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PETROLOGY OF HIGH-Al-HORNBLENDE- AND MAGMATIC-EPIDOTE-BEARING PLUTONS IN THE SOUTHEASTERN CAPE BRETON HIGHLANDS, NOVA SCOTIA

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ABSTRACT

Six large late Precambrian plutons in the southeastern Cape Breton Highlands of Nova Scotia are composed dominantly of diorite, quartz diorite, tonalite, and granodiorite. Their petrochemical characteristics indicate that they are the plutonic equivalents of moderate- to high-K orogenic andesites, formed in a continental margin subduction zone. The occurrence of high-Al hornblende and magmatic epidote in the plutons in the northwest suggests that crustal levels of *ca.* 20 km are exposed in that area. Calculated pressures of hornblende crystallization decrease systematically to the southeast, indicating that granodiorites exposed in that sector crystallized in the epizone. The magmas may have formed by variable amounts of partial melting of mafic granulitic source-rocks, followed by fractionation of mafic minerals and some plagioclase, to produce the internal variation within each pluton.

Keywords: diorite, quartz diorite, tonalite, granodiorite, I-type granite, calc-alkaline, subduction, catazonal, mesozonal, epizonal, Cape Breton Island.

SOMMAIRE

Nous décrivons six plutons volumineux, d'âge précambrien, situés dans la partie sud-ouest du Cap Breton (Nouvelle-Écosse); ils contiennent surtout diorite, diorite quartzifère, tonalite et granodiorite. Leurs caractéristiques pétrochimiques en font les équivalents plutoniques d'une suite andésitique à teneur en potassium moyenne à élevée, typique d'un milieu de subduction près d'une marge continentale. La présence de hornblende riche en Al et d'épidote magmatique dans les plutons du secteur nord-ouest fait penser que des niveaux d'environ 20 km de profondeur y affleurent. Les pressions de cristallisation de la hornblende diminuent progressivement vers le sud-est, et les granodiorites de ce secteur semblent épizonales. Les magmas pourraient résulter d'un taux variable de fusion partielle d'une suite granulitique mafique; un fractionnement de minéraux mafiques (surtout) et de plagioclase est responsable de la variation interne de chaque pluton.

(Traduit par la Rédaction)

Mots-clés: diorite, diorite quartzifère, tonalite, granodiorite, granite de type I, suite calco-alcaline, subduction, catazone, mésozone, épizone, île du Cap-Breton.

INTRODUCTION

Six large plutons composed of hornblende-bearing diorite, quartz diorite, tonalite, and granodiorite are major components of the southeastern Cape Breton Highlands of Nova Scotia (Fig. 1). U–Pb dating has indicated that these plutons crystallized in the time interval between about 565 and 555 Ma (Dunning *et al.* 1990), and hence are approximately contemporaneous. Three of the plutons locally contain epidote having characteristics indicative of magmatic origin, according to the criteria of Zen & Hammarstrom (1984a, b, 1988), and all have mineral assemblages appropriate for the application of the hornblende geobarometer (Hammarstrom & Zen 1986, Hollister *et al.* 1987, Johnson & Rutherford 1989, Rutter *et al.* 1989).

The purpose of this paper is to document the mineral chemistry and petrological characteristics of these plutons, and to use the occurrence of magmatic epidote, combined with the hornblende geobarometer, to interpret their depths of crystallization. This study is particularly significant given the continuing controversy about the applicability of hornblende compositions as geobarometers *versus* geothermometers (*e.g.*, Blundy & Holland 1990, Vyhnal *et al.* 1991).

