Canadian Mineralogist
Vol. 24, pp. 137-146 (1986)

PETROGENESIS OF TWO CONTRASTING DEVONIAN GRANITIC PLUTONS, CAPE BRETON ISLAND, NOVA SCOTIA

SANDRA M. BARR
Department of Geology, Acadia University, Wolfville, Nova Scotia B0P 1X0

CALVIN R. PRIDE*
Department of Geology, University of Ottawa, Ottawa, Ontario K1N 6N5

ABSTRACT

The large, mesozonal White Point pluton in northeastern Cape Breton Island, Nova Scotia, consists of muscovite-biotite granite grading into biotite granite and granodiorite; it is intruded by abundant pegmatite and aplite dykes. The Gillis Mountain pluton in southeastern Cape Breton Island is small, composite, and high-level; it consists of quartz monzodiorite, porphyritic granite and fine-grained granite, with scattered granitic and aplitic dykes. Petrogenetic modeling based on whole-rock geochemistry indicates that the White Point magma originated by anatexis of metasedimentary rocks, with subsequent fractional crystallization more or less *in situ*. In contrast, the Gillis Mountain pluton resulted from emplacement of magma pulses from a deeper evolving magma-chamber with a long history of fractionation. The low initial $^{87}Sr/^{86}Sr$ ratio indicates either a mantle source or derivation from material with limited previous crustal history.

Keywords: granite, petrogenesis, geochemistry, modeling, anatexis, Cape Breton, Nova Scotia, Devonian.

SOMMAIRE

Le pluton de White Point, en Nouvelle-Écosse, est grand, profond, mésozonal; il consiste en un granite à muscovite et biotite qui passe à granite et granodiorite à biotite; il est recoupé par de nombreux dykes (pegmatite et aplite). Le pluton de Gillis Mountain est petit, composite, à haut niveau; il se compose de monzodiorite quartzifère, granite porphyritique et granite à grain fin, avec dykes épars (granitiqes et aplitiques). Un modèle pétrogénétique, fondé sur la géochimie des roches totales, indique que le magma de White Point trouve son origine dans l'anatexie de roches métasédimentaires, suivie de cristallisation fractionnée plus ou moins *in situ*. Par contre, le pluton de Gillis Mountain est le résultat de la mise en place du magma au cours de ses pulsations à partir d'une chambre magmatique, à grande profondeur, que caractérise une longue histoire de fractionnement. La faible valeur initiale du rapport $^{87}Sr/^{86}Sr$ indique que la source réside soit dans le manteau, soit dans la dérivation d'un matériau dont l'histoire dans l'écorce terrestre fut brève.

(Traduit par la Rédaction)

Mots-clés: granite, pétrogenèse, géochimie, modèle, anatexie, Cap-Breton, Nouvelle-Écosse, Dévonien.

INTRODUCTION

Granitic plutons of Cape Breton Island range in age from late Hadrynian to Carboniferous (*e.g.*, Cormier 1972, 1979, 1980). Those of known or inferred Devonian age (Fig. 1) appear to be generally of two types: small high-level stocks and larger deeper-level bodies. These types are exemplified by the Gillis Mountain and White Point plutons, respectively. The purpose of this paper is to describe and discuss the markedly contrasting mineralogy, geochemistry, and petrogenesis of these two plutons.

PETROLOGY

Other than age, the Gillis Mountain and White Point plutons have essentially no features in common (Table 1). As described by Barr & O'Beirne (1981) and Barr *et al.* (1982), Gillis Mountain is a composite intrusive body ranging from quartz monzodiorite to granite. The dominant rock-type is porphyritic granite containing about 25% strongly zoned plagioclase (average andesine) phenocrysts. Potassium feldspar (interpreted to be sanidine transitional to orthoclase on the basis of small optic-axial angle) and quartz occur mainly in the groundmass with hornblende and biotite, the latter two minerals generally forming 10–15% of the rock.

In contrast, the White Point pluton consists of medium-grained equigranular granite with local gradational variations to granodiorite (Wiebe 1975, Barr *et al.* 1982). The dominant minerals are quartz, microcline and albite–oligoclase, in approximately equal amounts. Biotite is the only ferromagnesian mineral present (up to 3 or 4 vol. %). Muscovite (interpreted to be of primary origin) is nearly ubiquitous but typically forms less than 2% of the rock. Monazite, zircon and apatite are common accessory minerals.

Evidence for a high level of emplacement for the Gillis Mountain pluton includes lack of regional metamorphism in the country rocks, sharply discordant contacts, a well-developed medium-grade contact-metamorphic aureole and prominent porphyritic texture. In contrast, a much deeper level of

---

*Present address: International Development Research Centre, P.O. Box 8500, Ottawa, Ontario K1G 3H9.

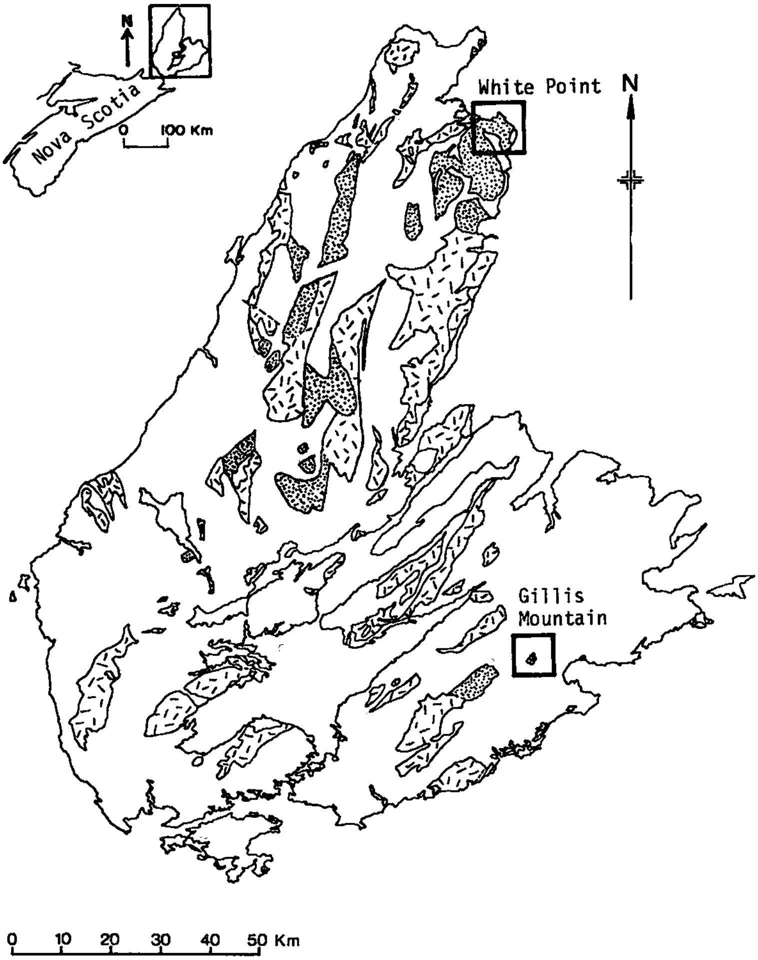

FIG. 1. Distribution of granitic intrusive complexes in Cape Breton Island, showing location of Gillis Mountain and White Point plutons. Stippled pattern indicates probable Devono-Carboniferous plutons; slash pattern indicates older plutons.

