locaux de Druses pegmatitiques et par un complexe stratifié de veines à bordures greisen. Un complexe de veines stratifiées, à bordures greisen s'est formé dans une partie du granite muscovite-biotite, au sud de Sandwich Point, et même si cette zone montre tous les traits caractéristiques de la minéralisation d'autres parties du batholithe, elle est stérile.

INTRODUCTION

The South Mountain Batholith outcrops over much of southwestern Nova Scotia, from just west of Yarmouth to Halifax (Fig. 1). The early workers suggested that it is made up of two suites of granites characterized by different petrography and mode of occurrence (Gossip 1864, p. 49, Honeyman, 1883, p. 60, Malcolm, 1914, pp. 78-79, Wright 1931, p. 384). Zoned plutons of coarse-grained biotite granodiorite, biotite granite and muscovite-biotite granite are cut by large dykes of finer grained alaskite and leucogranite (Cormier and Smith, 1973, Smith 1974,

McKenzie and Clarke, 1975, Smith and Turek, 1976, Smith 1979a,b). These rocks are stanniferous, peraluminous (S-type) granites (Smith and Turek 1975, 1976, McKenzie and Clarke, 1975, Smith 1979a, b, Smith *et al.*, 1982). The magmas from which they formed were derived from a (largely) metasedimentary source area (Smith and Turek, 1976, Smith, 1979a, b, Longstaffe and Smith, 1978, Longstaffe *et al.*, (1980). There is evidence that tin and uranium mineralization is associated with the most highly differentiated rocks of the suite, and especially with a paraintrusive suite of rocks (biotite leucogranites, argillized and sericitized granites, albitized granites, albitites, and

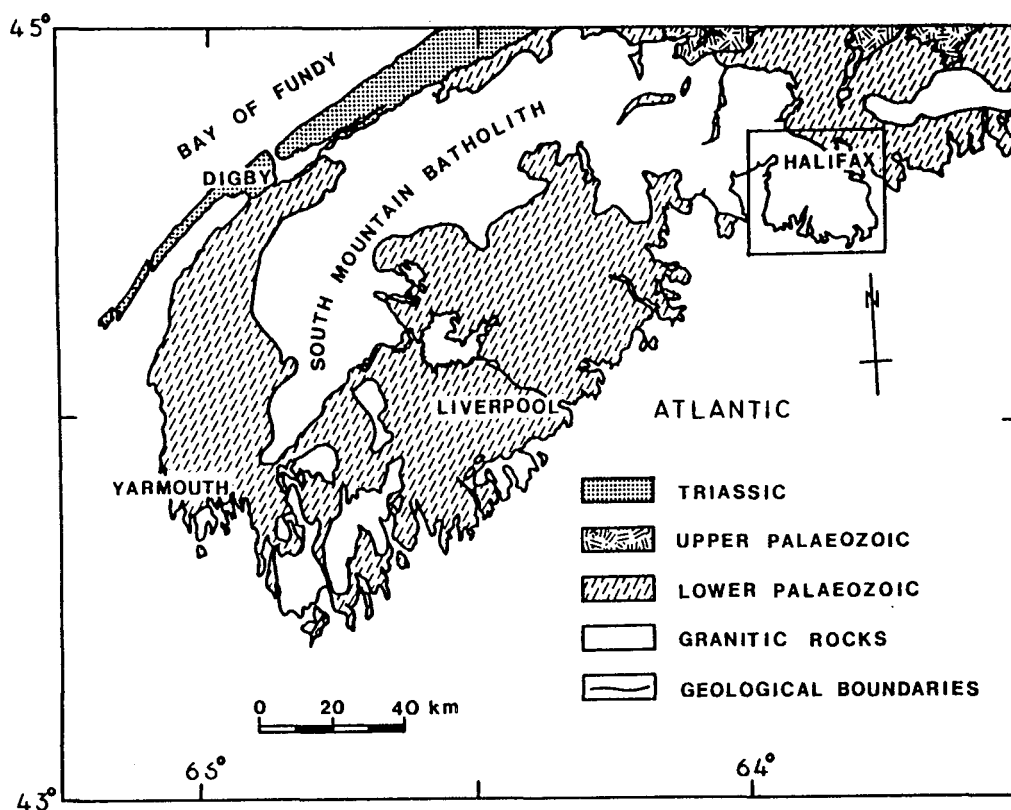


Figure 1 - The geology of southwestern Nova Scotia, showing the outcrop area of the South Mountain Batholith.

greisen) (Smith and Turek, 1976, Chatterjee and Muecke 1982, Smith et al., 1982).

The field relationships have generally been confirmed by geochronological studies (Fairburn, et al., 1960, 1964, Lowdon, 1960, Lowdon, et al., 1963, Cormier and Smith 1973, Clarke and Halliday, 1980), which also suggest that intrusion took place in a series of episodes extending from the early Devonian into the Carboniferous. The details of the intrusive sequence are still poorly known because the majority of the batholith has not yet been mapped. There may be two separate suites of granites in the batholith, only the later of which produced tin and uranium mineralization (Chatterjee et al., 1983).

The best exposed part of the batholith is in the vicinity of Halifax, where a complete suite of the granitic rocks, and paraintrusive rocks

are present. Geochemical, geochronological, and stable isotope studies have already been carried out on some of these rocks (Cormier and Smith, 1973; Smith, 1974, 1975, 1979a, b; Smith and Turek, 1976; Longstaffe et al., 1980; Smith et al., 1982). In this study new field and petrographic observations, together with new geochemical data including rare-earth elements (REE) are used to clarify the evolution of the granitic rocks and the paraintrusive suite in this area.

GEOLOGICAL SETTING

The South Mountain Batholith is intruded into a conformable pile of lower Paleozoic metasedimentary and metavolcanic rocks at least 12 km thick (Taylor and Schiller, 1966). The stratigraphic relationships indicate that intrusion, crystallization, uplift and erosion of the batholith took place between Emsian and Tournaisian (?) times (Clarke and Halliday, 1980;

Chatterjee and Muecke, 1982). The available geochronological data confirm that the emplacement of the granites took place during this time interval. The ages cluster around 370-380 Ma (Reynolds *et al.*, 1980) and range from 395-336 Ma (Cormier and Smith, 1973, recalculated by Keppie and Smith, 1978, using decay constants and isotopic abundances after Steiger and Jager, 1977).

