PETROLOGY OF THE ZONED, PERALUMINOUS HALIFAX PLUTON, SOUTH-CENTRAL NOVA SCOTIA

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The Halifax Pluton (HP) is a large (approximately 900 km^2), discrete plutonic body which forms the southeastern end of the South Mountain Batholith (SMB). The HP comprises a zoned sequence of rock units into which a second, generally more evolved sequence of rocks was intruded. Rocks of the zoned sequence are predominantly medium- to coarse-grained, have megacrystic textures, are generally monzogranitic in composition (with minor granodiorite) and have biotite (4-15%), muscovite (trace-4%) and cordierite (0->4%) as essential constituents. The second sequence is primarily fine- to medium-grained with highly variable textures (e.g., porphyritic, equigranular, graphic), is generally monzogranitic in composition with minor leucogranite (<2% mafic minerals) and syenogranite, and have muscovite (2-10%), biotite (0-8%) and cordierite (0-2%) as essential minerals. Andalusite, generally absent from the zoned sequence, is commonly present as an accessory phase. Contacts between the two sequences are invariably intrusive.

Petrographic and geochemical evidence suggests that the outer segment of the zoned sequence is normally zoned (i.e., more evolved toward the core). This may be explained by sidewall crystallization in a magma chamber with the removal of plagioclase and biotite (with accessory zircon, monazite, xenotime, apatite and ilmenite). Conversely, the inner portion of the pluton is reversely zoned (i.e., less evolved toward core with an increase in biotite) which cannot be explained by fractional crystallization. Therefore, a model involving vertical stratification in the melt is proposed.

The presence of the zoned arrangement of rock units coupled with high contents of MgO, P_2O_5 and normative corundum, enstatite, hypersthene, apatite and high modal amounts of cordierite compared with the central SMB suggest that the HP evolved as a discrete pluton.

Le pluton de Halifax (PH) est un bâti plutonique distinct de grande taille (environ 900 km^2) qui constitue l'extrémité sud-est du Batholite de South Mountain (BSM). Le PH comprend une série d'unités rocheuses zonée à travers laquelle s'est injectée une seconde série de roches généralement plus évoluée. Les termes de la série zonée montrent surtout un grain intermédiaire à grossier ainsi que des textures mégacristes et ont généralement une composition monzogranitique (avec quelque granodiorite). Les constituants essentiels en sont la biotite (4-15%), la muscovite (trace - 4%) et la cordiérite (0->4%). La seconde série présente un grain surtout fin à intermédiaire, exhibe des textures variées (e.g., porphirique, grenue, graphique) et possède une composition généralement monzogranitique avec quelque leucogranite (minéraux mafiques 2%) et syénogranite. Ses minéraux essentiels sont la muscovite (2-10%), la biotite (0-8%) et la cordiérite (0-2%). Bien que généralement absente de la série zonée, l'andalousite forme communément une phase accessoire. Les contacts entre les deux séries sont invariablement intrusifs.

A la lumière de la pétrographie et la géochimie, le liseré de la série zonée semble zoné normalement (i.e., plus évolué vers le coeur). Ceci peut s'expliquer par la cristallisation des épontes de la chambre magmatique et l'élimination du plagioclase et de la biotite (avec les zircon, monazite, xénotime, apatite et ilménite). Par contre, la portion interne du pluton montre une zonation inverse (i.e., moins évoluée vers le coeur avec une augmentation de la biotite) qui ne peut s'expliquer par la cristallisation fractionnée. On propose donc un modèle nécessitant une stratification verticale du bain.

La présence d'une zonation des unités rocheuses combinée aux contenus élevés de M_gO, P_2O_5, corindon normatif, enstatite, hypersthène, apatite ainsi qu'aux valeurs modales élevées de la cordiérite, par rapport à la portion centrale du BSM suggèrent que le PH a évolué en tant que pluton distinct.

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INTRODUCTION

The South Mountain Batholith (SMB), one of the largest granitoid bodies in the Appalachian Orogen, has received much attention during the past 15 years (Cormier and Smith, 1973; Smith, 1974, 1975, 1979; McKenzie and Clarke, 1975; Chatterjee and Muecke, 1982; Clarke and Muecke, 1985). Recent mapping of the Halifax-St. Margaret's Bay area has revealed some fundamentally important petrological features which had previously received only cursory attention. For example, this work has revealed that this segment of the batholith is composed of a complexly zoned suite of granitoid rocks characterized by their strongly peraluminous nature. The zonation of this intrusion, high contents of P_2O_5, MgO and normative corundum, and the high modal percentage of cordierite compared to published data for the rest of the batholith suggest that the Halifax Pluton (HP) may have evolved as a separate pluton within the SMB.

It is generally agreed, based on whole rock geochemistry and Sr and O isotope studies, that the SMB was generated by partial melting of a crustal protolith (sedimentary?) (Fairbairn **et al.**, 1964; Smith, 1979; Smith **et al.**, 1982; Longstaffe **et al.**, 1980; Clarke and Halliday, 1980; Halliday **et al.**, 1981; Clarke and Muecke, 1985; Smith **et al.**, 1986). There is also general agreement that the most important petrogenetic mechanism in the SMB was fractional crystallization involving biotite (and included accessories) and plagioclase followed by alkali feldspar, quartz and muscovite(?) (Smith, 1974, 1979; McKenzie and Clarke, 1975; Clarke and Muecke, 1985; and Smith **et al.**, 1982, 1986). Post-dating crystallization of the SMB, there

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ensued a period of widespread deuteric alteration that was confined primarily to the two-mica monzogranite units (Smith *et al.*, 1982, 1986). However, there is some debate regarding the overall petrogenetic history of the SMB. McKenzie and Clarke (1975), Charest *et al.* (1985) and Clarke and Muecke (1985) suggested that the entire SMB represents a single co-magmatic suite in which the monzogranitic and leucogranitic rocks were fractionated from, and auto-intruded into, a parental envelope of granodiorite. Conversely, Smith and Turek (1976) and Smith (1979) proposed that each of the monzogranite plutons is unique, with its own independent crystallization history. In this latter scenario the SMB represents a composite batholith formed by the coalescing of small discrete plutons.

The occurrence of both normal and reverse zonation within granitoid plutons has been well documented over the past two decades (e.g., Karner, 1968; Ermanovics, 1970; Halliday *et al.*, 1980; Rice, 1981; Ludington, 1981; Ayuso, 1986; Baker and McBirney, 1986; Bourne and Danis, 1987). Mechanisms which have been evoked to explain the zoning have included thermogravitational diffusion (TGD), convective fractionation, fractional crystallization, multiple intrusion, hybridization, and flow differentiation. Most explanations suggested have involved one or more of the above processes.

The purpose of this paper is to address the petrogenetic history of the HP and propose a model for its formation which is consistent with all known field and chemical evidence.

REGIONAL GEOLOGICAL SETTING

The SMB, located within the Meguma Zone (Fig. 1) of the Appalachian Orogen, is a post-tectonic granitoid complex of Devono-Carboniferous age (circa 370-360 Ma) as determined by Rb-Sr (Fairbairn *et al.*, 1964; Clarke and Halliday, 1980) and K-Ar and Ar-Ar (Reynolds *et al.*, 1981, 1987) dating techniques. The batholith intruded regionally metamorphosed and deformed rocks of the Cambro-Ordovician Meguma Group and the overlying Siluro-Devonian White Rock and Torbrook Formations. The former is comprised of Goldenville Formation metapsammites and overlying Halifax Formation metapelites, whereas the latter comprises mixed volcanic, volcaniclastic and metasedimentary rocks. The SMB is overlain by coarse clastic terrestrial sedimentary rocks of the Horton Group of Tournaissian age (Bell and Blenkinsop, 1960; Howie and Barss, 1975). Thus, the SMB must have been intruded, unroofed and deposited upon within a very short period of time (i.e., 10 Ma).