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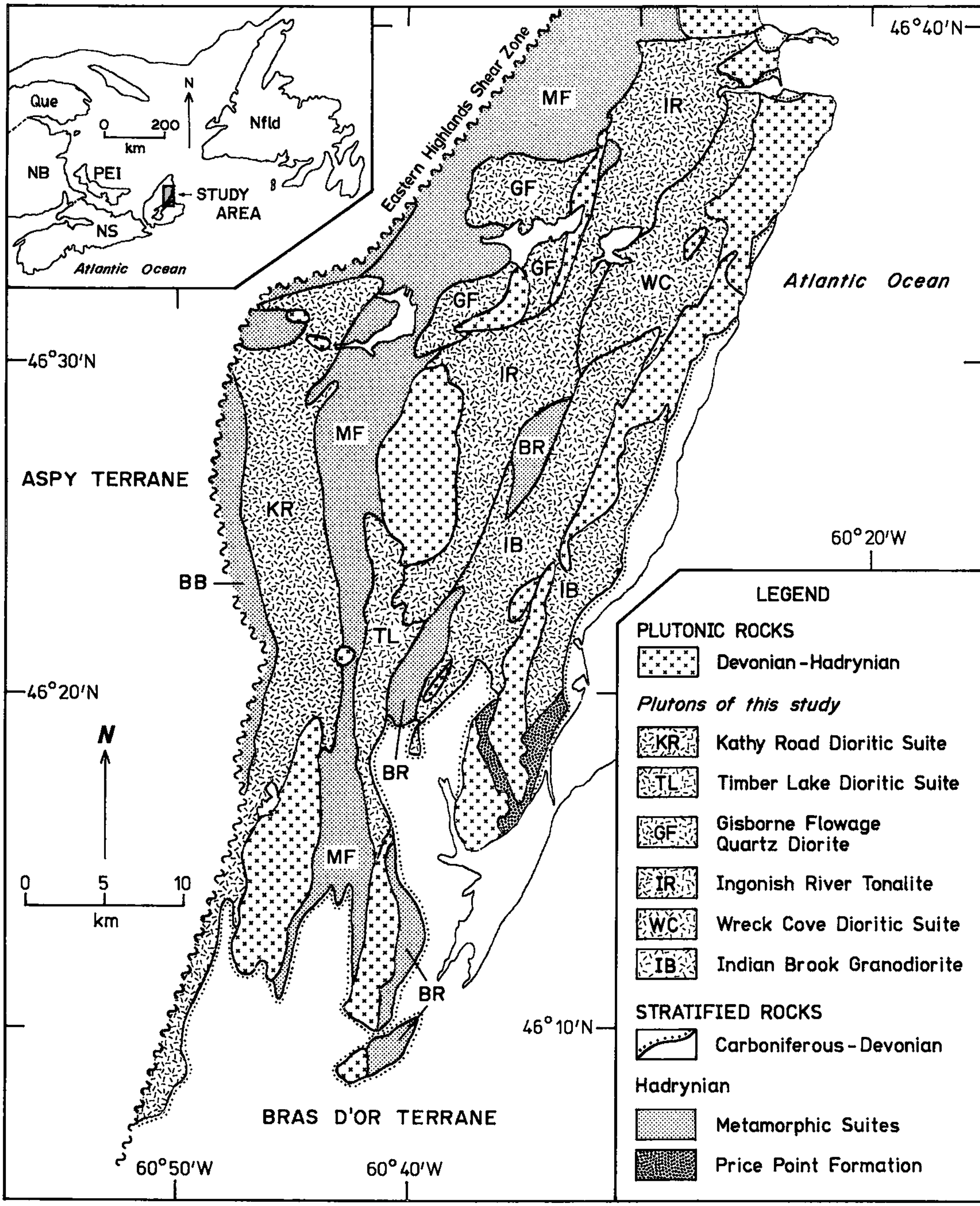

FIG. 1. Simplified geological map of the southeastern Cape Breton Highlands showing plutons that are the focus of this study and associated units (after Barr *et al.* 1985, Farrow 1989, Raeside & Barr, in press). Hadrynian metamorphic suites are Bateman Brook Metamorphic Suite (BB), McMillan Flowage Formation (MF), and Barachois River Metamorphic Suite (BR). Inset map shows location of the study area in eastern Cape Breton Island.