emplacement is indicated for the White Point pluton by the gneissic character of its country rocks, the extensive development of an injection complex around the pluton, and abundance of muscovite and microcline. The Gillis Mountain pluton is clearly post-tectonic, whereas the White Point is foliated and inferred to be syntectonic. However, the plutons have identical whole-rock Rb–Sr ages of 384 ± 10 Ma (Gillis Mountain) and 386 ± 1 Ma (White Point) (Cormier 1979, written comm. 1981).

The Gillis Mountain pluton has been cited as one of the few examples of a "porphyry-type" Cu–Mo deposit in the northern Appalachians (Hollister *et al.* 1974, Kirkham & Soregaroli 1975). It contains abundant pyrite, chalcopyrite and molybdenite, both as disseminations and along fractures, and locally has undergone extensive hydrothermal alteration. No mineralization is known to be associated with the White Point pluton, which is remarkably fresh and free of evidence of widespread hydrothermal activity.

CHEMISTRY

Detailed analytical results for major elements and many trace elements, as well as a discussion of precision and accuracy, are given in Barr *et al.* (1982). The rare-earth elements (*REE*), Hf and Th were determined by instrumental neutron-activation analysis after the method described by Gordon *et al.* (1968) and Gibson & Jagam (1980). Powdered samples were irradiated for approximated 6 hours at a flux of 10^{12}n/cm^2/s, and counted using an Aptec 2-cm^2 Ge planar detector. BCR-1 was the standard used (Flanagan 1973). Based on duplicate and stan-

TABLE 1. COMPARATIVE GEOLOGICAL FEATURES OF THE GILLIS MOUNTAIN AND WHITE POINT PLUTONS*

FEATURE	GILLIS MOUNTAIN	WHITE POINT
Size	6 km^2 (isolated stock)	30 km^2 (part of much larger intrusion)
Shape	Subelliptical	Irregular lobate
Country rocks	Cambrian clastic sedimentary rocks	Precambrian orthogneisses
Contact aureole	Well developed; Hornblende-hornfels facies	None apparent. Spectacular injection complex of dykes from the pluton extends several km from contacts
Main rock types	Composite intrusion: quartz monzodiorite, porphyritic granite, and fine-grained granite	Essentially one lithology: granite gradational to granodiorite
Dykes	Scattered aplite and porphyry dykes in pluton	Very abundent pegmatite and aplite dykes in pluton and country rocks
Structures	Unfoliated Post-tectonic	Foliated (weak to moderate) Syntectonic
Mineralization	"Porphyry-type" Cu-Mo	None known
Major minerals	Plagioclase (andesine) Sanidine/orthoclase Quartz Biotite Hornblende No muscovite	Plagioclase (albite-oligoclase) Microcline Quartz Biotite No hornblende Muscovite
Age**	384+10 Ma	386+1 Ma

* Additional details in Wiebe (1975), Barr & O'Beirne (1981), and Barr et al.(1982)

** From Cormier (1979 and written communication, 1981)

TABLE 2. MEANS AND STANDARD DEVIATIONS* FOR MAJOR AND TRACE ELEMENT DATA FROM GILLIS MOUTAIN AND WHITE POINT PLUTONS

GILLIS MOUNTAIN PLUTON

	Quartz Monzodiorite (n=9)		Porphyritic Granite (n=28)		Fine Grained Granite (n=7)		Minor Phases (n=7)	
SiO$_2$ (%)	60.14	1.37	67.40	1.10	68.27	1.42	69.99	3.62
TiO$_2$	1.39	0.11	0.62	0.07	0.62	0.07	0.40	0.23
Al$_2$O$_3$	16.29	0.74	15.07	0.64	14.83	0.29	13.92	1.08
Fe$_2$O$_3$	7.77	0.74	4.01	0.50	3.94	0.23	2.80	1.50
MnO	0.11	0.03	0.05	0.01	0.05	0.01	0.03	0.03
MgO	2.60	0.34	1.39	0.17	1.14	0.15	0.70	0.54
CaO	4.81	0.36	2.70	0.53	2.18	0.29	1.58	1.24
K$_2$O	2.28	0.49	3.53	0.42	4.01	0.13	3.72	0.70
Na$_2$O	3.64	0.15	3.69	0.18	3.58	0.15	3.67	0.29
P$_2$O$_5$	0.36	0.04	0.15	0.03	0.13	0.03	0.12	0.09
As (ppm)	8	3	7	3	5	2	8	1
Ba	797	87	882	112	938	90	700	351
Cu	168	197	202	556	85	115	76	90
F	630	100	510	120	620	70	390	120
Pb	18	8	99	199	103	175	109	175
Mo	4	1	4	2	5	1	3	1
Rb	101	20	170	28	159	17	212	82
Sr	465	35	302	38	244	25	179	84
S	2110	2550	1230	1510	2340	1420	1080	1500
Sn	2	1	2	1	3	1	3	1
Th	9	2	15	3	15	1	17	5
U	2	1	4	1	4	1	6	3
Zn	84	20	153	198	154	134	348	751
	(n=2)		(n=5)		(n=2)			
B	6	1	6	2	7	0	-	
Be	3	1	3	1	4	1	-	
Li	16	8	31	6	31	9	-	
Zr	160	0	223	31	279	2	-	