The SMB is peraluminous and is composed of a series of granodiorite-monzogranite-leucogranite units. Recent mapping in the eastern half of the SMB (MacDonald *et al.*, 1987) indicates that the batholith contains approximately 20 major monzogranitic and granodioritic units (generally 10-100 km^2) and approximately 50 smaller (<1-5 km^2) leucomonzogranites (2-6% total mafics) and leucogranites (<2% total mafics). Contacts between units are both gradational and intrusive, which, when coupled with the large number of units, indicates a complex history of emplacement. There

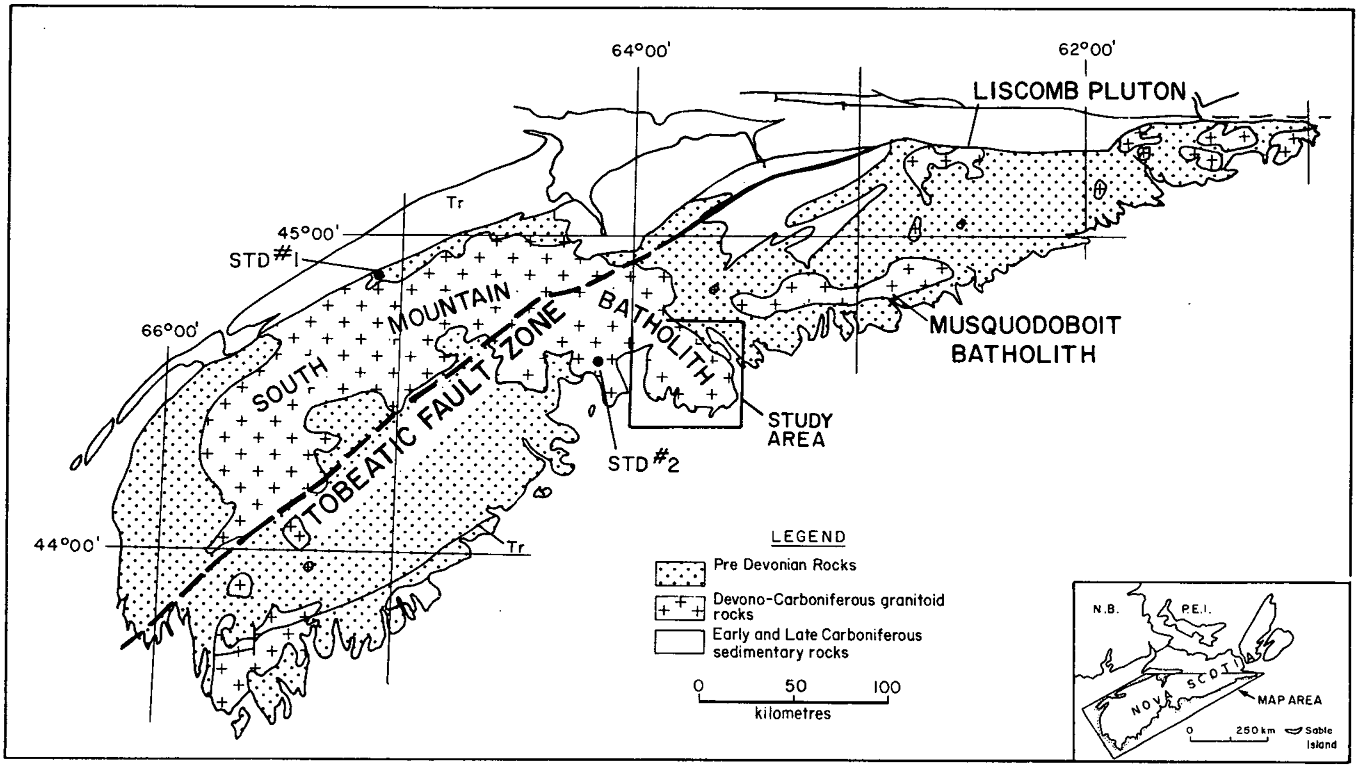

Fig. 1. Location map for the study area, South Mountain Batholith and Musquodoboit Batholith. Note the position of the Tobeatic Fault Zone of Giles (1985). Also note the location of the two bench standards from Table 2.

are discrete plutonic centres within the SMB (e.g., the HP) which have their own crystallization history and unique chemical and mineralogical characteristics (Smith, 1979; MacDonald *et al.*, 1987). This suggests that the SMB did not crystallize from a single parental melt but instead is composite in nature.

The present surface map of the SMB indicates a roughly arcuate shape for the intrusion (Fig. 1). However, in the reconstruction of the Meguma Zone by Giles (1985) the batholith would have been elliptical at the time of emplacement. This reconstruction restores approximately 110 km of sinistral movement along the proposed post-Visean, pre-Triassic Tobeatic Fault Zone.

GEOLOGY OF THE HALIFAX PENINSULA

Field Relationships

Exocontact

The granitic rocks of the HP display sharp, steep (>70°), discordant contacts with the host metasedimentary rocks of the Meguma Group. Very little lit-par-lit injection of dike material into the surrounding metasedimentary rocks is observed.

Hornblende-hornfels facies metamorphism is developed in the metasedimentary rocks around the HP. The hornfels is manifested primarily by porphyroblasts of inclusion-rich cordierite and andalusite (chiastolitic variety) and a general silicification of the rock. Porphyroblasts are generally unoriented, but in a few locations orientation of the minerals in the plane of foliation may indicate syntectonic growth. Porphyroblasts may, therefore, have been growing prior to the actual emplacement of the granites at the present level, with the heat source being the underlying (rising) granites (O'Brien, personal communication, 1987).

For the most part the emplacement of the SMB has not disturbed the regional structural trends within the Meguma Group, thus prompting Smith (1974) and McKenzie and Clarke (1975) to assume a passive stoping emplacement mechanism. However, Faribault (1908) has mapped the "Transverse Anticline" and "Transverse Syncline" in the Hammond's Plains area on the northern flank of the HP. As the name implies, these structures are perpendicular to the regional trend and occur proximal to the granite contact. Similar structures were noted in the Mahone Bay area by O'Brien (personal communication, 1987) where the regional structures appear to be oriented parallel to the granite/metasedimentary rock contact. Thus, while most evidence indicates a passive stoping mechanism of emplacement for the SMB, locally forceful intrusion may have occurred.

Endocontact

The most spectacular example of contact-related phenomena is exposed at Chebucto Head (Fig. 2) in the Harrietsfield monzogranite (unit 4). Features including finely laminated (schlieren-like) bands with cross-cutting (cross-bedding?) relationships and dykes of alkali feldspar megacrysts and xenoliths have been interpreted by Smith (1975) to represent flow sorting and episodic shearing during the emplacement of the SMB. Clarke and Muecke (1980) related the same layering to episodic flowage of magma through narrow orifices which filtered out coarse material. Some of these features have been observed elsewhere in the HP; however, nowhere are they as spectacular as at Chebucto Head. Regardless of which interpretation is chosen, the layering at Chebucto Head presumably reflects the emplacement of a crystal mush which behaved essentially as a fluid.

Other than the above features, there are relatively few endocontact effects in the HP. The granitic rocks are not chilled and there is no significant increase in the abundance of xenoliths next to the metasedimentary rocks.

Xenoliths

Xenoliths in the HP can be classed as: (1) "fresh" Meguma-like xenoliths typically with primary sedimentary features +/- porphyroblasts of andalusite and cordierite; (2) fine-grained equigranular xenoliths commonly exhibiting "gneissic" (?) banding; (3) fine- to medium-grained xenoliths with abundant medium- to coarse-grained megacrysts of quartz, alkali feldspar and plagioclase; and (4) medium- to coarse-grained xenoliths with a "ghost-like" appearance (i.e., granitic rocks with a slightly higher biotite content). Of the above groups, only #1 is conclusively of "Meguma" origin.

Units characterized by the highest xenolith content are those with the highest biotite content, e.g., granodiorite (unit 1) and Sandy Lake/Peggy's Cove monzogranites (units 2a and 2b); all of the above xenolith types can be observed in these units. The more evolved, biotite-poor rocks have fewer xenoliths (mostly types 2-4) even when in direct contact with the Meguma metasedimentary rocks (e.g., unit 6 at Ferguson's Cove).

Distribution of Units and Contact Relationships

Figure 2 shows the results of recent detailed geological mapping in the HP. Rocks of the HP can be divided into two sequences on the basis of texture and field relationships. These are: (A) a zoned sequence of biotite granodiorite (unit 1), biotite monzogranite (units 2a and 2b), muscovite-biotite +/-cordierite leucomonzogranite (unit 3), cordierite-biotite monzogranite (unit 4a), biotite monzogranite (unit 4); and (B) muscovite-biotite leucomonzogranite (units 5a, 5b, 5c, and 6). Previous mapping by Smith (1974) indicated the presence of two separate sequences, and suggested that the HP was zoned; however, the rocks were not as rigorously subdivided as in the present study. In addition, Smith (1974) classified the sequence B rocks as alaskites whereas they commonly contain substantial biotite +/-cordierite (>5%) which is similar to some sequence A rocks (e.g., unit 3).

Sequence A rocks are mostly light grey, fine- to coarse-grained, and megacrystic with varying proportions of alkali feldspar, plagioclase, biotite and cordierite. Appreciable amounts of muscovite (i.e., >1%) are found only in unit 3.

Sequence B rocks, of variable colour and texture, are predominantly porphyritic and equigranular, fine- and medium- grained, predominantly muscovite- and biotite-bearing, and commonly contain andalusite.