GEOLOGICAL SETTING

Plutons included in this study are the Kathy Road Dioritic Suite, Timber Lake Dioritic Suite, Gisborne Flowage Quartz Diorite, Wreck Cove Dioritic Suite, Ingonish River Tonalite, and Indian Brook Granodiorite, as mapped and named by Barr *et al.* (1985, 1987) and Raeside & Barr (in press). Together, they comprise about half the area of the Bras d'Or terrane (Barr & Raeside 1989) of the southeastern Cape Breton Highlands (Figs. 1, 2, inset). Also present in the area are more felsic hornblende-free plutons that range in age from Hadrynian to Devonian; these are not included in

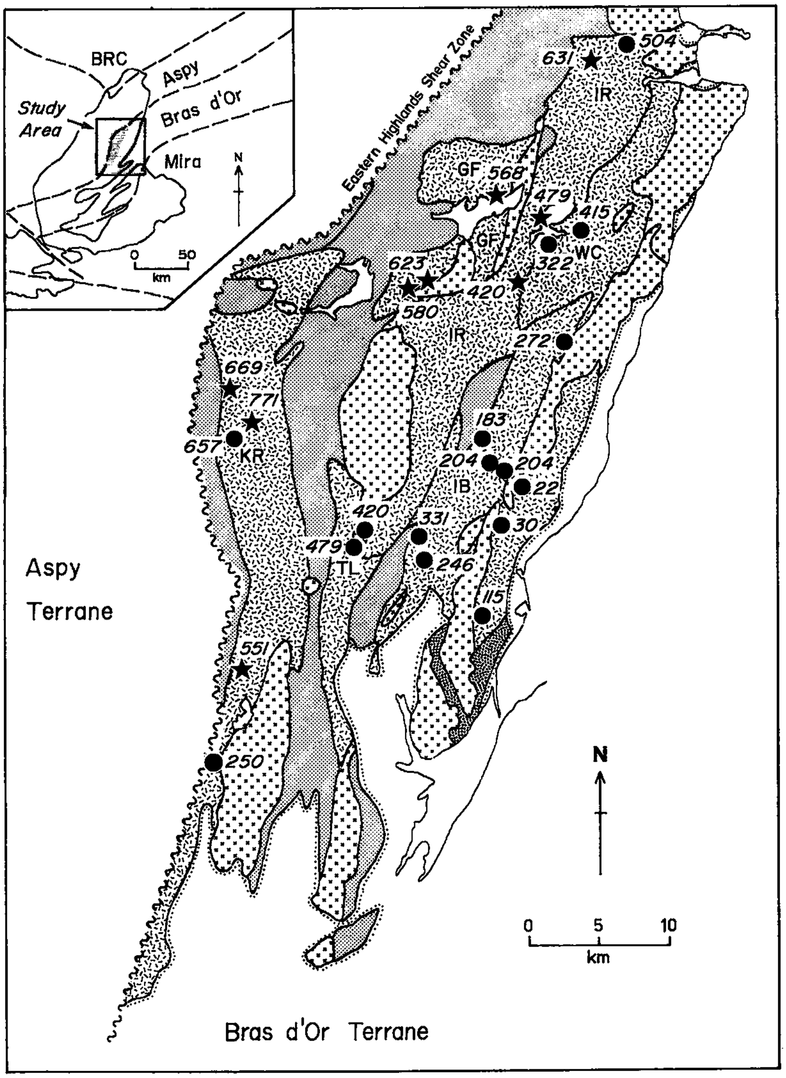

FIG. 2. Simplified geological map of the southeastern Cape Breton Highlands (legend as in Fig. 1), showing locations for samples in which mineral compositions were analyzed; stars indicate locations of samples in which magmatic epidote was observed; circles indicate locations of other samples. Adjacent numbers are average pressures (in MPa) of hornblende crystallization calculated using the equation of Johnson & Rutherford (1989). The data are from Table 2, in which samples are listed from north to south within each pluton. Inset map shows proposed terranes in Cape Breton Island after Barr & Raeside (1989).

the present study. Metamorphic rocks of the Bateman Brook Metamorphic Suite, McMillan Flowage Formation, Barachois River Metamorphic Suite, and Price Point Formation occur in association with the plutonic units (Fig. 1) (Barr *et al.* 1985, Raeside & Barr 1990, in press). Although contacts are not well exposed and faulting is widespread, all of these units appear to have been intruded by one or more of the 565–555 Ma plutons.