WHITE POINT PLUTON

	Granodiorite (K16-1009) (n=1)	Granodiorite (n=5)		Granite (n=32)		Aplite (n=2)	
SiO$_2$	63.14	67.81	2.29	73.20	1.16	74.02	0.60
TiO$_2$	0.73	0.38	0.21	0.13	0.05	0.04	0.00
Al$_2$O$_3$	18.35	16.18	1.09	14.15	0.80	14.47	0.35
Fe$_2$O$_3$	3.30	2.65	1.08	1.43	0.24	0.70	0.01
MnO	0.02	0.03	0.02	0.01	0.00	0.01	0.00
MgO	1.57	1.01	0.76	0.26	0.11	0.08	0.08
CaO	4.50	2.76	0.75	1.58	0.38	1.15	0.45
K$_2$O	2.68	2.98	0.67	4.40	0.74	3.88	0.79
Na$_2$O	4.75	4.59	0.59	3.93	0.58	4.38	0.01
P$_2$O$_5$	0.21	0.17	0.09	0.08	0.03	0.04	0.00
As	14	4	2	7	3	5	2
Ba	860	739	255	463	264	13	8
Cu	15	7	6	4	10	1	1
F	840	670	360	430	90	400	0
Pb	22	29	7	44	34	28	6
Mo	1	1	1	15	72	2	1
Rb	95	135	28	216	59	431	62
Sr	790	676	225	244	233	67	12
S	60	150	250	30	20	20	10
Sn	2	4	2	4	4	5	1
Th	7	8	5	16	8	10	1
U	4	2	1	3	2	3	1
Zn	65	60	26	41	13	0	
		(n=3)		(n=9)		(n=1)	
B	7	4	1	5	1	8	
Be	4	6	1	7	2	17	
Li	109	75	21	66	20	29	
Zr	160	224	34	153	22	155	

* Tables of data for individual samples are available from the authors and in Barr et al. (1982).

dard results, the accuracy and precision of the data may be taken as follows (percent of amount present): Ce,Nd,Sm,Eu,Yb,Th, Hf: ± 5%; Tb, Lu: ± 10%.

Absolute chemical comparisons between the Gillis Mountains and White Point plutons are complicated by different abundances of SiO$_2$, even in the granites of the two intrusive bodies. The White Point granite contains about 73% SiO$_2$ and has lower TiO$_2$, total Fe, MgO and CaO than the Gillis Mountain granite, which averages about 68% SiO$_2$ (Table 2). Levels of Al$_2$O$_3$, K$_2$O and Na$_2$O are similar in the two granites, but the Gillis Mountain pluton shows ubiquitous evidence of alteration, which may have modified the bulk composition. However, this alteration has not been sufficiently intense, even in the most altered samples, to destroy the primary mineralogy or to lower the K/Rb ratio below normal magmatic values (150–350) to levels consistent with intense porphyry-copper alteration (*e.g.*, Armbrust *et al.* 1977).

Variation diagrams of the major element oxides show good linear trends in both plutons (Barr *et al.* 1982) as exemplified by MgO and CaO trends (Fig. 2) broadly compatible with fractional crystallization. In Gillis Mountain, however, there are at least 2 and possibly 3 distinct groups of data, with a gap between each (Fig. 2a). The early quartz monzodiorites form a distinctly less-fractionated group, and the late aplites a separate group at the more fractionated, low Mg–Ca end of the diagram, although the aplite position is based on a small sample-size (2). Such discontinuous but colinear trends can be produced in

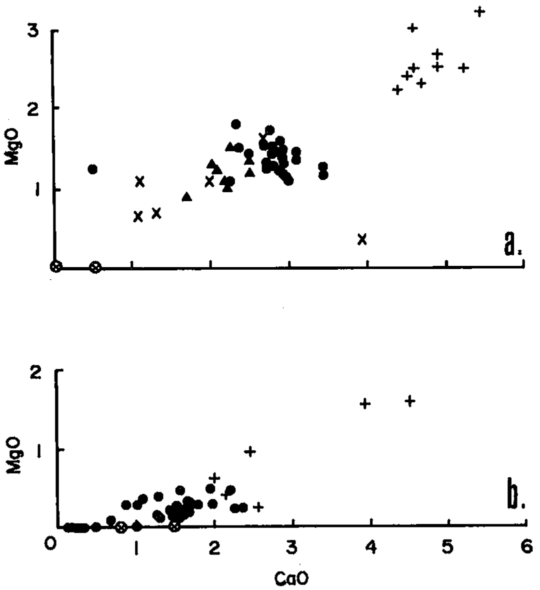

FIG. 2. Plot of MgO *versus* CaO for representative samples from the Gillis Mountain (a) and White Point (b) plutons.

cogenetic sequences by accumulation, separate intrusive events tapping an evolving magma-chamber(s) at depth at different times, or separate events of melting of the same (or similar) parent. Clearly intrusive relationships favor one of the latter two possibilities; as the more fractionated rocks were intruded later (opposite to the expected sequence of melting), periodic tapping of an evolving magma-chamber is considered most likely.

In the case of White Point, most of the samples fall within one group (Fig. 2b). The two least-fractionated samples, however, do form a separate group. In this pluton a strong case can be made for a cumulate origin for this group, as will be shown later.

REE data for selected samples covering the range of compositions of both plutons are given in Table 3. Chondrite-normalized curves are presented in Figure 3. The White Point samples (Fig. 3a) are generally enriched in the light *REE* (*LREE*) but otherwise show varied patterns and a wide range in total *REE* abundances. In general, the *LREE* decrease, the heavy *REE* (*HREE*) increase, and a negative Eu-anomaly develops and becomes more pronounced from the least-fractionated granodiorite to the aplite, although there are exceptions and reversals in these trends.