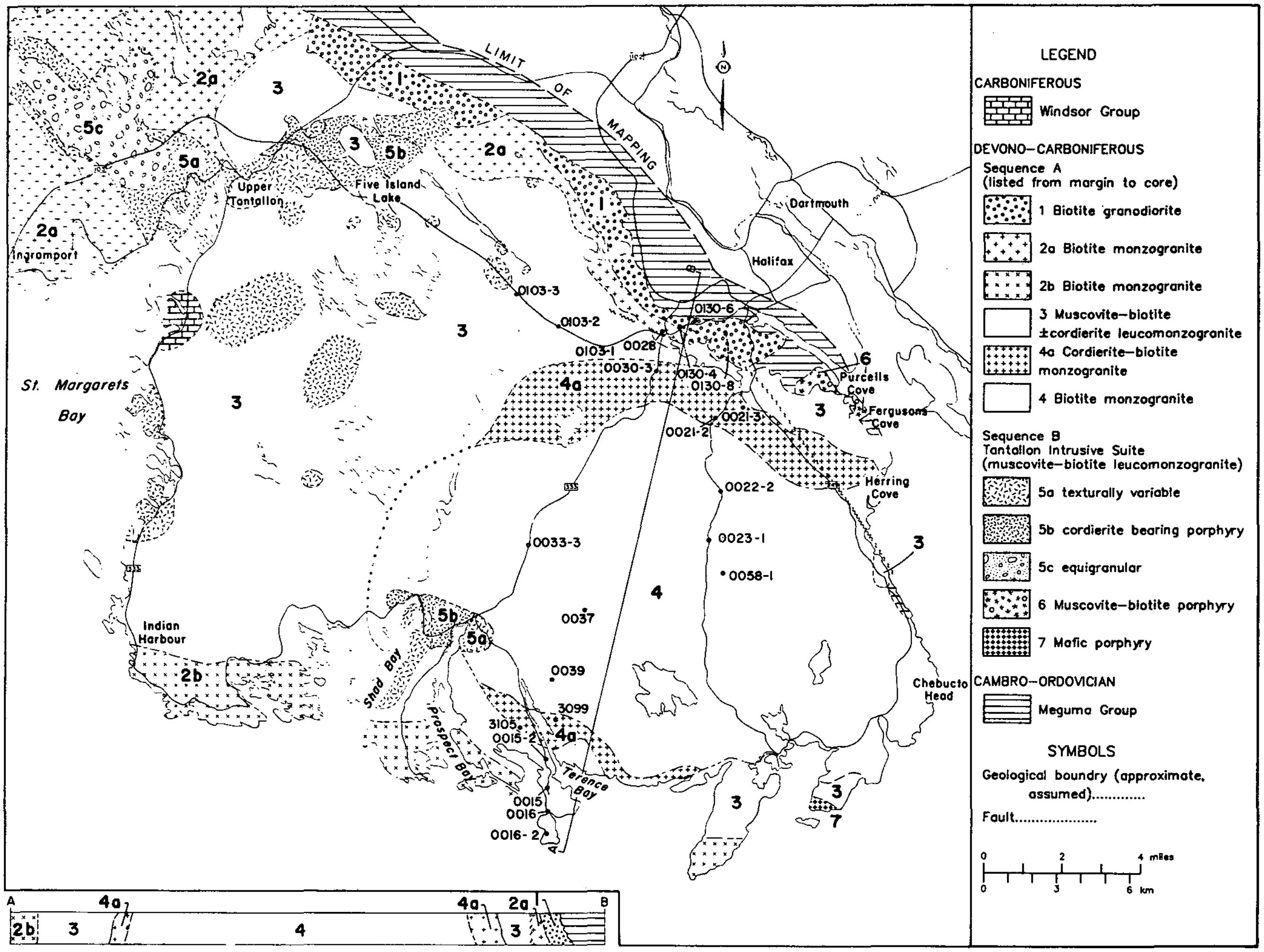

Fig. 2. Geological map of the Halifax Pluton, NTS map sheets 11D/05 and 11D/12.

Contacts between the units in the zoned sequence (A) are rarely exposed, but where observed are predominantly gradational but locally sharp (intrusive). Well exposed gradational contacts were observed between units 1 and 2a, 2b and 3, and 4 and 4a. However, an intrusive contact between units 2b(?) and 3 is exposed near Indian Harbour. An intrusive contact between units 3 and 4 is exposed along the shoreline north of Chebucto Head; no contact features are present (e.g., chilling, xenoliths or dykes), and thus relative age relationships could not be determined. Elsewhere the transition between units 3 and 4 is gradational with unit 3 becoming enriched in biotite and 4a becoming coarser with more alkali feldspar megacrysts with increased proximity to the contact. Similar gradational to sharp intrusive contacts have been observed elsewhere in the SMB and presumably reflect movement of co-magmatic rocks during crystallization.

The boundary between sequences A and B is invariably marked by sharp intrusive contacts (e.g., near Five Island Lake, north of Ingramport and west of Purcell's Cove) with some xenoliths of sequence A occurring in sequence B (e.g., northwest of Upper Tantallon along Highway #103), implying that sequence B represents a later intrusive event.

The contact between units 5a and 5c, although poorly exposed, is inferred to be gradational with unit 5a possibly representing a chilled margin to 5c. The contact between unit 5b and the rest of the Tantallon Intrusive Suite (TIS) is not exposed, but is inferred to be intrusive. The biotite-rich nature of unit 5b suggests that it is the most "primitive" member of TIS.

PETROLOGY

A detailed petrographic study of more than 250 representative thin sections from the HP was conducted and is summarized in Table 1. The zonality of the HP is expressed by subtle petrographic variations which include:

(1) The abundance of alkali feldspar megacrysts. Traversing inward from the margin of the HP alkali feldspar megacrysts increase from <2% in unit 1 to 10-15% in unit 2a (and 2b) and 15- >50% in unit 3. A decrease in the amount of megacrysts is noted near the core of the pluton (i.e., 10-15% in unit 4).

(2) The type of zoning displayed by individual plagioclase crystals varies, with spectacular examples of oscillatory and normal zoning occurring within units 1 and 2, and predominantly normally

Table 1. Petrographic Features of the Halifax Pluton.

UNIT	ROCK TYPE	GRAIN SIZE	TEXTURE	MEGA-CRYSTIC	PHENO-CRYSTS	PLAGIOCLASE				ALKALI FELDSPAR			BIOTITE		MUSCOVITE			CORDIERITE			GARNET			ANDALUSITE
						COMPOSITION	ZONING	MYRMEKITE	ALT	EXSOLUT	MICROCL	ALT	(%)	ALT	(%)	REPL	EUH	(%)	FRESH	ALT	(%)	INCL	CLUST	(%)
1	GDIO	f-m mnr C	MEGA	0 - 1		An_{15-33}	2>1>3	common	0 - 1	1		1	12-15	0 - 1	trace	KP		0 - trace	none	PI				
2a & 2b	MONZ (GDIO)	m - c	MEGA	1 > 2		An_{11-36}	2>1>3 >>0	common	0 - 1	1>>2	trace	1	10->12	0 - 1	trace - <1	KF>>CD	trace	0 - <1	trace	PI>CH >MU	common occurrence trace abundance	x		
4	MONZ	f - c	MEGA (SERI)	1		An_{3-30}	1>2>3 >>0	common	0 - 1 >>2-3	1>2 >>0		1-2	8-10	1(2)	trace - 1 locally 2-3	KF>PL >CD	trace	0 - 1 up to >4 in *DCmgNPa*	trace	PI>CH> MU	trace occurrence and *abundance*		x	
3	MONZ (SYEN)	f - c	MEGA	1 - 2		An_{2-27}	1>0>2	trace	2 - 3	1=2	trace	2	>2->6	1 - 4	1 - 2 locally 3 - 4	KF>CD> PL	common	0 - >4 avg 1-2	none	MU>CH >PI	trace occurrence + abundance		x	
5a,c	MONZ (SYEN)	f,m,c	EQUI PORP MEGA SACH PEGM (SERI) (GRAP)	0 >1	QZ> KF>PL >MU>BI >>CD	An_{1-15}	0>1	none	2 - 3	0>1	common	2-3	>1-4	1 - 4 avg 2-3	1->4	KF>CD >BI	common	common occurrence trace abundance	none	MU>CH >>PI				common occurrence trace - locally 2
5b	MONZ	f-c	PORP	1	KF>QZ >PL>CD	An_{16-28}* An_{2-4}	1>3*	none	2-3 1-2	1>0	minor	2	4->5	3 - 4	2 - 3	KF>PL >>CD	trace	<1-2	none	MU>PI				
6	MONZ	f-m m-c	PORP (GRAP)	1	PL>QZ >KF>>BI	An_{15-34}* An(9)	0>1	none	0-4 avg 2	0>>1	none	2	>1-5	1 - 3	<2 - >10	KF>>CD	common	0 -1	none	PI>MU >CH				common occurrence trace abundance
7	MONZ	f-m m-c	PORP	0	PL>QZ> KP	An_{15-30}	2>1* 0>1	common	0-2	1	none	1	12-15	0 - 1	trace - 1	PL>KP >>CD	trace	0 - trace	none	PI>MU	trace occurrence + abundance		x	