GRANITIC ROCKS OF THE HALIFAX - ST. MARGARETS BAY AREA

a) Mineralogy and Petrography

The initial mapping of this area was carried out in detail on the well exposed, eastern side of the peninsula (Smith, 1974). The conclusions drawn from this work were used to interpret the reconnaissance mapping of the poorly exposed, western half of the peninsula (Smith, 1974, Fig. 1). It was suggested that a zoned pluton, comprising biotite-granodiorite, porphyritic biotite-granite, and muscovite-biotite granite occupied the whole peninsula and was cut by five large dykes of alaskite, four of which occur in the western half of the area.

Recent mapping, combined with airborne gamma ray spectrometric patterns (Ford, 1982), and supported by petrographic and geochemical data, has led to a complete revision of the distribution of the rock types in the western half of the peninsula (Fig. 2). The interpretation of the relationships between the rock types remains unchanged. Most of this area is underlain by a leucocratic, even-grained to sparsely porphyritic, muscovite-biotite granite. It is surrounded by a comparatively narrow zone of porphyritic biotite granite to the north and south and a much wider zone. The porphyritic biotite granite grades into biotite granodiorite to the north and south (Fig. 2). The boundary between the muscovite-biotite granite and the porphyritic biotite granite is only exposed near Halifax where the two

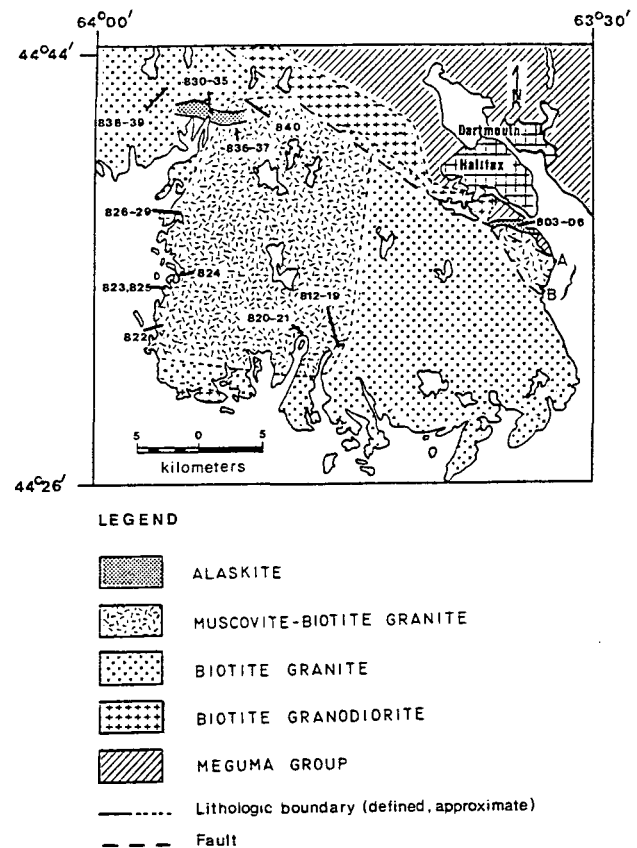


Figure 2 - Geological map of the area between Halifax and St. Margarets Bay, showing sample locations NS 803-806 Ferguson Cove, 812-821 Shad Bay, 822-825 Hacketts Cove, 826-829 Seabright, 830-840 Upper Tantallon. A - Sandwich Point, B - Herring Cove.

rocks appear to grade into each other (Smith 1974, p. 651). Elsewhere the boundary on the map is approximate. This gradation is confirmed by the variation in the proportions of the principal minerals and accessories present in the rock. There is a systematic decrease in quartz, plagioclase, and biotite and increase in potash-feldspar from the granodiorite to the muscovite-biotite granite (Table 1). Two large porphyritic alaskite dykes occur, one at the north eastern edge of the intrusion and another in the northwest (Fig. 2, Table 1). This pattern of rock distribution is well established through much of the South Mountain Batholith (Smith, 1974, 1979a, b; McKenzie and Clarke, 1975).

New samples were collected from

Table 1

Modal mineralogy of the new rock samples from the area between Halifax and St. Margarets Bay and Mean compositions of the principal rock types determined by Cormier and Smith (1974). A = Alaskite, MBGr = Muscovite-biotite granite

	Sample	Qu%	Pl%	K-Sp%	Bio%	Chl%	Musc%	Acc%	Rock Type
Ferguson Cove	803	35.2	11.1	47.8	0.1	3.1	2.0	0.6	A
	804	35.7	12.6	43.4	0.2	2.7	5.3	-	"
	805	47.7	17.0	26.5	0.1	3.4	5.2	0.1	"
	806	48.1	15.1	22.0	0.3	2.0	12.5	0.1	"
Shad Bay	812	46.8	17.2	23.9	5.2	1.7	4.9	0.1	MBGr
	813	34.6	17.2	39.0	2.7	0.9	5.5	-	"
	814	34.3	18.8	39.9	3.4	0.5	3.1	-	"
	815	39.4	14.8	35.7	7.3	1.5	1.3	-	"
	816	53.7	15.7	22.2	5.8	0.7	2.0	-	"
	817	41.4	27.4	20.4	6.1	1.4	3.3	-	"
	818	29.3	30.6	26.6	6.6	3.2	3.7	-	"
	819	44.3	28.7	16.4	5.1	1.9	3.5	-	"
	820	25.2	26.3	39.8	3.2	2.5	3.0	-	"
	821	36.5	24.4	28.8	4.3	1.9	4.0	-	"
Hacketts Cove	822	35.5	28.1	28.4	0.4	2.9	4.7	-	MBGr
	823	41.3	23.3	25.6	1.9	1.6	6.3	-	"
	824	39.8	22.7	28.4	2.2	1.3	5.6	-	"
	825	34.1	23.6	34.6	1.0	2.0	4.5	0.1	"
Seabright	826	37.2	34.1	19.4	5.6	1.1	2.6	-	MBGr
	827	41.3	24.5	27.2	1.9	0.6	4.6	-	"
	828	35.3	33.5	19.7	5.8	0.9	4.7	-	"
	829	25.6	29.3	38.2	3.0	1.5	2.5	-	"
Upper Tantalion	830	43.7	22.0	25.4	1.3	0.9	6.6	-	A
	831	38.6	20.1	31.5	0.1	1.7	7.9	-	"
	832	34.9	22.3	36.3	0.3	1.2	4.9	-	"
	833	34.0	22.9	34.8	0.9	0.6	6.8	-	"
	834	37.1	20.7	32.7	2.2	-	7.4	-	"
	835	40.0	19.5	29.6	0.6	0.9	9.3	-	"
	836	37.7	23.8	27.3	4.0	0.8	6.3	0.1	MBGr
	837	36.1	26.0	29.1	1.0	1.7	6.1	-	"
	838	34.7	22.6	37.0	2.2	0.2	3.2	-	A
	839	36.9	19.1	39.5	1.5	0.6	2.5	-	"
	840	27.7	28.2	34.5	2.5	0.5	6.6	-	MBGr
Means ^a									
Biotite									
Granodiorite		34.4	34.5	14.1	16.0	0.4	0.4	0.4	
Biotite									
Granite		28.6	29.6	34.0	3.0	2.0	2.6	0.3	
2-Mica									
Granite ^b		34.7	24.9	30.8	3.6	1.4	4.5	-	
Alaskite ^b		39.8	22.9	28.1	0.9	1.3	7.0	0.1	