TABLE 3. REE DATA (ppm) FOR GILLIS MOUNTAIN AND WHITE POINT PLUTONS

Gillis Mountain		La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
Quartz Monzodiorite	1105	39.9	76.5	33.0	5.6	1.9	0.89	2.1	0.39
Quartz Monzodiorite	1136	33.4	66.3	28.8	5.9	1.8	0.87	2.3	0.38
Porphyritic Granite	1075	32.5	58.7	23.4	4.4	1.1	0.51	1.7	0.28
Porphyritic Granite	1094	25.3	47.6	19.2	3.8	0.35	0.45	1.6	0.27
Porphyritic Granite	1120	32.6	60.9	24.5	4.7	1.2	0.57	2.0	0.35
Fine-grained Granite	1119	40.9	79.7	31.9	6.0	1.3	0.78	2.6	0.45
Porphyry Dyke	1061	39.4	63.8	24.0	4.2	0.91	0.51	1.5	0.24
Aplite Dyke	1079	3.0	9.0	7.6	3.6	0.45	1.05	7.3	1.27
White Point									
Granodiorite	1009	74.7	54.6	38.9	24.0	16.5	8.6	4.6	-
Granodiorite	1026	104.5	66.7	39.4	25.4	11.0	12.3	9.6	-
Granodiorite	1111	25.5	15.3	13.4	9.5	10.1	4.3	4.0	-
Granite	1061	15.7	10.3	7.4	5.5	4.1	2.7	2.4	-
Granite	1098	49.1	34.1	22.5	19.7	6.8	11.4	7.9	-
Aplite	1035	28.8	22.1	15.6	21.0	2.1	15.3	13.7	11.2

The Gillis Mountain samples (Fig. 3b) generally have linear patterns and are *LREE*-enriched, with a very small Eu-anomaly or none at all. The quartz monzodiorites have the highest overall concentrations of *REE,* along with the fine-grained granite. In general, the samples from the other units of the pluton have very similar relative patterns, but lower absolute concentrations and a small to pronounced negative Eu-anomaly. The aplite dyke shows quite a different pattern, however, being *LREE*-depleted, *HREE*-enriched and having a pronounced negative Eu-anomaly.

Other trace-element differences between the plutons are also striking (Table 2). The White Point rocks are lower in Ba and higher in Li, Sn and U, and show a wide spread in contents of these elements, as well as Rb and Sr, compared to Gillis Mountain. The Gillis Mountain pluton is higher in Mo, Cu, Pb and Zn, and shows very large ranges in these elements, obviously related to the abundance of sulfide mineralization (although samples containing obvious sulfides were not selected for analysis).

Initial $^{87}Sr/^{86}Sr$ ratios for the two plutons are very different: 0.703 ± 0.002 for Gillis Mountain (Cormier 1979) and 0.7097 ± 0.0011 for White Point (R.F. Cormier, written comm., 1981).

FRACTIONATION HISTORY

White Point pluton

Perhaps the most informative elements to use in evaluating the fractionation history of relatively unaltered granitic rocks are Rb, Sr and Ba, as their behavior in such systems is strongly tied to the major minerals of granitic rocks, *i.e.,* plagioclase, K-feldspar, biotite and muscovite (*e.g.,* McCarthy & Hasty 1976). The data for these elements from the White Point pluton are shown in Figure 4. Given the demonstrated importance of cumulate–liquid mixtures in many granitic systems (*e.g.,* Lee & Christiansen 1983, Tindle & Pearce 1981, McCarthy & Groves 1979), the White Point pluton was modeled using the initial concentrations given in Table 4 and the Rayleigh fractionation relationship:

for the liquid (C^L)

$$C^L = C^\circ F^{(D-1)}$$

and for the instantaneous cumulate (C^R)

$$C^R = DC^\circ F^{(D-1)}$$

where C° is the initial concentration of the element of interest, D is the bulk-distribution coefficient for that element and F is the weight fraction of melt remaining. The initial concentrations given in Table 4 were chosen to give as good a fit as possible to the observed data, but they are probably only crude approximations to the actual initial concentrations. For the early stage of crystallization (granodiorite), it was assumed that the minerals plagioclase, biotite and quartz crystallized in the approximate proportions in which they occur in the rocks, specifically 60, 15 and 25%, respectively (Barr *et al.* 1982). For the later and dominant stage of crystallization (granite), it was assumed that the minerals plagioclase, biotite, quartz, K-feldspar and muscovite crystallized in the approximate proportions observed in the rocks, 33, 2, 30, 34 and 1%, respectively. For ease of calculation, these proportions were kept constant in both cases.

The results of the modeling are shown in Figure 4, the solid line representing the changing composition of the liquid and the dashed line that of the simultaneous cumulate. For the most part, the fit between model and observed data is excellent. For example, in Figures 4a and 4b, the model simulated very well the kink in the trend of the data due to the beginning of K-feldspar crystallization. The bulk of the data in all three plots falls between the limits of the pure liquid and pure cumulate, indicating that most samples are mixtures of liquid and cumulate material. The additional scatter shown by a few samples, especially on the cumulate side, may be at least partly explained by occasional preferential accumulation of one mineral phase over another or variable relative amounts of the minerals crystallizing, since the model assumes constant proportions. In granites such as this one that have not had a long history of fractionation and are reasonably close to their source (see later discussion), a further possibility is that some of the scatter is inherited from the source (*i.e.*, variable degrees of melting, variable source-rocks or variable amounts of source-material xenoliths present). The importance of the cumulate nature of many samples of the granite is emphasized by overlapping trends for the granites and granodiorites (Figs. 4a, b), a feature typical of the discontinuous path followed by the evolving cumulate (McCarthy & Groves 1979).

The modeling was stopped at approximately 65% crystallization (F 0.35). With the exception of the late aplite dykes, this seems sufficient to describe the variability of the data. The late aplites lie a little beyond this level of fractionation (approximately >70%) and too far off the liquid line on the Sr and Ba plot (Fig. 4a) to fit the model. This is probably due to the increasing proportion of K-feldspar crystallizing at a late stage of evolution of the body, as this would move the liquid and cumulate fractionation-lines toward parallelism with the Ba axis because of the large distribution-coefficient for Ba between K-feldspar and liquid.

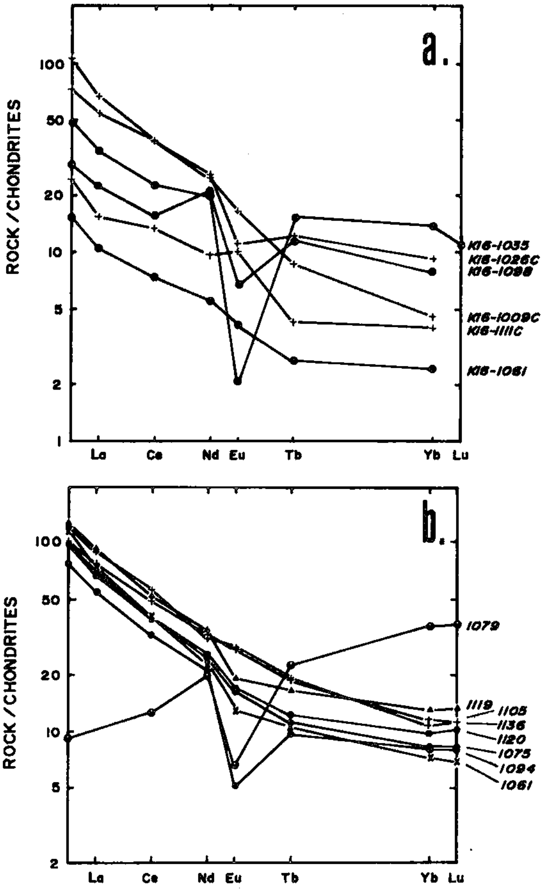

FIG. 3. Chondrite-normalized *REE* patterns for White Point (a) and Gillis Mountain (b) plutons.