EXPLANATION

UNIT - refers to map code
ROCK TYPE - GDIO - granodiorite; MONZ - monzogranite; SYEN - syenogranite. Brackets used to denote minor occurrence.
GRAIN SIZE - *fine* - <0.1 cm; medium - 0.1 - 0.5 cm; coarse >0.5 cm
TEXTURE - EQUI - equigranular; PORP - porphyritic; MEGA - megacrystic; SERI - seriate; SACH - saccharoidal; PEGM - pegmatitic; GRAP - graphic
MEGACRYSTIC - 0 - non-megacrystic; 1 - slightly megacrystic (<15%); 2 - very megacrystic (15-50%)
PHENOCRYSTS - list minerals (abbreviations listed below in descending order)
PLAGIOCLASE - composition - * indicates phenocryst composition
- zoning - 0 - unzoned; 1 - slight normal zoning; 2 - oscillatory zoning; 3 patchy
- myrmekite - mostly as thin rims
- ALT - alteration - 0 - fresh; 1 - slight; 2 - moderate; 3 - extensive; 4 - total replacement
ALKALI FELDSPAR - exsolution - 0 - non exsolved; 1 - minor exsolution (rod & bead); 2 - "patch" perthite
- MICROCL - microcline twinning (invariably with patchy development)
- ALT - same as above
BIOTITE - ALT - same as above
- (Note: all units have apatite, zircon, monazite, ilmenite ± xenotime as inclusions in biotite)
MUSCOVITE - REPL - list of minerals being replaced in descending order
- EUH - euthedral "primary looking" crystals
CORDIERITE - fresh - indicates the presence of some unaltered material
- ALT - list alteration products in descending order
GARNET - INCL - occurs as inclusions in plagioclase cores
- Clust - associated with biotite clusters (xenocrystic?)

LIST OF MINERAL ABBREVIATIONS
QZ - quartz; KF - alkali feldspar; PL - plagioclase; BI - biotite; MU - muscovite; CD - cordierite; GR - garnet

NOTES:
1. All quartz displays undulose extinction and commonly development of subgrains
2. All rocks contain quartz + alkali feldspar + placioclase

zoned or unzoned crystals in unit 3. In the core, unit 4 plagioclase displays normal and oscillatory zoning similar to that in the outer HP.

(3) Myrmekitic rims on plagioclase are most abundant in units 1, 2a, 2b, and in the core of the pluton (unit 4), whereas this feature is absent from most samples of unit 3.

(4) The presence and type of perthitic exsolution in alkali feldspar varies from margin to core of the HP. Perthitic features in units 1, 2a, and 2b are predominantly "rod" and "bead" type where the exsolved albite constitutes approximately 10-15% of the crystals. In contrast, alkali feldspar in unit 3 has abundant "patch perthite" where albite may constitute up to 50% of individual crystals. In the core of the HP, unit 4 contains rod and bead exsolution; however, patch perthite may be present in minor amounts.

(5) Biotite varies in modal abundance from 12-15% in unit 1, to 10-12% in units 2a and 2b, 2-7% in unit 3 and 8-10% in unit 4. Biotite compositions (unpublished microprobe data) also vary from most "primitive" (i.e., lowest Fe/(Fe+Mg) in units 1 (0.637), 2a (0.642), and 2b (0.649), to the more evolved compositions in unit 3 (0.750) and then more "primitive" in unit 4 (0.641).

(6) Muscovite increases from the margin of the HP (i.e., trace to <1% in units 1, 2a, and 2b) to 1-4% in unit 3 and then decreases slightly to trace to 1% (locally 2-3%) in unit 4. Euhedral, primary-looking crystals are essentially absent in units 1, 2a, 2b, and 4, whereas they are present in unit 3.

(7) Cordierite is present in trace to minor amounts in most rocks, however, at the boundary between units 3 and 4 cordierite may constitute up to >5% of the mode. There is generally a progressive change in alteration of cordierite from predominantly pinite (with minor chlorite and muscovite) in the more "primitive" rocks (i.e., units 1, 2a, 2b, and 4) to predominantly muscovite and chlorite with minor pinite in unit 3. This may reflect interaction of the cordierite phase with a progressively evolving fluid phase.

(8) The degree of alteration increases from unit 1 to 2a and 2b, and then to unit 3, followed by a decrease in unit 4. In addition to the alteration of cordierite described above, alteration features include: (i) sericitization of plagioclase (especially in the more calcic cores); (ii) sericitization of alkali feldspar; (iii) chloritization of biotite; and (iv) the replacement of plagioclase by alkali feldspar.

As previously mentioned, field relations indicate that sequence B rocks represent a separate, relatively younger intrusive event(s). A detailed investigation of these rocks indicates that there are substantial petrographic differences from the "older" zoned sequence. These features are summarized as follows:

(1) Colour is often buff, grey, orange, pink and red (cf. whitish-grey sequence A rocks).

(2) Grain sizes are generally fine- to medium-grained with very little coarse grained material, except for local pegmatites and minor coarse-grained phenocrysts (cf. coarse-grained megacrystic phases in sequence A rocks).

(3) Texture is predominantly porphyritic and equigranular with minor megacrystic, saccharoidal, pegmatitic, graphic and seriate textures (cf. megacrystic texture in sequence A rocks).

(4) Plagioclase is generally unzoned and of albitic composition (compositions determined both optically and by microprobe analysis), except for plagioclase phenocrysts (of oligoclase-albite composition with some andesine) (cf. zoned plagioclase of andesine to albite composition in sequence A).

(5) Myrmekitic rims, a common feature in the more mafic rocks of the zoned sequence (A), are absent in sequence B.

(6) Biotite (0-5%) is generally less abundant than in the majority of the rocks of sequence A (4 to >15%). Compositions are for the most part more evolved with higher (Fe/Fe+Mg) ratios (e.g., 0.868 for units 5a and c).

(7) Muscovite is more abundant (1-10%) than in the majority of sequence A rocks except for local areas of unit 3 where up to 4% muscovite occurs. Primary-looking, euhedral muscovite grains are common in sequence B whereas they are uncommon in sequence A (except in some samples of unit 3).

(8) Alteration products after cordierite are predominantly muscovite and chlorite (i.e., similar to unit 3) as opposed to pinite in the biotite-rich rocks of sequence A.

(9) Andalusite is a common accessory in sequence B rocks (i.e., observed in 50% of samples) compared to its rare occurrence in sequence A lithologies.

In summary, there are subtle yet consistent petrographic differences between the units which define the zoned sequence (A) as outlined in Table 1. These petrographic features suggest that the marginal areas of the HP are normally zoned. Conversely, the core of the pluton (i.e., units 4 and 4a) is slightly less evolved than the surrounding rocks of unit 3, thus a reverse zonation is represented.

A clear distinction can also be made petrographically between the rocks of sequence A and sequence B which supports the hypothesis of separate crystallization histories for the two suites.

GEOCHEMISTRY

Considerable geochemical data have been published for the granitic rocks of the HP; however, several problems are involved in integrating this data into the present survey. The data presented in Smith (1974) could not be used because sample locations were not provided and the rock units do not correspond to the units presented in this study. For example, "granodiorite" in Smith (1974) includes units 1, 2a, and 2b whereas "quartz monzonite" includes rocks from units 2b, 3, 4, and 4a of this study. Sample locations were provided in a more recent re-appraisal of the HP (Smith *et al.*, 1986); however, investigations of most of these locations indicated that glacially transported boulders were often sampled. These boulders commonly represented a different unit than the underlying bedrock and, therefore, several of the interpretations presented in Smith *et al.* (1986) are suspect. Thus, a comprehensive geochemical study was undertaken to: (1) establish the geochemical composition of the each rock unit; (2) quantify the nature and degree of geochemical zoning in sequence A rocks; and (3) establish the compositional ranges for sequences A and B and thus determine the relationship between the two suites.

One hundred and sixteen representative samples were chosen for major and trace element chemical analysis. Sample selection was based on results of systematic geological mapping, investigation of stained slabs and detailed petrography of more than 250 thin sections. A minimum of 25 kg of material was collected from large outcrop areas to eliminate potential problems of heterogeneity. Samples were crushed to less than 2.5 cm and homogenized, and then approximately 4 kg of fresh material was handpicked to eliminate weathering, fracture-related alteration and xenoliths. This material was ultrasonically cleaned, dried, crushed to less than 5 mm and split to form a 200 gm subsample which was subsequently crushed in a shatter box to minus 200 mesh.

Bench standards were prepared for quality control in the analytical procedures. Standard #1 is a medium grained, non-megacrystic biotite granodiorite which was collected in a rock quarry near Nictaux (Fig. 1). Standard #2 is a biotite monzogranite which was collected along Highway #103 near the Aspotogan Peninsula (Fig. 1). Approximately 200 kg of fresh material was collected and crushed according to the above procedure. Mean values and standard deviations for trace and major element compositions for the two standards are presented in Table 2.

Samples, analytical splits and bench standards were sent to the Nova Scotia Regional XRF Centre at St. Mary's University for analysis of major elements and a suite of trace elements (Ba, Rb, Sr, Y, Zr, Nb, Pb, Zn, Cu, Ni, V and Cr). The same suite of samples and standards was sent to Bondar-Clegg Laboratories for analysis of Sc, As, Rb, Sb, Ba, La, Hf, Ta, W, Au, Th, U, Li, B, F and Sn.