^a From Cormier and Smith, 1979, Table 1

^b Includes Samples from this Study

Ferguson Cove (NS 803-806), Shad Bay (NS 812-21), Hacketts Cove (NS 822-825), Seabright (NS 826-829), and Upper Tantallon (NS 830-840) (Fig. 2) and used to establish the nature of the rocks exposed at each locality. The petrography and modal mineralogy (Table 1) of the Ferguson Cove and Upper Tantallon rocks shows that they belong to the alaskite dyke suite. Those of the other three areas belong to the muscovite-biotite granite suite exposed at Indian Harbour and Ferguson Cove (Table 1). Details of these suites have already been given in several places (Cormier and Smith, 1973; Smith, 1974, 1975, 1979) and only tabulated data and important similarities and differences are noted here.

The mineralogy of the alaskites and muscovite-biotite granites is very similar, the muscovite-biotite granite is made up principally of quartz, plagioclase (An_{7-15}) potash feldspar, biotite and muscovite, and the alaskites contain phenocrysts of quartz, plagioclase (An_{7-12}), and biotite set in an anhedral matrix of quartz, albite, potash feldspar, and muscovite. Micrographic intergrowths of quartz and alkali feldspar occur in the matrix of the Upper Tantallon dyke but not in the dyke at Ferguson Cove.

Accessory minerals in both suites include apatite, ilmenite (partially or completely replaced by rutile), zircon, monazite, and uraninite, all of which are included in or aggregated with the biotite, and are more abundant in the muscovite-biotite granite. In addition, pinite after cordierite is abundant in the muscovite-biotite granite and rare in the alaskite, only occurring in the dyke exposed at Upper Tantallon. Minor andalusite occurs in a few of the samples from each rock suite. The same accessory minerals (except andalusite) occur in greater abundance in the biotite granodiorite and the porphyritic biotite granite.

The gradational relationships noted in the field and in mineralogy between

the biotite granodiorite, porphyritic biotite granites, and the muscovite-biotite granites of the Halifax - St. Margarets Bay area show that they are all genetically related. The spatial and temporal association and mineralogical similarities shown by the alaskites to these other rocks suggest that they too belong to the suite.

The muscovite-biotite granite and alaskite suites show the same wide variety of pervasive alteration effects which are patchily developed throughout both rock types. These effects are noted to a lesser degree in the biotite granodiorite and biotite granite. Plagioclase crystals and phenocrysts have saussuritized cores and show minor sericitic alteration. The potash feldspars have been made turbid by incipient kaolinization, most obvious in the alaskites. Large crystals of patch perthite replace plagioclase phenocrysts in the alaskites. Muscovite occurs as large ragged flakes, surrounding and penetrating all the other major minerals, and much of it is considered secondary. All of the biotite is partially or completely replaced by chlorite.

Members of the paraintrusive suite are very well developed in the muscovite-biotite granite in the area extending from Sanwich Point to Herring Cove (section A to B on Fig. 2). These include lenticular miarolitic pegmatites, aplite/pegmatite dykes and a greisen-bordered sheeted quartz-vein complex. The greisens comprise principally quartz-sericite-pyrite-arsenopyrite with very rare sphalerite, and are notably different in composition to the precursor muscovite-biotite granite. They have been studied (Smith *et al.*, 1982) and are interpreted as resulting from the effects of the localized release of large quantities of hydrothermal fluids which have largely escaped from the system. This contrasts with the pervasive but patchy alteration described above which produces mainly hydrous (secondary) minerals in the granitic rocks, and which is most

pronounced in the muscovite-biotite granite and alaskite. The pervasive alteration results from subsolidus recrystallization, promoted by the release of small quantities of aqueous fluid at the end stages of crystallization. The absence of associated quartz veining over most of the rock outcrops suggests that in contrast to the greisenization, no material escaped from the system during the pervasive recrystallization, but the elements were redistributed during the recrystallization (Smith *et al.*, 1982).

Thus, the mineralogy and field relationships of these rocks suggest that three separate processes were involved in their evolution. The major rock types and their distribution were controlled by magmatic (crystal-melt) processes. The rocks produced were affected by a pervasive hydrothermal event followed by localized intense hydrothermal veining and alteration. These events should be reflected in the geochemistry of the rocks.

b) Geochemistry

Thirty-one representative samples of the alaskite (12) and muscovite-biotite granite (19) were analyzed for their major and trace element contents by X-ray fluorescence techniques. The sample locations are given on Figure 2. Major elements were analyzed on fused glass discs and trace elements were determined on rock powder pellets. Full details of the methods and their precision are given elsewhere (Peck, 1984).

Table 2 summarizes the results of these analyses and also compares the new data with previous work on this pluton (Smith 1979b). The mean contents of TiO_2 , MnO , MgO , CaO , Al_2O_3 , and Fe_2O_3 , P_2O_5 , Ba, and Zr decrease and K_2O and Rb increase systematically (Figs. 3 and 4). Smith (1974) reported a break in the systematic variation of Na_2O , Rb, Ba, K/Rb, K/Ba, and Ca/Sr ratios between the muscovite-biotite granite and alaskites. When the

additional data is plotted the break is seen to be more apparent than real (Figs. 3 and 4), but the distribution of Na_2O , Rb, and Ba is more irregular than that of other elements.

The systematic variations in whole rock geochemistry can be readily accounted for by fractional crystallization of quartz, plagioclase, and biotite (Smith, 1974, 1979a, b; McKenzie and Clarke, 1975). However, it is not possible to model the evolution of the rocks mathematically, using the measured Rb, Ba, and Sr contents of feldspar and micas separated from them (Smith *et al.*, 1982). This observation together with the increase in concentration dispersion shown by K_2O suggests that the distribution of these elements is not controlled by crystal melt equilibria but by some other process. Since the whole rock chemistry is unaffected it is suggested that the five elements have been redistributed by the pervasive subsolidus recrystallization described above.

c) Rare-earth element distribution

The concentrations and distributions of the rare-earth elements (REE) are commonly used in igneous petrogenesis to define the processes leading to the formation of the magmas and to trace the evolution of the magma (Albuquerque, 1977; Muecke and Clarke, 1981; Mahood and Hildreth, 1983; Mittlefeldt and Miller, 1983). These elements may also be used to define the nature of the hydrothermal processes affecting granitic rocks (Taylor and Fryer, 1982).