Because they are generally separated by other units, contact relations among the plutons are known in only some cases, and relative ages are mainly based on radiometric ages. U–Pb (zircon) data indicate that the Kathy Road Dioritic Suite (560 ± 2 Ma) and the Gisborne Flowage Quartz Diorite (564 ± 2 Ma) are of similar age (Dunning *et al.* 1990). Although undated, the Timber Lake Dioritic Suite is similar in petrological features to the Kathy Road Dioritic Suite, and hence is assumed to be of essentially the same age. The Ingonish River Tonalite is somewhat younger, with a U–Pb (zircon) age of 555 ± 2 Ma (Dunning *et al.* 1990). The tonalite contains dioritic xenoliths near contacts with the Wreck Cove Dioritic Suite, indicating that the Wreck Cove unit is older than the tonalite, consistent with the maximum $^{40}Ar/^{39}Ar$ hornblende plateau age of about 561 Ma for the Wreck Cove diorite (Reynolds *et al.* 1989). U–Pb dating of zircon and titanite has demonstrated minimum and maximum ages of crystallization of 564 ± 5 Ma and 575 Ma for the Indian Brook Granodiorite (Dunning *et al.* 1990).

PETROGRAPHY

Dioritic plutons

Rocks of the Kathy Road Dioritic Suite, Timber Lake Dioritic Suite, Wreck Cove Dioritic Suite, and Gisborne Flowage Quartz Diorite vary from diorite through quartz diorite to tonalite (using the classification of Streckeisen 1976), with quartz diorite being the most abundant lithology. The dominant major minerals are plagioclase (andesine) and hornblende, with much less abundant quartz and biotite. K-feldspar is a minor interstitial component in many samples, and clinopyroxene, partially replaced by amphibole, occurs rarely in the Kathy Road, Timber Lake, and Wreck Cove plutons. Locally, diorites of these three plutons lack biotite and are very hornblende-rich. The Gisborne Flowage pluton is characterized by a much greater abundance of biotite compared to the other three dioritic plutons.

Textures are typically medium-grained hypidiomorphic granular to inequigranular, and rarely porphyritic. In the latter case, the phenocrysts are of plagioclase or hornblende. Compositional and textural variations appear to be gradational within each suite; Wreck Cove is the most varied pluton, and in some areas, changes in both composition (from diorite to quartz diorite or tonalite) and texture (from fine- to coarse-grained and locally pegmatitic and from porphyritic to equigranular) occur within a single large outcrop. In some outcrops of the Kathy Road and Timber Lake plutons, compositional banding suggestive of igneous layering is present. Foliation is present locally in all four dioritic plutons. Generally, it appears to have been the result of shearing near the margins; however, in places flow foliation defined by alignment of hornblende and plagioclase has been preserved.

Accessory minerals include epidote, titanite, apatite, allanite, zircon, ilmenite, and magnetite. Secondary (alteration) products include epidote, chlorite, actinolitic amphibole, and "saussurite". Although secondary epidote is abundant, some of the epidote in most samples from the Gisborne Flowage Quartz Diorite and in many samples from the central and northern parts of the Kathy Road Dioritic Suite is inferred to be of magmatic origin (Fig. 2) because it displays the characteristic features described by Zen & Hammarstrom (1984a). These include epidote with euhedral contacts with biotite, epidote forming overgrowths on partially resorbed, embayed hornblende, epidote with zoning and with zones of inclusions, and epidote displaying wormy intergrowths with plagioclase. In both plutons, magmatic epidote occurs only in samples that contain modal biotite.

Ingonish River Tonalite

The Ingonish River Tonalite is similar in both major and accessory mineralogy to the dioritic plutons but is more leucocratic, with more abundant plagioclase and quartz relative to mafic minerals. It also contains more biotite relative to hornblende than the dioritic plutons, with these two mafic minerals occurring in approximately equal abundance. The amount of K-feldspar (microperthitic microcline) increases in abundance toward the south, where the pluton is locally granodioritic to monzogranitic in composition. The texture is generally medium- to coarse-grained hypidiomorphic granular, with mafic minerals tending to occur in clusters. Magmatic epidote is a prominent accessory mineral in many samples, and displays features like those described in the dioritic plutons. Other accessory minerals and secondary minerals in the tonalite also are similar to those in the dioritic plutons.