A summary of all geochemical results and normative mineralogy is presented in Table 2. Means and standard deviations are presented for groups with more than nine samples, whereas only the means are given for smaller subsets. Table 2 also contains averaged data and C.I.P.W. normative values for granodiorite, monzogranite, dike rocks and minor intrusions from the central part of the SMB (McKenzie and Clarke, 1975).

Major Elements

The outer portion of the zoned sequence (A) from unit 1 to unit 3 is marked by a progressive increase in SiO_2 (68.11-72.95%) and a concomitant decrease in TiO_2 (0.59-0.20%), Al_2O_3 (15.52-14.32%), $Fe_2O_{3(t)}$ (4.18-2.09%), MnO (0.09-0.05%), MgO (1.50-0.77%) and CaO (1.79-0.64%). Normative quartz, orthoclase, corundum and Thornton-Tuttle Differentiation Index (TTDI) increase toward unit 3 whereas normative anorthite, enstatite,

Table 2. Average major and trace element chemistry and normative mineralogy for various units of the Halifax Pluton. Table also contains averaged compositions for granodiorite, adamellite (i.e., monzogranite) and dike rocks and minor intrusions from the central SMB (after McKenzie and Clarke, 1975), and results for the two bench standards used in this study.

	Sequence A										Sequence B								McKenzie and Clarke (1975)						Standards			
UNIT	1		2a		2b		4		3		5a.c		5b		6		7		Granodiorite		Monzogranite		Dyke Rocks		STD # 1		STD # 2	
Major Elements (%)	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 9	SD	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 23	SD	$\bar{X}$ N = 25	SD	$\bar{X}$ N = 17	SD	$\bar{X}$ N = 4	*	$\bar{X}$ N = 5	*	$\bar{X}$ N = 2	*	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 10	SD	$\bar{X}$ N = 12	SD
SiO_2	68.11	0.71	69.30	1.18	69.80	0.43	71.33	1.34	72.95	0.80	74.55	0.69	71.49		74.69		69.03		69.13	1.32	73.42	1.27	74.38	1.21	68.01	0.45	70.88	0.66
TiO_2	0.59	0.02	0.48	0.10	0.40	0.05	0.40	0.08	0.20	0.07	0.09	0.04	0.31		0.18		0.42		0.62	0.10	0.24	0.09	0.15	0.09	0.37	0.00	0.37	0.01
Al_2O_3	15.52	0.37	15.11	0.19	15.10	0.43	14.49	0.41	14.32	0.33	14.22	0.34	14.91		13.99		14.74		14.37	0.33	13.74	0.40	13.71	0.42	16.47	0.18	14.56	0.23
Fe_2O_3(tot)	4.18	0.19	3.59	0.66	3.06	0.29	2.94	0.47	2.09	0.38	1.34	0.20	2.46		1.95		3.24		4.48	0.67	2.04	0.30	1.47	0.39	3.36	0.02	3.28	0.08
MnO	0.09	0.01	0.08	0.01	0.07	0.005	0.06	0.01	0.05	0.01	0.05	0.01	0.05		0.05		0.07		0.10	0.01	0.11	0.15	0.04	0.01	0.07	0.00	0.08	0.00
MgO	1.50	0.08	1.33	0.18	1.16	0.11	1.04	0.09	0.77	0.11	0.58	0.11	1.04		0.74		2.86		1.05	0.20	0.35	0.12	0.19	0.15	1.46	0.01	1.11	0.04
CaO	1.79	0.11	1.40	0.32	1.30	0.12	1.07	0.24	0.64	0.19	0.36	0.06	0.83		0.45		1.76		1.98	0.23	0.67	0.19	0.52	0.16	2.87	0.02	1.18	0.01
Na_2O	3.49	0.05	3.35	0.17	3.22	0.15	3.22	0.13	3.22	0.15	3.46	0.39	3.52		3.14		4.09		3.28	9.19	3.36	0.12	3.58	0.47	4.18	0.16	2.99	0.50
K_2O	3.80	0.13	4.29	0.31	4.70	0.34	4.40	0.16	4.66	0.18	4.42	0.21	4.19		4.48		3.81		3.84	0.28	4.75	0.24	4.53	0.45	1.98	0.01	4.34	0.05
P_2O_5	0.19	0.01	0.19	0.01	0.16	0.02	0.25	0.02	0.22	0.03	0.25	0.07	0.26		0.21		0.20		0.09	0.03	0.12	0.08	0.16	0.10	0.14	0.00	0.18	0.00
L.O.I.	0.65	0.12	0.62	0.13	0.66	0.13	0.71	0.10	0.63	0.11	0.68	0.12	0.97		0.98		0.60		0.88	0.14	0.76	0.15	0.78	0.10	0.67	0.12	0.65	0.15
TOTAL	99.93	0.25	99.76	0.37	99.67	0.28	99.94	0.26	99.80	0.34	99.97	0.39	100.04		100.70		100.85		99.38	0.56	99.33	0.47	99.42	1.15	99.61	0.53	99.63	0.59

*SD - Standard deviation not calculated for N<9

C.I.P.W. NORM (%)

QZ	27.94	29.21	29.26	32.89	34.79	36.88	32.71	37.87	23.14	30.13	34.50	35.73	28.56	33.55
OR	22.62	25.57	28.11	26.21	27.77	26.24	24.99	26.50	22.46	22.94	28.41	27.11	11.83	25.91
AB	29.75	28.59	27.51	27.46	27.48	29.48	30.06	26.50	34.53	28.06	28.78	30.68	35.67	25.56
AN	7.70	5.75	5.46	3.70	1.75	0.10	2.44	0.86	7.41	9.34	2.57	1.55	13.47	4.73
C	2.89	2.89	2.76	3.11	3.37	3.74	3.73	3.66	1.16	1.45	2.17	2.39	2.61	3.26
EN	3.76	3.34	2.94	2.61	1.93	1.48	2.59	1.82	7.11	2.64	0.88	0.48	3.68	2.79
IL	0.17	0.17	0.15	0.13	0.13	0.11	0.11	0.13	0.15	0.22	0.24	0.09	0.15	0.17
HM	4.21	3.62	3.10	2.96	2.11	1.35	2.48	1.95	3.23	4.49	2.05	1.48	3.40	3.31
HY	3.76	3.34	2.94	2.61	1.93	1.48	2.59	1.82	7.11	2.64	0.88	0.48	3.68	2.79
RU	0.49	0.39	0.32	0.34	0.13	0.02	0.26	0.11	0.34	0.51	0.12	0.11	0.30	0.28
AP	0.45	0.45	0.38	0.60	0.53	0.60	0.62	0.50	0.47	0.22	0.29	0.38	0.34	0.43
TTDI*	83.21	86.26	87.64	89.66	93.42	96.34	91.50	94.63	81.29	82.59	93.85	95.91	78.67	88.28

*Thornton Tuttle Differentiation Index

UNIT	1		2a		2b		4		3		5a.c		5b		6		7		Granodiorite		Monzogranite		Dyke Rocks		STD # 1		STD # 2	
Trace Elements ppm	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	*	$\bar{X}$	*	$\bar{X}$	*	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Ba	588	84	474	149	442	123	355	103	208	92	59	85	258		137		354		691	79	253	134	131	155	349	6	440	7
Rb	164	17	203	40	194	17	238	27	275	42	349	101	256		286		201		145	17	334	92	451	208	65	1	219	6
Sr	171	22	122	35	116	26	94	27	57	27	18	13	71		34		120		141	25	11	18	10	18	314	2	108	1
Hf	6	0.5	4	1.3	4	0.7	4	1.0	3	1.0	1	0.5	3		2		3								3	0.3	4	0.4
Zr	177	14	148	26	128	19	132	19	86	23	46	13	103		73		119		210	44	85	35	34	43	106	2	140	3
Ta	1.1	0.2	1.2	1.0	1.1	0.1	1.7	0.3	1.8	0.5	2.6	1.1	2.0		1.9		1.3								0.9	0.2	1.1	0.2
Nb	12	0.9	12	1.0	10	0.6	14	1.5	11	1.4	11	3.0	13		11		11								10	1	11	0.5
Sc	9.4	1.2	7.1	1.9	6.2	1.2	5.9	1.1	4.0	0.8	2.8	0.8	4.7		3.7		7.1								5.3	0.2	5.9	0.3
V	44	5	31	9	25	6	28	8	12	6	3	2	20		8		35								28	2	27	3
La	34	3	28	9	25	5	24	4	15	5	5	3	17		12		21								18	1	26	2
Y	32	3	31	2	29	4	25	3	23	4	18	4	20		23		22								17	1	26	0.7
Th	12.3	1.3	11.5	1.0	11.2	1.5	11.3	1.4	8.3	2.0	3.9	1.3	9.0		6.5		10.0								5.8	0.2	11.6	0.5
U	3.0	0.5	3.5	1.0	3.1	0.7	4.3	1.5	5.8	2.5	10.3	4.7	5.3		4.2		4.0								2.1	0.1	2.5	0.2
Li	76	13	96	23	76	10	90	11	95	25	112	65	80		89		94								52	7	128	16
F	645	111	699	319	571	70	691	98	753	194	742	377	1003		553		650								328	21	695	46
B	26	8	24	16	27	6	30	6	34	23	26	5	30		37		25								25	3	23	6
As	4.6	7.2	1.8	5.7	2.3	0.9	2.2	1.1	3.7	3.6	5.7	7.5	6.5		3.9		4.4								2.1	0.2	2.7	0.2
Au*	6	5	9	16	7	6	10	11	12	10	19	20	12		7		20								14	1	11	1
Sn	5	3	8	10	7	4	10	3	12	5	21	10	19		10		13		11	3	16	7	24	13	5	3	14	3
W	1	0.3	1	7.2	1	0	2	1.1	2	1.9	5	2.3	4		11		1								1	0.3	1	0.3
Cu	1	3	4	5	1	2	1	3	0	1	1	2	1		1		2								3	2	1	2
Pb	23	6	23	3	27	9	26	15	21	3	20	5	21		19		16								10	2	22	4
Zn	70	12	66	15	64	27	71	43	51	15	43	18	55		57		58		69	8	60	10	50	16	42	2	68	3