Given the above model, it is now much easier to interpret the rather variable *REE* data presented earlier. The patterns reflect, in large part, variable mixtures of cumulate (or restite) and liquid. Where the cumulate component predominates, the *REE* abundances are lower and the samples exhibit a positive Eu-anomaly or none at all (Fig. 3, K16–1111C and K16–1061). Such samples also tend to be high in aluminum (*e.g.*, K16–1111C, Barr *et al.* 1982). Neglecting these two dominantly cumulate specimens, the remaining three samples, although still at least partly cumulates, show consistent behavior: decreasing *LREE*, increasing *HREE* and an increasingly negative Eu-anomaly with differentiation, such as has been observed in many high-silica granitic and rhyolitic systems (*e.g.*, Lynch & Pride 1984). The decreasing *LREE* trend may be due to monazite frac-

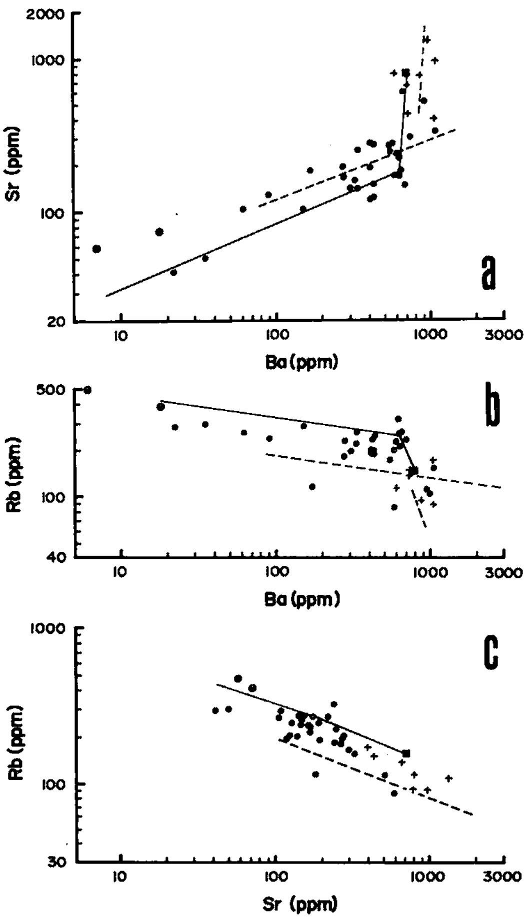

FIG. 4. Sr–Ba (a), Rb–Ba (b) and Rb–Sr (c) plots for samples from the White Point pluton compared to results from modeling studies. Crosses, granodiorite; closed circles, granite; circle with cross, aplite; square, initial concentration; solid line, liquid line of descent; broken line, cumulate "line of descent".

TABLE 4. MODELING RESULTS FOR WHITE POINT PLUTON

	Granodiorite				Granite			
F	1		0.4		1		0.4	
ppm	C^O	C^R	C^L	C^R	C^O	C^R	C^L	C^R
Rb	155	67	261	112	261	117	432	194
Sr	700	1738	179	446	179	459	43	109
Ba	750	905	620	748	620	3023	18	87

C^O for granodiorite: assumed parental magma composition
C^L: concentration in liquid
C^R: concentration in residue
F : proportion of melt remaining
Note: C^L for the granodiorite at F=0.4 is C^O for the granite fractionation. See text for further details of modeling.

tionation (*e.g.*, Mittlefehldt & Miller 1983) and the increasing negative Eu-anomaly to feldspar fractionation.

Gillis Mountain pluton

For Gillis Mountain, similar modeling was attempted. In this case, major elements, in addition to trace elements, were used to constrain the various schemes of fractional crystallization using mineral-composition data of O'Beirne (1979). The fine-grained nature of the early quartz monzodiorites and the late fine-grained granites, and the scarcity of phenocrysts in both, indicate that they were probably emplaced as liquid-dominant systems that cooled rapidly. This is confirmed by the tight clustering or linear trends exhibited by these lithologies on the Ba–Sr, Ba–Rb and Sr–Rb plots of Figure 5 (*cf.* the wider cumulate/liquid trends observed for White Point on Fig. 4). The porphyritic granite shows a somewhat greater scatter on these plots and may have undergone some *in situ* fractionation. The data cluster into three major groups (especially on the Ba–Sr plot, Fig. 5a), the quartz monzodiorite, the porphyritic granite and the fine-grained granite and minor phases, coinciding with the order of emplacement, oldest to youngest. The aplites form a minor fourth group. The lack of major within-phase fractionation is evident from the major-element data of Barr *et al.* (1982), which tend to cluster for each separate rock-type (Table 2). Given the close coherence and "smooth" trends exhibited by the various lithologies of Gillis Mountain, on both major- (Fig. 2) and trace-element diagrams (Fig. 5), they are likely to be cogenetic, related by fractionation in a deep-level magma chamber. The observed discontinuities and clearly cross-cutting relations reflect periodic tapping of this evolving magma.

Plagioclase was probably a major fractionating phase throughout the crystallization history of this magma chamber given: 1) the trend directly away from the plagioclase corner on the plagioclase – quartz – K-feldspar diagram (Fig. 6), 2) the abundant presence of plagioclase phenocrysts in the porphyritic granite and microphenocrysts in the quartz monzodiorite and fine-grained granite, and 3) the decreasing Sr concentrations throughout the sequence.