The concentrations of 6 rare earth elements in fifteen rock samples from the granitic and paraintrusive rock suite of the Halifax area were measured by INAA techniques. The work was carried out at Michigan State University. The relative error and normalization concentrations, from Yoder (1976) are given in Table 3.

Two very different groups of REE

Table 2.

Major element and trace element geochemistry of the muscovite-biotite granites and alaskites from the Halifax - St. Margarets Bay area.

Sample No. NS	FERGUSON COVE							SHAD BAY										HACKETTS COVE				
	211	216	217	803	804	805	806	812	813	814	815	816	817	818	819	820	821	822	823	824	825	
SiO ₂	74.39	76.82	75.99	75.80	76.43	75.81	78.13		74.14	75.33	73.13	74.03	72.31	72.64	73.49	74.92	71.74	71.96	72.41	71.97	75.28	72.68
TiO ₂	0.21	0.14	0.09	0.16	0.17	0.17	0.18	0.31	0.20	0.34	0.24	0.32	0.30	0.32	0.26	0.34	0.31	0.18	0.18	0.15	0.18	
Al ₂ O ₃	14.08	12.99	13.46	12.71	12.83	12.86	11.39	13.44	13.37	13.41	13.32	13.72	13.69	13.46	12.96	13.65	13.39	14.12	14.10	13.74	14.58	
Fe ₂ O ₃	1.66	1.66	1.23	1.41	1.24	1.82	1.69	2.38	1.76	2.44	1.75	2.28	2.27	2.40	1.88	2.44	2.34	1.47	1.54	1.52	1.51	
MnO	0.06	0.07	0.03	0.04	0.03	0.05	0.06	0.05	0.05	0.04	0.04	0.05	0.04	0.05	0.05	0.04	0.05	0.04	0.04	0.04	0.03	
MgO	0.51	0.49	0.36	0.16	0.18	0.35	0.29	0.44	0.25	0.46	0.11	0.42	0.31	0.54	0.36	0.45	0.34	0.70	0.24	0.04	0.05	
CaO	0.80	0.60	0.36	0.39	0.39	0.56	0.46	0.74	0.55	0.87	0.63	0.96	0.85	0.85	0.82	0.85	0.70	0.65	0.62	0.47	0.65	
Na ₂ O	3.55	2.54	3.37	3.09	3.36	3.39	2.21	3.53	3.69	3.29	3.67	3.68	3.36	3.44	3.37	3.49	3.52	3.49	3.54	3.44	3.99	
K ₂ O	4.44	4.34	4.62	4.59	4.33	4.61	4.10	4.48	4.28	4.33	4.47	4.48	4.10	3.99	4.08	4.58	4.46	4.43	4.48	4.07	4.66	
P ₂ O ₅	0.24	0.18	0.18	0.17	0.18	0.18	0.17	0.25	0.23	0.23	0.21	0.22	0.26	0.26	0.25	0.23	0.22	0.32	0.30	0.26	0.33	
LOI	0.71	0.73	0.89	0.81	0.95	0.78	0.64	0.50	0.89	0.81	1.02	0.77	1.12	1.08	0.93	0.89	1.04	1.13	1.08	1.06	1.08	
V				11	11	10	11	21	12	16	26	27	23	24	20	27	24	11	13	9	13	
Co				2	-	1	1	2	1	3	1	4	3	4	2	5	3	1	2	1	1	
Ni				2	2	2	3	3	-	1	4	1	1	3	3	2	2	2	3	3	2	
Cu	6	5	5	4	2	-	4	4	1	-	4	-	1	2	3	34	23	13	5	8	5	
Zn	49	39	27	-	-	21	12	26	13	6	35	35	37	34	22	27	36	5	17	7	9	
Rb	254	254	253	232	228	262	234	267	300	250	258	249	241	235	224	240	253	218	214	464	215	
Sr				18	16	25	21	56	20	27	62	69	59	60	57	76	66	52	55	24	57	
Y				23	18	13	19	17	12	13	17	17	16	17	14	17	17	12	8	3	9	
Zr				71	72	63	64	112	63	77	130	124	106	120	93	127	115	56	59	43	59	
Nb				9	10	8	9	14	13	12	15	14	13	15	11	13	13	10	11	15	12	
Sn	10	20	15	1	2	3	5	-	4	2	3	-	3	3	2	3	4	6	6	-	6	
Ba	276	276	108	74	67	78	58	184	35	63	240	276	201	204	206	279	244	269	270	43	286	

For sample location and lithology, see Appendix 1

Table 2 (cont'd).