*ppb

hypersthene, ilmenite, hematite and rutile decrease in this zone. These variations are consistent with normal zoning (i.e., increase in the degree of differentiation toward the core of the pluton). In the inner portion of the HP the transition from unit 3 to units 4a and 4 displays a reversal of the above trend with decreasing SiO_2 (72.95-71.33%) and increasing TiO_2 (0.20-0.40%), Al_2O_3 (14.32-14.49%), $Fe_2O_{3(t)}$ (2.09-2.94%), MnO (0.05-0.06%), MgO (0.77-1.04%) and CaO (0.64-1.07%). This is accompanied by a decrease in normative quartz, orthoclase, corundum and TTDI and increasing normative anorthite, enstatite, hypersthene, hematite and rutile. These trends are consistent with reverse zoning near the core of the HP.

With the exception of unit 5b, all rocks in sequence B are more evolved than those of sequence A. Sequence B rocks have higher SiO_2, normative quartz, corundum, apatite and TTDI and lower TiO_2, Al_2O_3, $Fe_2O_{3(t)}$, Mgo and CaO and normative anorthite, enstatite, ilmenite, hematite, hypersthene and rutile than the majority of sequence A rocks. Conversely, unit 5b is more primitive than the rest of sequence B rocks and has major element contents and normative mineralogy which is intermediate between units 3 and 4. The implications of this will be discussed later.

Rocks from this study were compared with rocks of similar composition from the central part of the SMB (McKenzie and Clarke, 1975) as determined by the TTDI. Granodiorite, adamellite and leucogranite from the central SMB (TTDI- 82.59, 93.85, 95.91, respectively) were compared with units 1, 3, and 5a, c (TTDI- 83.21, 93.42, 96.34, respectively) from this study. Several major elements and normative compositions are similar for the HP and central SMB; however, the HP is enriched in MgO, P_2O_5 and normative corundum, enstatite, hypersthene and apatite and depleted in normative anorthite. These geochemical differences have been noted previously by MacDonald and Clarke (1985) who concluded that the MB, HP and indeed most of the eastern Meguma granitoid rocks display similar geochemical characteristics.

Smith (1979) conducted a similar geochemical comparison between the HP and two plutonic centres in the central SMB and noted statistical differences between the individual plutons. However, as stated above, the rock classification scheme used by Smith (1979) was much less definitive than that of this study. For example, Smith's (1979) "granodiorite" (SiO_2= 69.27%) consists of units 1, 2a, and 2b (SiO_2= 68.11, 69.30 and 69.80, respectively) of this study, whereas his "biotite granite" unit (SiO_2= 73.09) consists of units 2b, 3, and 4 (SiO_2= 69.80, 72.95 and 71.33, respectively) in our study. Therefore, Smith (1979) was not necessarily comparing similar rock types from different localities within the SMB.

Trace Elements

To facilitate discussion, the trace elements have been grouped into "compatible" and "incompatible" elements. Thus, with respect to the present study "compatible" elements should show a depletion commensurate with progressive differentiation, whereas "incompatible" elements will show enrichment trends. Certain elements display strong compatible/incompatible trends whereas others display much weaker trends.

The transition from the margin to the core of the zoned sequence (A) is marked by an initial decrease in the compatible elements (Sc, Ba, La, Hf, Th, Sr, Y, Zr and V) and a concomitant increase in the incompatible elements (U, Rb, Ta, W and Sn) from unit 1 through units 2a and 2b to unit 3 (e.g., Figs. 3a to 3f). These trends indicate normal zoning in the outer section of the HP. From unit 3 to the core of the pluton (i.e., unit 4) there is a slight reversal in all trends, with increasing compatible elements and decreasing incompatible elements (e.g., Figs. 3a to 3f). These data agree with the observed reversal in petrographic and major element trends and suggest reverse zoning in the central regions of the HP.

To graphically represent the nature of the zoning in the HP, an idealized cross section through the sequence has been prepared (Fig. 4). Locations for the 22 samples are given in Figure 2. The relative position of each sample was projected onto a central line. Figure 4 presents cross sections for Zr, Rb, Th, U, and La; these elements were chosen because they show some of the smoothest trends and maximum variations. An "average" line linking points has been visually estimated to represent the overall trends. Average compositions and standard deviations from Table 2 are also plotted for each unit and indicate that the analyses used in Figure 4 are representative of their respective units. All five elements indicate normal zoning near the margins of the sequence with decreasing Zr, Th and La and increasing U and Rb from unit 1 to units 2a, 2b, and 3. Conversely there is a slight, yet consistent, reversal of the geochemical zoning from unit 3 to 4a and 4 with increasing Zr, Th, and La and decreasing U and Rb.

Contoured plots for Zr and La were prepared using 87 samples from the zoned sequence (A) and are presented in Figures 5a and 5b. Both elements show remarkably consistent patterns throughout the HP. The geological boundaries have not been included in Figure 5; however, it is apparent that the highest contents of Zr and La are near the perimeter of the HP (i.e., near units 1, 2a, and 2b) and rapidly decrease inward as expressed by closely spaced contours. Both elements continue to decrease in the western HP (i.e., over unit 3) whereas they increase in the eastern HP (i.e., over units 4a and 4), as shown in the cross section in Figure 4. These data indicate that reverse zoning is present in the eastern HP whereas the western HP is normally zoned.

The majority of rocks in sequence B (i.e., units 5a, 5b, and 6) are geochemically more differentiated than those in sequence A, with lower concentrations of compatible elements and elevated levels of incompatible elements. However, unit 5b rocks contain slightly higher compatible element and lower incompatible element contents than the average compositions of unit 3 which it clearly postdates from field data. The implications of this will be discussed below.

DISCUSSION

All previous workers have concluded that the major factor controlling the composition of the various rocks in the SMB was fractional crystallization with the progressive removal of biotite (and included accessories) and plagioclase followed by alkali feldspar and quartz (Smith, 1974, 1979; McKenzie and Clarke, 1975; Clarke and Muecke, 1985). The progressive decrease in biotite and plagioclase (Table 1) and the "smooth" geochemical trends (Figs. 3, 4) displayed by the rocks in this study suggests that fractional crystallization was an important factor. For example, the outer, normally zoned segment of the HP may represent sidewall fractional crystallization or accretion as suggested by Smith (1979). The core of the pluton (i.e., unit 4), however, is clearly not a differentiate of the surrounding rocks (i.e., unit 3) and, therefore, must be explained by an alternative mechanism.