Major- and trace-element modeling is broadly compatible with derivation of the granites from the quartz monozodiorite magma by fractional crystallization of plagioclase and hornblende at depth (*e.g.*, Table 5), both observed to be microphenocrystic phases of the quartz monzodiorite. One problem with this interpretation, however, involves the *REE* data. The *REE* are observed to decrease in concentration from the quartz monzodiorites to the granites (Fig. 3b). Hornblende fractionation could qualitatively account for the decrease in the middle and heavy rare-earth elements (*e.g.*, Hanson 1978), although extensive fractionation of hornblende should cause a more severe depletion in the middle *REE* (compared to the *HREE*) and a distinct upward kink from Yb to Lu (*e.g.*, Pride & Moore 1983). Apatite fractionation, permissible to a limited extent by the decrease in P_2O_5 (Barr *et al.* 1982), could also cause a depletion in the middle and heavy *REE*. The main problem, however, is the corresponding decrease in the *LREE*, not usually observed in intermediate rocks. This requires fractionation of a *LREE*-enriched accessory phase such as monazite or allanite, for which there is no independent evidence. This problem is more severe in the fine-grained granite, which is more similar to the quartz monzodiorite, but with slightly higher *HREE* and a small negative Eu-anomaly. Thus the total abundances in the *REE* decrease from the quartz monzodiorite to the porphyritic granite and increases again toward the fine-grained granite. The previously presented evidence for the cogenetic nature of the various phases and their dominantly "liquid" nature calls into question the usefulness of the *REE* in understanding the fractionation history of such rocks, given their highly variable patterns.

Fractionation within the granites (*i.e.*, from the porphyritic granite to the fine-grained granite and minor phases) cannot be explained by *in situ* fractional crystallization of K-feldspar or biotite, major (>25%) and minor (<5%) phases, respectively, of the porphyritic granite. For example, the constant to increasing concentrations of Ba and the increasing concentrations of Rb virtually rule out significant removal of these minerals. However, a model involving fractionation of plagioclase and a mafic phase(s) exhibiting low distribution-coefficients for Rb, Sr and Ba (*e.g.*, hornblende, magnetite, ilmenite, pyroxene) provides an excellent fit for the trace elements Rb, Sr and Ba (Table 6). This fractionation would have taken place in an evolving magma-chamber at depth. Given the uncertainties in the Fe/Mg ratio of these mafic minerals, it is difficult to arrive at a good numerical major-element fit using compositions of phases in the porphyritic granite. All reasonable solutions, however, exclude quartz or K-feldspar and contain substantial plagioclase as a fractionating phase. Thus the major-element results agree qualitatively with the trace-element model. The slightly larger negative Eu-anomaly and higher *HREE* in the fine-grained granite probably rule out hornblende as the major mafic phase.

The only samples showing the effects of substantial *in situ* fractionation are the late aplites. They plot away from the other rocks on the trace-element plots (Fig. 5), being much lower in Ba and Sr and higher in Rb. They also have very evolved major-element compositions (*e.g.*, >75% SiO_2, <1.5% FeO + MgO + CaO). They plot along a line parallel to the "granite" fractionation line for White Point (Fig. 5, particularly 5a), indicating derivation from the group defined by the fine-grained granite plus minor phases by extensive "granite" fractionation involving plagioclase, K-feldspar, quartz and minor mafic phase(s). As was the case for the White Point aplites, the Gillis Mountain aplites are strongly depleted in *LREE* and Eu and enriched in *HREE* compared to the other granitic lithologies, a trend shown by many aplitic rocks (*e.g.*, Lynch & Pride 1984, Noyes *et al.* 1983, Mittlefehldt & Miller 1983).

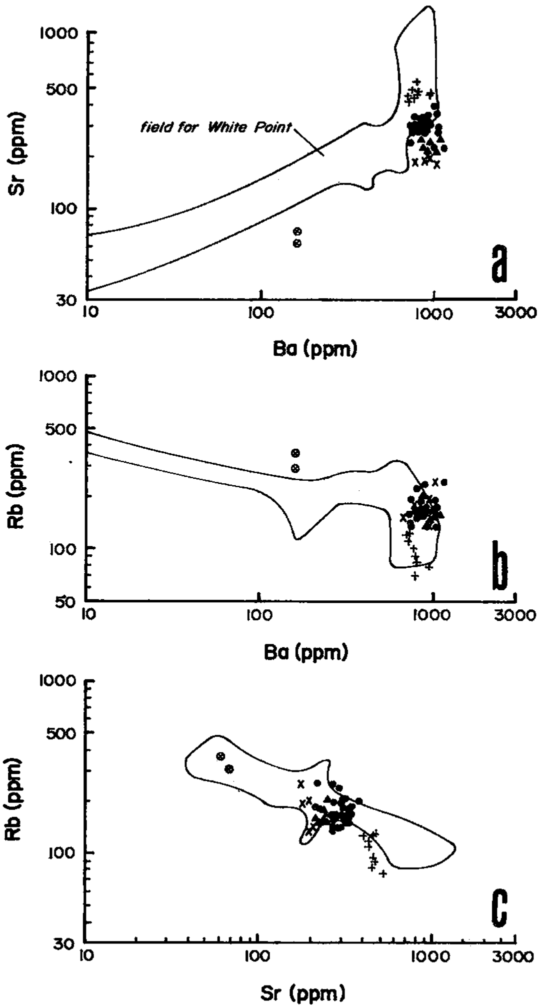

FIG. 5. Sr–Ba (a), Rb–Ba (b), and Rb–Sr (c) plots for samples from the Gillis Mountain pluton, with fields for White Point pluton for comparison. Crosses, quartz monzodiorite; closed circles, porphyritic granite; triangles, fine-grained granite; x, minor phases (dykes); circles with crosses, aplite dykes.

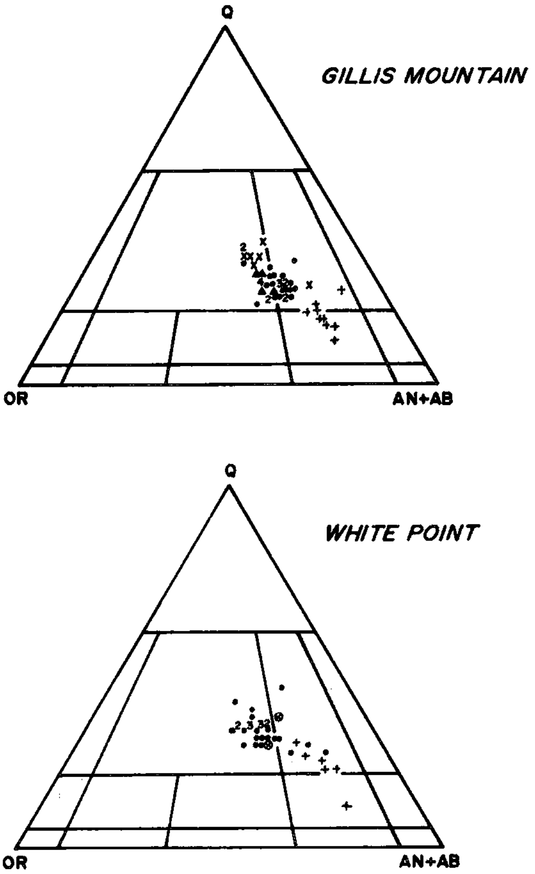

FIG. 6. Normative quartz – orthoclase – (anorthite + albite) triangular plots for Gillis Mountain and White Point plutons. Fields are from Streckeisen (1976). Symbols as in Figures 4 and 5. Numbers in plots represent number of samples plotting at that position.