Sample No. NS	SEABRIGHT				UPPER TANTALLON											Averages†			
	826	827	828	829	830	831	832	833	834	835	836	837	838	838	840	B.Gd	B.Gr	MBGr.*	Alaskite*
SiO ₂	75.28	75.47	73.74	75.02	74.71	75.05	74.54	75.54	74.81	75.58	74.90	76.60	75.67	75.43	74.69	69.27	73.09	74.00	75.55
TiO ₂	0.16	0.14	0.16	0.13	0.11	0.11	0.11	0.12	0.11	0.10	0.17	0.12	0.11	0.13	0.23	0.64	0.32	0.21	0.13
Al ₂ O ₃	13.16	13.44	13.39	13.76	13.90	13.78	13.56	13.70	13.58	14.02	13.09	13.70	13.31	12.95	13.57	15.52	14.33	13.59	13.37
Fe ₂ O ₃	1.81	1.43	1.84	1.43	1.44	1.62	1.25	1.31	1.33	1.03	1.78	1.57	1.21	1.40	1.94	3.50	2.28	1.82	1.70
MnO	0.05	0.04	0.06	0.05	0.04	0.04	0.05	0.05	0.04	0.03	0.06	0.04	0.05	0.04	0.05	0.10	0.07	0.05	0.04
MgO	0.07	0.15	0.09	0.08	0.05	0.18	0.25	0.06	0.02	0.03	0.14	0.06	0.13	0.08	0.33	1.22	0.69	0.25	0.28
CaO	0.48	0.56	0.61	0.55	0.44	0.43	0.44	0.42	0.40	0.42	0.78	0.39	0.40	0.40	0.58	2.18	1.17	0.68	0.50
Na ₂ O	3.54	3.41	3.59	3.42	3.68	3.72	3.40	3.45	3.58	3.60	3.14	3.48	3.62	3.53	3.54	3.00	3.21	3.45	3.37
K ₂ O	4.25	4.40	4.26	4.43	4.08	4.12	4.13	4.17	4.32	3.79	4.22	4.32	4.53	4.76	4.35	4.12	4.55	4.47	4.36
P ₂ O ₅	0.20	0.20	0.27	0.20	0.24	0.24	0.23	0.21	0.22	0.20	0.20	0.22	0.18	0.14	0.24	0.22	0.22	0.24	0.20
LOI	0.82	0.88	0.90	0.87	1.05	0.99	1.01	1.01	1.10	1.20	1.08	1.13	0.91	0.83	1.11	0.39	0.50	0.89	0.82
V	10	9	11	9	7	9	6	6	9	6	12	7	6	7	19			16	8
Co	2	1	2	2	-	-	2	-	3	-	3	2	2	-	2	23	22	2	1
Ni	1	1	1	-	-	-	3	-	2	-	-	3	-	-	2	25	23	2	1
Cu	2	3	7	-	1	3	9	1	13	12	3	6	2	33	-	10	9	6	7
Zn	23	8	25	10	-	-	11	12	-	-	28	-	-	16	13	66	52	10	17
Rb	384	328	353	342	431	413	424	417	417	405	320	324	311	279	327	159	216	281	323
Sr	23	26	34	39	7	7	7	8	7	5	23	12	8	15	38	156	84	43	18
Y	13	13	7	10	7	7	7	7	5	3	14	14	10	14	15	-	-	13	11
Zr	52	48	53	46	41	38	37	36	32	29	59	48	33	36	80	-	-	80	46
Nb	13	9	10	9	12	13	10	11	11	8	12	12	9	9	13	-	-	12	10
Sn	7	9	5	8	14	12	12	12	10	9	9	7	9	7	7	6	-	6	11
Ba	52	82	72	53	5	6	3	8	6	-	58	34	2	10	116	731	389	161	65

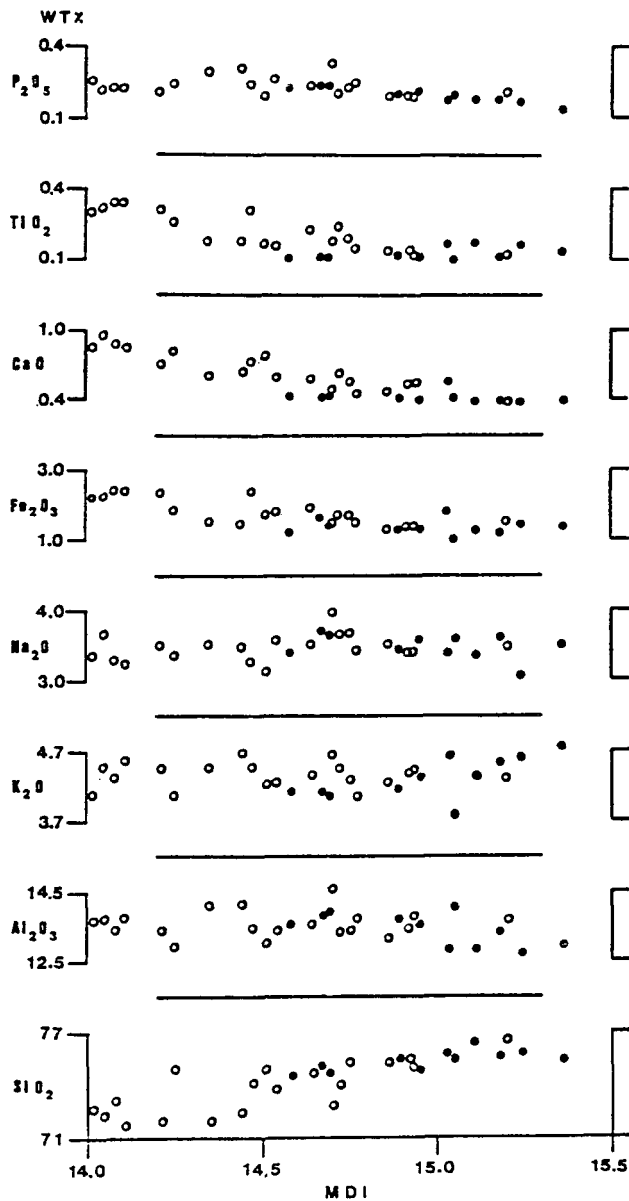


Figure 3 - Major element chemistry of the muscovite-biotite granites (o) and alaskites (●) of the Halifax - St. Margarets Bay area plotted against the Modified Larsen Differentiation Index ($MDI = 1/3 Si + K - (Ca + Mg)$).

pattern are noted. The first is typical of the biotite-granodiorite, biotite-granite, muscovite-biotite granite and alaskite suite, and is used to model the magmatic processes qualitatively. The second is typical of the paraintrusive suite and is used to define the nature of the hydrothermal processes affecting these rocks. Samples selected to illustrate

the magmatic processes show minimum effects of pervasive alteration. No REE data is available from mineral separates so it is not possible to define the changes produced by the pervasive alteration.

The grandiorite, porphyritic biotite granite, muscovite-biotite granite and alaskite show broadly similar patterns, with decreasing ΣREE , La/Sm ratios,