Baker and McBirney (1985) proposed a model for the formation of zoned magma chambers which involves the following processes: (1) sidewall fractional crystallization along the cool walls of the magma chamber; (2) the creation of a fractionated (highly evolved) "boundary layer" which forms at the interface between the cooling "rind" and the pristine magma in the core of the chamber. The existence of this boundary layer is dependant upon sluggish diffusion rates within the magma; (3) in granitoid systems this boundary layer will be less dense than the magma at the core of the chamber and will, therefore, rise to apical parts of the chamber and thus provide a mechanism for vertical stratification. This model avoids the problems associated with crystal settling in very viscous magmas as outlined by Rice (1981). Baker and McBirney (1985) have also shown that thermal (soret) diffusion, as outlined by Hildreth (1981),

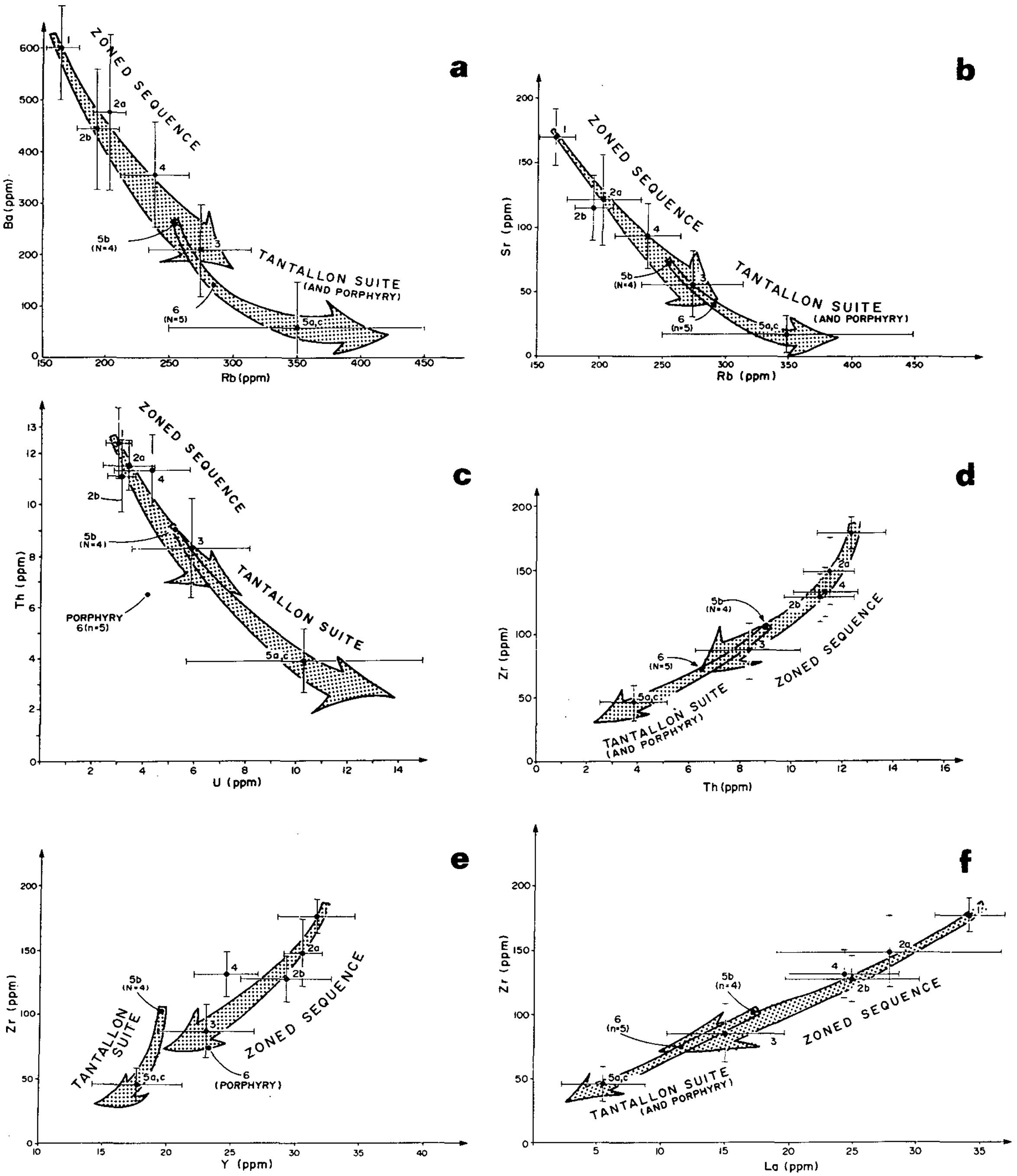

Fig. 3. Selected trace element variations which show the range of compositions in both the zoned sequence A and the late-stage sequence B (i.e., Tantallon suite and porphyry). Figures 3a, b, and c show the compatible nature of Ba, Sr, and Th compared to the incompatible nature of Rb and U. Figures 3d, e, and f show the compatible nature and smooth trends of Th, Y, and La versus Zr. This suggests the progressive removal of these elements in accessory phases. The reverse zonation of the HP is displayed by the primitive nature of unit 4 compared to the surrounding unit 3.

is not a feasible mechanism for developing large-scale stratification within magma chambers.

A reversely zoned pluton in Maine has recently been studied by Ayuso (1986). On the basis of geochemical and petrological evidence the compositional reversal was explained by the upwelling of a lower, more mafic part of a stratified sequence into the core of the pluton during emplacement. Bourne and Danis (1987), in trying to explain a reversely zoned, quartz monzodiorite-leucomonzogranite complex in Quebec, invoked a two-stage model to explain the zoning. These authors envisaged first the development of a lower magma chamber which through sidewall fractional crystallization became vertically stratified, subsequently a "leaky" roof-zone enabled successively less evolved melt to escape and formed an upper, reversely zoned pluton.

By combining the models from Ayuso (1986), Baker and McBirney (1985) and Bourne and Danis (1987) a

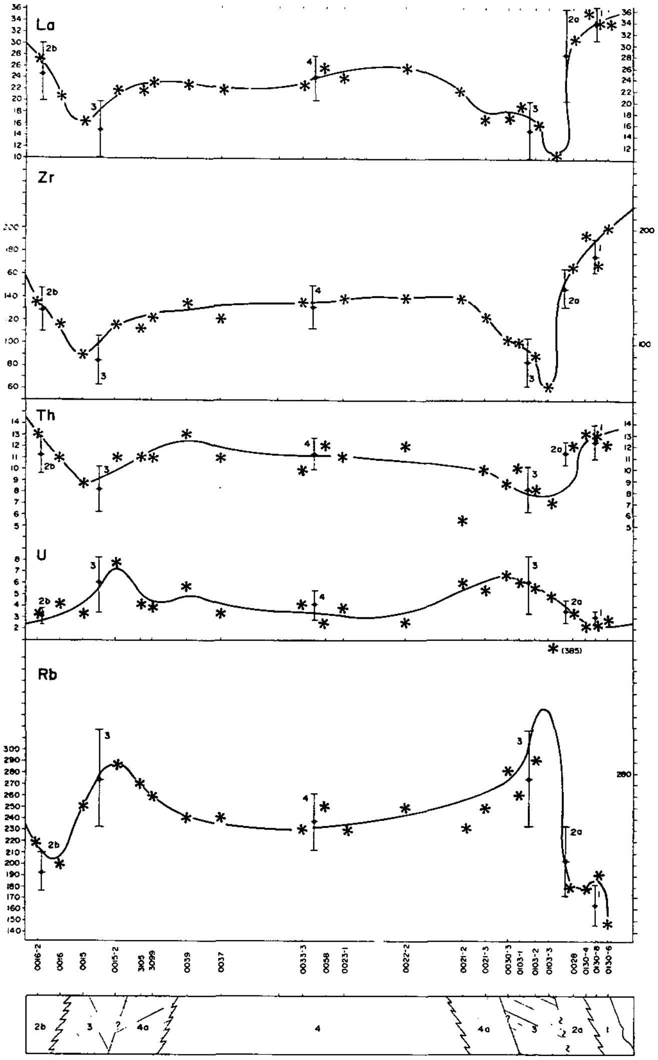

Fig. 4. Geochemical traverses across the zoned pluton for Rb, U, Th, Zr, and La. Note the reversal of the geochemical trends over the core of the pluton.

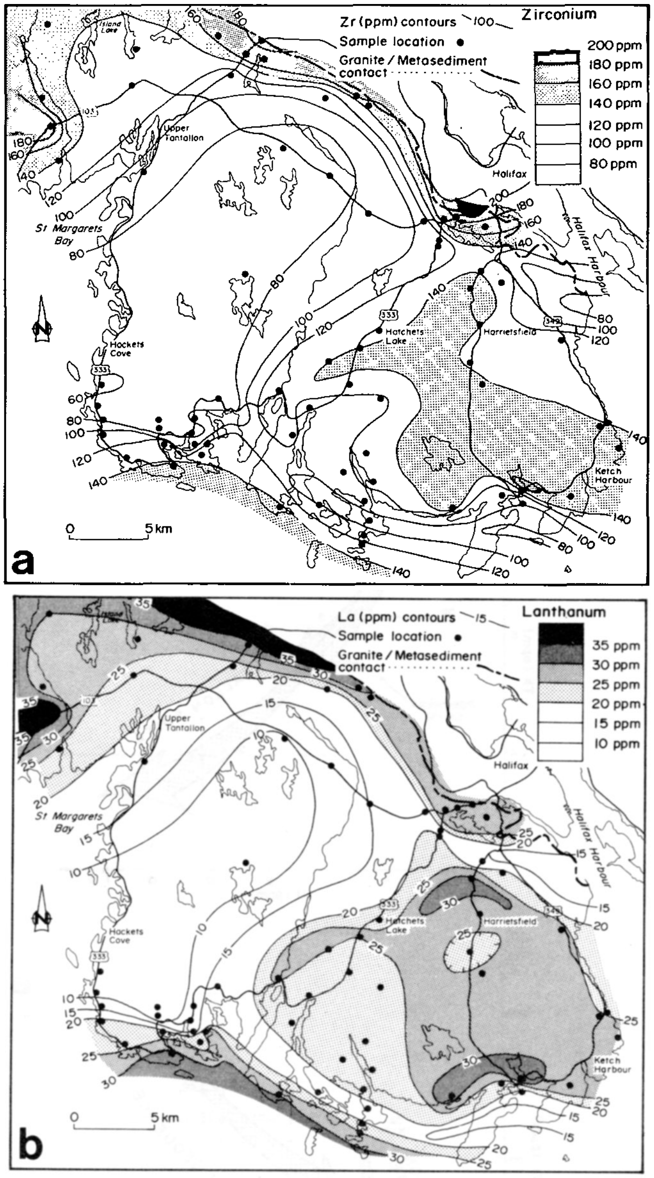

Fig. 5. Contoured plots of Zr (5a) and La (5b) for 87 samples from the zoned sequence (A). Note the normal zoning trends in the western HP and along the margins of the HP which are reversed over the eastern HP.