TABLE 5. MAJOR- AND TRACE-ELEMENT MODELING RESULTS* FOR GILLIS MOUNTAIN PLUTON

	1113	1064	Model
SiO_2	60.68	67.31	65.17
Al_2O_3	15.35	14.50	15.21
FeO	6.66	3.68	4.74
MgO	2.50	1.43	1.52
CaO	4.60	2.68	2.37
Na_2O	3.58	3.59	3.23
K_2O	2.52	4.68	3.73
Rb	103	167	145
Sr	442	340	319
Ba	760	850	990

*Derivation of a typical porphyritic granite (sample 1064) from a typical quartz monzodiorite (sample 1113) by fractional crystallization of 20% plagioclase and 10% hornblende. For major elements, R = 0.11. Distribution coefficients for trace-element modeling are those of Arth & Hanson (1975) for dacitic rocks (for plagioclase) and rhyolitic rocks (for hornblende).

TABLE 6. WITHIN-"GRANITE" FRACTIONATION MODEL FOR GILLIS MOUNTAIN PLUTON AT F=0.75*

	1064 (C^0)	Model (C^L)	1060
Rb	170ppm	224ppm	246ppm
Sr	340	175	180
Ba	850	1056	1035

*After removal of 75% plagioclase and 25% hornblende (or any other mafic phase(s) with low distribution coefficients for Rb, Sr, and Ba) from sample 1064 (porphyritic granite). All Rb, Sr, and Ba are concentrated in the residual liquid. The model yields values very similar to those in sample 1060 (one of the late minor intrusions).

PETROGENESIS

The large number of aplite and pegmatite dykes, the deep level of emplacement, the dominantly minimum-melt-like composition and the high initial $^{87}Sr/^{86}Sr$ ratio together suggest that the White Point pluton was anatectically derived, probably at a slightly deeper level than presently exposed, by H_2O-saturated melting of metasedimentary rocks. The magma was emplaced during a single event, and subsequent minor fractional crystallization, more or less *in situ,* led to the variety of rocks exposed and the observed chemical variations. White Point thus has many of the features of the S-type granites of Chappell & White (1974).

By contrast, a high level of emplacement and a long history of fractionation are indicated for Gillis Mountain. The pluton was emplaced in a series of pulses from a deeper, evolving magma-chamber. Low initial $^{87}Sr/^{86}Sr$ ratios indicate a mantle source, or derivation from material that had only limited previous crustal history. The quartz monzodiorites show many chemical similarities to orogenic andesitic rocks, especially those from western South America, being only slightly higher in Ti and lower in Mg compared to means for such rocks (Ewart 1982) at the appropriate SiO_2 interval. The granitic rocks of Gillis Mountain plot along the trend for high-K dacites from the same environment on the K_2O *versus* SiO_2 plot of Ewart (1982). The presence of porphyry-type mineralization further strengthens the similarity. All of these characteristics are typical of I-type granites in a subduction-related, continental-margin environment, although it is not clear how this can apply to southeastern Cape Breton Island during the Devonian if tectonic models such as those of Keppie (1982) and Williams & Hatcher (1983) are correct. It is more likely that the differences between the plutons may not reflect different tectonic settings, but different nature of crust (source rock) between northern and southern Cape Breton Island.

The longer fractionation history of Gillis Mountain, involving fractional crystallization of a more mafic parent, and a dominantly anatectic origin for White Point readily account for differences in trace-element abundances between the two plutons. For example, the granites of Gillis Mountain are generally lower in Sr and higher in Ba than the White Point granodiorites of approximately the same major-element composition. This is explained by the longer history of fractionation of Gillis Mountain, involving the removal of plagioclase and mafic phases, which would decrease Sr and increase Ba. Because fractional crystallization is a much more efficient means of concentrating incompatible (Ba) and removing compatible (Sr) elements from residual magmas than partial melting (the major influence for White Point granodiorites), the White Point rocks do not show such an initial enrichment in Ba or depletion in Sr. Rb, being mostly an incompatible element (except during biotite fractionation), is higher in Gillis Mountain as well.

The later evolution of White Point, however, does show a strong decrease in Ba due to K-feldspar fractionation. Such behavior is exhibited only by the late aplites at Gillis Mountain. Although both plutons had similar Na_2O and K_2O contents at this stage, and plot in similar positions in the haplogranite system, the higher CaO (and, therefore, anorthite component) in Gillis Mountain expanded the plagioclase field at the expense of both quartz and K-feldspar compared to White Point (James & Hamilton 1969), suppressing the appearance of K-feldspar in Gillis Mountain.

The late aplite dykes, in both plutons, represent residual liquid resulting from extensive fractionation of quartz, plagioclase and K-feldspar. The more strongly depleted character of the White Point aplites with respect to Ba and Sr, compared to those of Gillis Mountain, again reflects the earlier beginning of K-feldspar fractionation.

CONCLUSIONS

Trace-element data, in particular Ba, Rb and Sr, combined with *REE* data, provide the major tools for petrogenetic modeling of these two contrasting granitic plutons. The history of the White Point pluton involved anatectic melting, a single event of emplacement and subsequent, more or less *in situ* fractional crystallization. *REE* patterns, although they appear highly variable, can be interpreted to reflect in large part variable mixtures of cumulate or residual material and liquid. The history of the Gillis Mountain pluton, in contrast, involved high-level intrusion of magma in a series of pulses from a deeper, evolving magma-chamber with a long history of fractionation. *REE* patterns do not appear to be consistent with other petrological evidence for intrusive sequence and genetic relations, and may be of limited use in petrogenetic interpretations for this type of body. The differences between these two plutons may reflect differences in the nature of the crust between northern and southern Cape Breton Island.