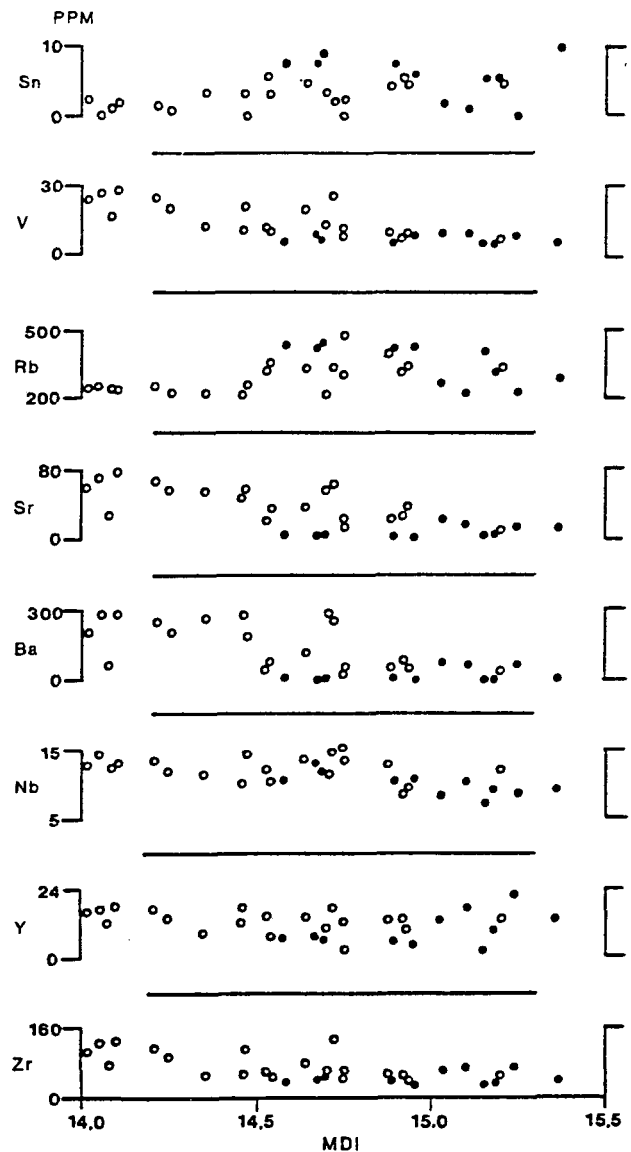


Figure 4 - Trace element chemistry of the muscovite-biotite granites (o) and alaskites (●) of the Halifax - St. Margarets Bay area, plotted against the Modified Larsen Differentiation Index.

Table 3.

Rare earth element contents of the principal granitoid rock types including the paraintrusive suite, from the Halifax - St. Margarets Bay area. Normalization concentrations from figs. 5 and 6 from Yoder (1976). Relative error calculated from:

$$RE = \frac{(\text{standard concentration}) - (\text{measured concentration})}{\text{standard concentration}} \times 100$$

RE for La = 10%, for Ce = 6%, for Sm = 5%, for Tb = 20%, for Lu = 20%, Yb could not be determined because of Ta interference

	<u>Biotite Granodiorite</u>		<u>Biotite Granite</u>		
	NS 231	NS 209	NS 213	NS 406	NS 219
	ppm	ppm	ppm	ppm	ppm
La	29	29	22	20	11
Ce	62	58	42	40	22
Sm	6.9	7.3	5.3	5.7	4.0
Eu	1.35	1.29	0.76	0.59	0.24
Tb	0.94	1.00	0.63	0.79	0.43
Lu	0.55	0.53	0.40	0.34	0.37
(La/sm)N	2.3	2.2	2.3	1.9	1.5
(Tb/Lu)N	1.2	1.4	1.1	1.7	0.8

	<u>Muscovite-biotite Granite</u>		<u>Alaskite/Leucogranite</u>		<u>Pegmatite</u>
	NS 210	NS 457	NS 216	NS 217	HX 28
	ppm	ppm	ppm	ppm	ppm
La	11	9	12	8	8
Ce	21	15	20	14	18
Sm	4.2	3.2	3.8	3.1	6.2
Eu	0.37	0.20	0.30	0.20	0.27
Tb	0.57	0.58	0.57	0.49	0.73
Lu	0.30	0.38	0.35	0.31	0.44
(La/sm)N	1.4	1.5	1.7	1.4	0.7
(Tb/Lu)N	1.4	1.1	1.2	1.1	1.2

	<u>Pegmatite</u>		<u>Greisen</u>		
	HX 114		HX 108	HX 124	HX 105
	ppm		ppm	ppm	ppm
La	7		13	10	4
Ce	9		25	19	8
Sm	2.7		4.3	3.8	2.3
Eu	0.44		0.41	0.27	0.34
Tb	0.31		0.53	0.46	0.32
Lu	0.25		0.35	0.32	0.23
(La/sm)N	1.4		1.7	1.4	0.95
(Tb/Lu)N	0.9		1.1	1.0	1.0

and an increasingly large negative Eu anomaly (Table 3, Fig. 5) $\Sigma 6\text{REE}$ decreases from ~ 100 ppm in the granodiorites to ~ 60 ppm in the porphyritic biotite granite, and ~ 35 ppm in the muscovite-biotite granite and the alaskite. The La/Sm ratios decrease from 2.3, through 1.9 to ~ 1.4

in these rocks. The heavy rare-earth elements (HREE) in these rocks are relatively unfractionated (Tb/Lu 1.2) and show a decrease in concentration through the range of rocks from ~ 20 to $\sim 10 \times$ chondrite (Table 3). Zircon, apatite, and monazite, are all included in, or aggregated with, the biotite.

These minerals must also be involved with the biotite in the fractionation process. The removal of ilmenite and zircon would lead to the observed depletion of TiO_2 and Zr. In addition REE preferentially enter both zircon (HREE) and apatite (LREE and HREE) (Hanson, 1978). However, these minerals are present in proportions on the order of 0.1% and the distribution coefficients are not large enough to cause effective depletion or fractionation of these elements. If apatite was the mineral controlling the REE patterns they should contain a positive Eu anomaly (Hanson, 1978) not a negative anomaly as noted.

Mittlefeldt and Miller (1983) have shown that up to 75% of the REE in felsic rocks may be present in monazite and that the removal of minute quantities of the mineral are sufficient to decrease LREE abundances by 10 or 20x. The LREE become increasingly strongly fractionated into monazite as the melt becomes more felsic (Miller and Mittlefeldt, 1982). In the Halifax suite the LREE are fractionated and decrease in abundance by $\sim 3\times$. The X-Ray spectrometry maps of the peninsula (Ford, 1982) show that the Th content decreases and the U content increases, and U/Th ratio generally increases, systematically as