model for the rocks of the HP has been developed (Fig. 6). The first stage in this model envolves sidewall fractional crystallization which was initiated along the cool (metasedimentary) walls of the magma chamber. The first unit to crystallize was unit 1 (i.e., biotite granodiorite), this was subsequently followed by units 2a and 2b (i.e., biotite monzogranite). The observed gradational contact between these units is consistent with this suggestion. A highly evolved boundary layer then developed at the interface between unit 2 (a+b) and the interior magma. This layer then ascended and gave rise to a vertically stratified magma chamber (Fig. 6). In this sequence unit 3 represents the most evolved material at the roof and unit 4 the most primitive magma. Unit 4a, which is the cordierite-rich zone, represents a horizontal transition layer between units 3 and 4. Subsequent injection (upwelling) of magma into the lower parts of the chamber forces the layers to "warp" upwards. The maximum upwelling occurred in the eastern portion of the HP. Erosion to the present level (Fig. 6) then produced the observed outcrop pattern (Fig. 2).

One of the most notable 'marker' horizons in the zoned sequence is the cordierite-rich zone (4a and adjoining areas of unit 3). This zone does not have an elevated content of xenolithic material, nor is it adjacent to the metasedimentary rocks. Therefore, a purely xenocrystic origin for cordierite, as outlined in Maillet and Clarke (1985), is not applicable for this zone. The authors feel that cordierite reflects a critical composition in the magma which presumably occurred at a distinct 'stratigraphic' zone in the magma chamber (Fig. 6). This interpretation is in accord with the findings of Cocker (1976) who concluded that the crystallization of cordierite in granitic rocks is dependant upon a critical Fe/Mg ratio and

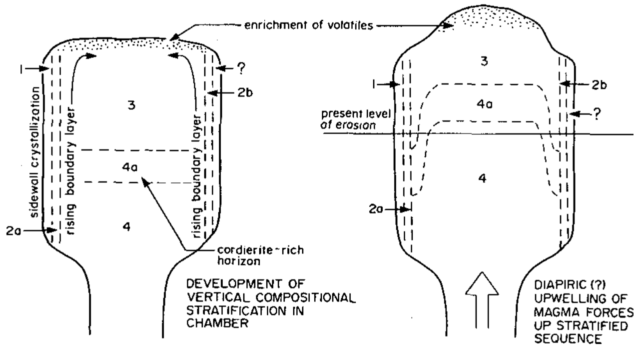

Fig. 6. A model for the formation of the zonation in the pluton. Crystallization commences along the cool metasedimentary walls (sidewall crystallization) followed by the rising of a fractionated boundary layer which causes vertical stratification of the central magma. Cordierite crystallizes in a discrete compositional layer in the sequence. Subsequent influx of magma into the lower part of the magma chamber "warps" the stratified sequence which, after erosion to present level, yields the observed outcrop pattern (i.e., Fig. 2).

amount of alumina oversaturation in the melt.

Unit 3, which is closest to the roof of the chamber, is the most texturally heterogeneous and pervasively altered unit in the zoned sequence. This may be explained by increased interaction with fluid phases which migrated towards the roof of the magma chamber (along with the rising boundary layer ?) and caused deuteric alteration effects such as "patch" perthite. The decrease in deuteric alteration and increased textural homogeneity from unit 3 to units 4a and 4 reflects the decreased interaction with hydrothermal fluids at deeper levels in the chamber.

Although more rigorous quantitative modelling is required to unequivocally exclude other petrogenetic processes such as TGD (e.g., Hildreth, 1981; Ludington, 1981), we feel that the crystal dominated processes were likely the most influential (e.g., Miller and Mittlefehldt, 1984).

The HP appears to be unique in the eastern SMB in that it contains substantially higher MgO, P_2O_5 and normative corundum, enstatite, hypersthene, apatite, and lower normative anorthite than rocks with similar Thornton Tuttle Differentiation Indices from the central part of the SMB (McKenzie and Clarke, 1975). Compositions are more similar to the MB (MacDonald and Clarke, 1985), which becomes part of the SMB in the reconstruction of Giles (1985) (Fig. 1). The fact that the HP differs from the other monzogranite plutons in the SMB, and appears to have its own crystallization history, supports the suggestion of Smith (1979) that the SMB is composite in nature and represents the coalescing of individual plutonic bodies.

Fractional crystallization has also been used to explain the evolution of late-stage rocks in the SMB (Smith, 1974; McKenzie and Clarke, 1975). Sequence B rocks (i.e., units 5a, 5c, and 6) are predominantly more geochemically and petrologically evolved (i.e., more fractionated) than their host rocks. However, unit 5b is slightly more primitive than and intruded into unit 3 (the most evolved rock of sequence A), which indicates that fractionation from unit 3 would be difficult. Although far from conclusive, this implies that sequences A and B represent two separate intrusive pulses which contradicts a single pulse, comagmatic history for the SMB.

Plots of La, Y and Th versus Zr for this study are presented in Figures 3d, 3e, and 3f. Progressive and consistent depletion of Th, La, Y and Zr occurs with progressive differentiation. Trends are very smooth and standard deviations (i.e., the bars in Fig. 3) are similar or even lower in the most evolved rocks (e.g., units 5a and 5c) when compared to the most primitive rocks (e.g., unit 1). Removal of these elements by fluid stripping would produce erratic results as the degree of removal would be proportional to the amount of alteration. This in turn would produce higher standard deviations in the most depleted rocks. Therefore, it is likely that the above elements were all progressively removed via accessory mineral phases such as zircon, monazite and xenotime; the presence of these latter two has recently been confirmed by electron microprobe analysis. The fractionation of monazite would also explain the light REE depletion in the HP, as outlined in Smith *et al.* (1986). This contrasts with the findings of Muecke and Clarke (1981) and MacDonald and Clarke (1985) who concluded that Th and REE were removed via a fluid phase by fluorine complexing.

CONCLUSIONS

Evidence presented in this paper indicates that the HP evolved as a discrete plutonic body within the SMB. The HP is characteristically enriched in MgO, P_2O_5 and normative corundum, enstatite, hypersthene, and apatite and depleted in normative anorthite when compared with the central portion of the SMB. The high normative corundum and MgO contents are expressed as high modal amounts of cordierite. These features are similar to those reported in the MB by MacDonald and Clarke (1985).

Individual rock units of sequence A define a symmetrically zoned pluton with both gradational and intrusive contacts between units. Petrographic and geochemical evidence indicates that the perimeter of sequence A (i.e., units 1, 2a, 2b, and 3) is "normally" zoned, whereas these trends are reversed in the transition from unit 3 to unit 4. Thus, the core of the pluton is "reversely" zoned.

Fractional crystallization of predominantly biotite (and accessory zircon, monazite, xenotime and ilmenite) and plagioclase can explain variations in the normally zoned perimeter of the pluton. The reversal in the core, however, may reflect an upwelling of lower layers in a stratified sequence similar to that of the Bottle Lake Complex in Maine (Ayuso, 1986).

Stratification within the HP was caused by a rising "boundary layer" of evolved melt into apical portions of the magma chamber, as suggested by Baker and McBirney (1985).

A separate, late-stage suite (sequence B) intruded the zoned sequence A. The majority of sequence B rocks are petrographically and geochemically more differentiated than those of sequence A. However, unit 5b is slightly more primitive than the most evolved rocks of sequence A (i.e., unit 3 which is intruded by unit 5b) suggesting that sequence B may represent a second pulse of magma.

The observations reported in this paper have only been possible after detailed field and laboratory work. The zonation in the HP is subtle, occurring in rocks which are all essentially medium- to coarse-grained and megacrystic, but which have slight, yet consistent variations in biotite, cordierite and muscovite contents. Similar zonation has been described in the Bottle Lake Complex Maine (Ayuso, 1986) and Lacorne Complex, Quebec (Bourne and Danis, 1987). Zoned plutons may be much more common in the Appalachian Orogen but their presence has not been widely recognized because of the lack of systematic mapping of granitic rocks.

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