ACKNOWLEDGEMENTS

Initial support for mapping and preliminary petrological studies of the White Point and Gillis Mountain plutons was provided by the Nova Scotia Department of Mines and Energy and the Canada Department of Regional Economic Expansion. This current study is funded by operating grants to the authors from the Natural Sciences and Engineering Research Council of Canada. We thank reviewers K.L. Currie and R.A. Jamieson and the editor, R.F. Martin, for their recommendations, which much improved the manuscript.

REFERENCES

ARMBRUST, G.A., OYARZUN, J. & ARIAS, J. (1977): Rubidium as a guide to ore in Chilean porphyry copper deposits. *Econ. Geol.* **72**, 1086-1100.

ARTH, J.G. & HANSON, G.N. (1975): Geochemistry and origin of the early Precambrian crust of northeastern Minnesota. *Geochim. Cosmochim. Acta* **39**, 325-362.

BARR, S.M. & O'BEIRNE, A.M. (1981): Petrology of the Gillis Mountain pluton, Cape Breton Island, Nova Scotia. *Can. J. Earth Sci.* **18**, 395-404.

______, O'REILLY, G.A. & O'BEIRNE, A.M. (1982): Geology and geochemistry of selected granitoid plutons of Cape Breton Island. *Nova Scotia Dep. Mines Energy Pap.* **82-1.**

CHAPPELL, B.W. & WHITE, A.J.R. (1974): Two contrasting granite types. *Pacific Geol.* **8**, 173-174.

CORMIER, R.F. (1972): Radiometric ages of granitic rocks, Cape Breton Island, Nova Scotia. *Can. J. Earth Sci.* **9**, 1074-1086.

______ (1979): Rubidium/strontium isochron ages of Nova Scotian granitoid plutons. *Nova Scotia Dep. Mines Energy Rep.* **79-1**, 143-147.

______ (1980): New rubidium/strontium ages in Nova Scotia. *Nova Scotia Dep. Mines Energy Rep.* **80-1**, 223-234.

EWART, A. (1982): The mineralogy and petrology of Tertiary – Recent orogenic volcanic rocks with special reference to the andesitic – basaltic compositional range. *In* Andesites: Orogenic Andesites and Related Rocks (R.S. Thorpe, ed.). John Wiley & Sons, New York.

FLANAGAN, F.J. (1973): 1972 values for international geochemical reference samples. *Geochim. Cosmochim. Acta* **37**, 1189-1200.

GIBSON, I.L. & JAGAM, P. (1980): Instrumental neutron activation analysis of rocks and minerals. *In* Neutron Activation Analysis in the Geosciences (G.K. Muecke, ed.). *Mineral. Assoc. Can., Short Course Handbook* **5**, 109-131.

GORDON, G.E., RANDLE, K., GOLES, G.G., CORLISS, J.B., BEESON, M.H. & OXLEY, S.S. (1968): Instrumental activation analysis of standard rocks with high resolution gamma ray detectors. *Geochim. Cosmochim. Acta* **32**, 369-396.

HANSON, G.N. (1978): The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet. Sci. Lett.* **38**, 26-43.

HOLLISTER, V.F., POTTER, R.R. & BARKER, A.L. (1974): Porphyry-type deposits of the Appalachian orogen. *Econ. Geol.* **69**, 618-630.

JAMES, R.S. & HAMILTON, D.L. (1969): Phase relations in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_8$–SiO_2 at 1 kilobar water vapour pressure. *Contr. Mineral. Petrology* **21**, 111-141.

KEPPIE, J.D. (1982): The Minas geofracture. *In* Major Structural Zones and Faults of the Northern Appalachians (P. St-Julien & J. Béland, eds.). *Geol. Assoc. Can. Spec. Pap.* **24**, 263-280.

KIRKHAM, R.V. & SOREGAROLI, A.E. (1975): Preliminary assessment of porphyry deposits in the Canadian Appalachians. *Geol. Surv. Can. Pap.* **75-1A**, 249-251.

LEE, D.E. & CHRISTIANSEN, E.H. (1983): The granite problem as exposed in the southern Snake range, Nevada. *Contr. Mineral. Petrology* **83**, 99-116.

LYNCH, G.V. & PRIDE, C. (1984): Evolution of a high-level, high-silica magma chamber: the Pattison pluton, Nisling Range alaskites, Yukon. *Can. J. Earth Sci.* **21**, 407-414.

MCCARTHY, T.S. & GROVES, D.I. (1979): The Blue Tier batholith, northeastern Tasmania. *Contr. Mineral. Petrology* **71**, 193-209.

______ & HASTY, R.A. (1976): Trace element distribution patterns and their relationship to the crystallization of granitic melts. *Geochim. Cosmochim. Acta* **40**, 1351-1358.

MITTLEFEHLDT, D.W. & MILLER, C.F. (1983): Geochemistry of the Sweetwater Wash pluton, California: implications for "anomalous" trace element behavior during differentiation of felsic magmas. *Geochim. Cosmochim. Acta* **47**, 109-124.

NOYES, H.J., FREY, F.A. & WONES, D.R. (1983): A tale of two plutons: geochemical evidence bearing on the origin and differentiation of the Red Lake and Eagle Peak plutons, central Sierra Nevada, California. *J. Geology* **91**, 487-509.

O'BEIRNE, A.M. (1979): *Geology of the Gillis Mountain Pluton, Cape Breton Island, Nova Scotia,* M.Sc. thesis, Acadia Univ., Wolfville, Nova Scotia.

PRIDE, C. & MOORE, J.M., JR. (1983): Petrogenesis of the Elzevir batholith and related trondhjemitic intrusions in the Grenville Province of eastern Ontario, Canada. *Contr. Mineral. Petrology* **82**, 187-194.

STRECKEISEN, A. (1976): To each plutonic rock its proper name. *Earth-Sci. Rev.* **12**, 1-33.

TINDLE, A.G. & PEARCE, J.A. (1981): Petrogenetic modelling of in situ fractional crystallization in the zoned Loch Dooh pluton, Scotland. *Contr. Mineral. Petrology* **78**, 196-207.

WIEBE, R.A. (1975): Origin and emplacement of Acadian granitic rocks, northern Cape Breton Island. *Can. J. Earth Sci.* **12**, 252-262.

WILLIAMS, H. & HATCHER, R.D., JR. (1983): Appalachian suspect terranes. *Geol. Soc. Amer. Mem.* **158**, 33-53.

Received July 10, 1984, revised manuscript accepted September 5, 1985.