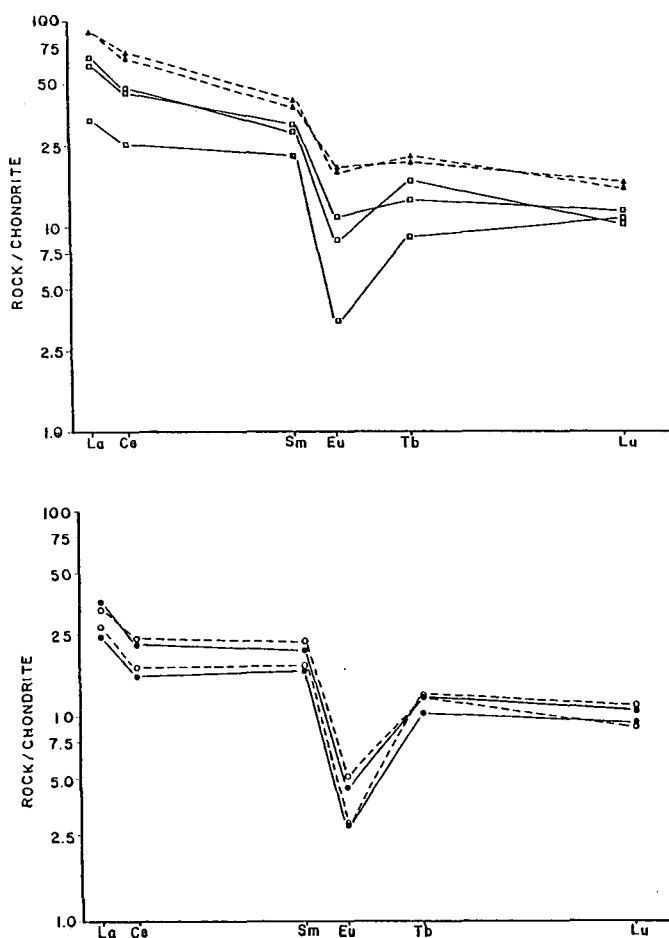


Figure 5 - Plot of chondrite normalized rare earth element abundances of selected granitic rocks from the Halifax - St. Margarets Bay area. Normalization concentrations from Yoder (1976). La = 0.330 ppm, Ce = 0.88 ppm, Sm = 0.181 ppm, Eu = 0.069 ppm, Tb = 0.047 ppm, Lu = 0.034 ppm. (a) Symbols. \blacktriangle Biotite granodiorite, \square Biotite granite. (b) Symbols. \bullet Muscovite-biotite granite, \blacklozenge Alaskite.

the rocks vary from biotite granodiorite, through biotite granite to muscovite-biotite granite and alaskite.

Monazite contains large quantities of Th and much less U and its early removal during fractional crystallization would account for the major trends described above, i.e., the depletion of Th, enrichment in U and increase in the U/Th ratio. These observations suggest that it is monazite which causes the strong depletion and fractionation of the LREE elements and that the depletion effects become greater as the melt becomes more felsic.

Thus, the removal of zircon, ilmenite, apatite, and monazite along with plagioclase, biotite, and quartz provides an adequate qualitative model for the evolution of this rock series by fractional crystallization. It is not possible to model the process quantitatively in the absence of precisely determined distribution coefficients for monazite.

The muscovite-biotite granite extending from Sandwich Point to the south (section A-B, Fig. 2), which is strongly greisenized, is exceptional in that it contains high Th and relatively low U. In addition, the pattern of distribution of the REE changes abruptly in the pegmatites and greisens, marking the change in the processes controlling the evolution of the rocks. The pegmatites crystallized in miarolitic vugs within the muscovite-biotite granite in the presence of an aqueous phase (Burnham, 1979). The greisens formed by the phyllic alteration of the muscovite-biotite granite in narrow zones adjacent to large (up to 20 cm) quartz veins of the sheeted complex exposed at Sandwich Point (section A-B, Fig. 2).

One of the pegmatites (HX28) and two of the greisens (HX108, HX124) show REE patterns very similar to the muscovite-biotite granite, confirming their relationship to the granite. The

remaining pegmatite and greisens show similar REE patterns which differ from the igneous patterns described above. The pegmatite (HX114) shows a greater depletion in the overall concentration of the REE, than the igneous rocks, especially La and Ce. The greisens (HX105, HX125) also show the overall depletion of the REE and especially a relative fractionation of La/Sm (Fig. 6). The negative Eu anomalies shown by these rocks are considered to be the result of the removal of plagioclase during fractional crystallization, and were inherited from the precursor muscovite-biotite granite.

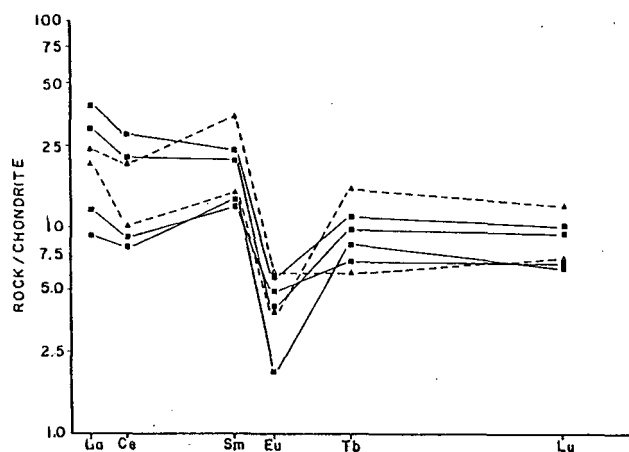


Figure 6 - Plot of chondrite normalized rare earth element abundances of selected paraintrusive rocks from the Sandwich Point - Herring Cove section. Normalization concentrations from Yoder (1976). Symbols. ▲ Pegmatite, ■ Greisen.

The zone of muscovite-biotite granite and alaskite, noted above, trending E-W from Sandwich Point (A, Fig. 2) shows U-Th relationships which differ from those of the typical igneous trend, in particular they show strong Th enrichment (Ford, 1982). This unusual trend coincides in areal distribution with the only extensive occurrence of a greisen-bordered sheeted vein complex and is therefore considered to be related to this hydrothermal phenomenon.

The greisen consists of quartz-sericite-pyrite-arsenopyrite, sphalerite without fluorite or topaz. This mineral assemblage is indicative of a relatively low pH hydrothermal fluid interaction with the precursor rock. The most common low pH hydrothermal fluids are Cl^- , F^- , and CO_3^{2-} bearing. Since carbonate is not one of the minerals found in the hydrothermal assemblage it is not likely to be the dominant anion present in the fluid. Both Cl^- and F^- are capable of complexing with the LREE and removing them, increasingly so as they get lighter (Taylor and Fryer, 1982). In addition F^- , which is known to be comparatively high in these magmas (Smith and Turek, 1976), may complex with the HREE and remove them (Taylor and Fryer, 1982) in the hydrothermal fluid. The pegmatites and greisens are characterized by the depletion in the lightest and heaviest REE (Fig. 5) and Th enrichment, and the hydrothermal fluid producing these patterns is believed to be F-rich.

DISCUSSION

The data given above suggest that at least three processes have been important in the evolution of the granitoid rocks and their associated paraintrusive suite in the Halifax area. These are fractional crystallization which produces the biotite granodiorite, biotite granite, muscovite-biotite granite and alaskite suite, pervasive patchy recrystallization which produces mainly secondary chlorite, muscovite, and potash-feldspar, and localized hydrothermal activity which produces an unmineralized greisen-bordered sheeted vein complex and miarolitic pegmatites. In addition, there are at least two more sets of thin quartz veins which are important locally.

Chatterjee *et al.* (1983) have shown that an earlier suite of "non-specialized" and a later suite of "specialized" (equivalent to the paraintrusive suite of Chatterjee and

Muecke, 1982) granites can be identified in the South Mountain Batholith. The granitic rocks of the Halifax area are initially rich in U and Th and have a U/Th ratio of ~ 1.0 and during fractional crystallization there is depletion in Sr, Ba, Zr (Fig. 4) and the REE (Fig. 5) and enrichment in Rb, Sn, and U (Fig. 4). These changes in trace element contents are typical of the Sn-mineralized suite (Chatterjee *et al.*, 1983). The greisen-bordered sheeted vein complex is developed in the muscovite-biotite granite and is associated with a somewhat more widespread zone of Th enrichment. This enrichment is developed near the margin of the batholith, hence this zone shows all of the features of the highly mineralized Davis Lake and Plymouth Plutons (Chatterjee and Muecke, 1982) and yet lacks mineralization. The late stage alaskite dyke at Upper Tantallon has unusually low K/Rb ratios (average 95) and low Ba content (134 ppm) and hence belongs to the "specialized" suite (Chatterjee *et al.*, 1983, Table 1, Fig. 2). It is patchily hematized and although hematization commonly precedes lode mineralization in Cornwall, is barren of mineralization. This dyke is the end product of fractional crystallization of rocks belonging to the Sn-mineralized suite, as shown above, but shows no evidence of Th enrichment.

Since the Upper Tantallon dyke does not show all of the features associated with known occurrences of Sn-mineralization, it is perhaps not surprising that it is barren of mineralization. However, the lack of mineralization in the Sandwich Point to Herring Cove area, which shows all of the necessary features, does require some explanation.

Many of the trends of geochemical change in these rocks are controlled by fractional crystallization, but the Sn-mineralization, which occurs in greisens, and the associated Th enrichment, are the results of hydrothermal activity (Smith *et al.*,

1982; Chatterjee *et al.*, 1983). The hydrothermal activity has also caused the depletion of the lightest and heaviest REE by leaching. Under these conditions Cu, Mo, Sn and W are also expected to be mobile (Taylor and Fryer, 1982) and may also have been leached from the rocks. Redeposition of the REE and the metals may be caused by changes in pH, fluid/rock ratios and anionic activities caused by the interaction of the magmatic hydrothermal brine with meteoric hydrothermal fluids (Taylor and Fryer, 1982). However, oxygen isotope studies of these granitic rocks have demonstrated that meteoric water was not involved in their evolution (Longstaffe *et al.*, 1980), perhaps because the present level of exposure is too deep. Sn - Cu - W deposits, if ever present, may have formed at higher levels where meteoric water would have been encountered, but have now been eroded away.

CONCLUSIONS

Data is presented above to show that a very large area of leucocratic muscovite-biotite granite is exposed on the western side of the peninsula between Halifax and St. Margarets Bay, and only two large alaskite dykes occur. These siliceous leucocratic rocks are affected by a pervasive hydrothermal alteration which causes redistribution of trace elements but little change in bulk composition. In addition, the muscovite-biotite granite is subjected to very strong localized alteration in a greisen-bordered sheeted quartz vein complex.

REE patterns show that the biotite granodiorite, porphyritic biotite granite, muscovite-biotite granite and alaskite dykes are related by fractional crystallization involving the removal of monazite in addition to quartz, plagioclase, biotite, ilmenite, apatite, and zircon.

The strong localized hydrothermal effects produce a marked change in REE

patterns which suggest that the rock has been leached by a hydrothermal fluid having a low pH (<3.5) and containing F. This fluid may have deposited Sn-W-Cu ores on coming into contact with meteoric water, but if so they are now eroded away.

ACKNOWLEDGEMENTS

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Appendix 1

Sample Location and Lithology

Sample No.-NS	Location	NTS ^a Grid Reference	Rock Type
211 ^b	Ferguson Cove	11D/12-542396	Alaskite
216 ^b	Ferguson Cove	11D/12-555393	Alaskite
217 ^b	Ferguson Cove	11D/12-554394	Alaskite
803	Ferguson Cove	11D/12-553392	Alaskite
804	Ferguson Cove	11D/12-554392	Alaskite
805	Ferguson Cove	11D/12-556391	Alaskite
806	Ferguson Cove	11D/12-557388	Alaskite
812	Shad Bay	11D/12-393305	Muscovite-biotite granite
813	Shad Bay	11D/12-393298	Muscovite-biotite granite
814	Shad Bay	11D/12-392299	Muscovite-biotite granite
815	Shad Bay	11D/12-392301	Muscovite-biotite granite
816	Shad Bay	11D/12-388289	Muscovite-biotite granite
817	Shad Bay	11D/12-394312	Muscovite-biotite granite
818	Shad Bay	11D/12-394310	Muscovite-biotite granite
819	Shad Bay	11D/12-393308	Muscovite-biotite granite
820	Shad Bay	11D/12-371316	Muscovite-biotite granite
821	Shad Bay	11D/12-370315	Muscovite-biotite granite
822	Hacketts Cove	11D/12-256328	Muscovite-biotite granite
823	Hacketts Cove	11D/12-265347	Muscovite-biotite granite
824	Hacketts Cove	11D/12-276362	Muscovite-biotite granite
825	Hacketts Cove	11D/12-266350	Muscovite-biotite granite
826	Seabright	11D/12-267398	Muscovite-biotite granite
827	Seabright	11D/12-267398	Muscovite-biotite granite
828	Seabright	11D/12-267398	Muscovite-biotite granite
829	Seabright	11D/12-264407	Muscovite-biotite granite
830	Upper Tantallon	11D/12-303485	Alaskite
831	Upper Tantallon	11D/12-303485	Alaskite
832	Upper Tantallon	11D/12-303485	Alaskite
833	Upper Tantallon	11D/12-303485	Alaskite
834	Upper Tantallon	11D/12-307482	Alaskite
835	Upper Tantallon	11D/12-307482	Alaskite
836	Upper Tantallon	11D/12-313480	Muscovite-biotite granite
837	Upper Tantallon	11D/12-316481	Muscovite-biotite granite
838	Upper Tantallon	11D/12-280508	Alaskite
839	Upper Tantallon	11D/12-280508	Alaskite
840	Upper Tantallon	11D/12-325499	Muscovite-biotite granite

^aNational Topographic Series

^bSamples from Smith, 1974