Indian Brook Granodiorite

The Indian Brook Granodiorite consists dominantly of zoned plagioclase (oligoclase–andesine), perthitic microcline, quartz, hornblende, and biotite. The texture is medium grained, hypidiomorphic granular. Abundant large interstitial grains of titanite are typically present; other accessory minerals include zircon, apatite, and magnetite. Alteration tends to be more intense than in the other plutons, and includes moderate to intense saussuritization of plagioclase, chloritization of mafic minerals, replacement of hornblende by actinolite, and pervasive hematitization. Although secondary epidote is abundant, no epidote with features indicative of magmatic origin was observed.

AMPHIBOLE CHEMISTRY

Chemical compositions

Representative compositions of the amphibole are presented in Table 1. The amphibole is calcic, as defined by Leake (1978), with $[Ca+Na]_B$ greater than 1.34 and Na_B less than 0.67. In most cases, the amphibole has $(Na + K)_A$ less than 0.5, and is mainly tschermakite to tschermakitic hornblende in the Kathy Road and Timber Lake suites, tschermakitic hornblende to magnesio-hornblende in the Gisborne Flowage, Wreck Cove, and Ingonish River plutons, and magnesio-hornblende in the Indian Brook Granodiorite. However, some grains, mostly in the Gisborne Flowage Quartz Diorite, have $(Na + K)_A$ slightly more than 0.5 and consist of magnesian hastingsite, magnesian hastingsitic hornblende, edenitic hornblende, ferrotschermakite, or ferroan pargasitic hornblende. However, for simplicity in subsequent discussion, all the amphibole is referred to as hornblende.

The suite of hornblende compositions display variation in aluminum content, both from one pluton to another and within individual plutons. On average, hornblende from the Kathy Road Dioritic Suite contains the highest total aluminum, and hornblende in the Wreck Cove and Indian Brook plutons has the lowest aluminum content (*e.g.*, Table 1). The differences in aluminum content appear to be reflected in color differences in thin section. Hornblende in the Wreck Cove and Indian Brook plutons is pleochroic, with Z = dark green, Y = medium green, and X = beige to pale yellow, whereas higher-aluminum hornblende in the Kathy Road, Gisborne Flowage, and Ingonish River plutons has Z = dark blue or blue-green, Y = medium blue-green, and X = beige to pale yellow.

Hornblende geobarometry and geothermometry

Geobarometers based on the aluminum content of hornblende equilibrated with quartz have been proposed by Hammarstrom & Zen (1986), Hollister *et al.* (1987), and Johnson & Rutherford (1989) for rocks containing the mineral assemblage quartz + plagioclase + K-feldspar + hornblende + biotite + titanite + an oxide phase (magnetite or ilmenite). The equations proposed by these investigators give somewhat different results, with the lowest calculated pressures obtained from the equation of Johnson & Rutherford (1989). For the present study, pressures were calculated using all

TABLE 1. REPRESENTATIVE COMPOSITIONS OF AMPHIBOLE FROM PLUTONS OF THIS STUDY

PLUTON	KRDS				TLDS		GFQD		IRT				WCDS		IBG			
Sample	SB-84-49		SB-84-134		AM-84-53		K09-S21		K09-S103		AM-84-52		CF-88-409		AM-84-36a		AM-84-86	
	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim	core	rim
SiO_2	41.79	42.72	42.15	42.20	41.23	42.49	40.83	40.99	42.55	43.35	41.83	41.72	45.82	45.59	47.03	46.98	46.73	47.75
TiO_2	0.77	0.73	0.75	0.84	1.19	1.07	0.62	0.57	1.02	1.03	0.90	0.96	0.65	0.69	0.99	1.04	1.23	1.02
Al_2O_3	14.18	13.53	12.25	12.13	11.16	10.99	12.06	12.38	12.04	11.56	10.84	11.03	8.93	9.21	7.35	7.33	7.23	6.71
Cr_2O_3	0.05	0	0.10	0.10	0.06	0.10	0.10	0.09	0.03	0	0.08	0.08	0.09	0.10	0.04	0.04	0.03	0.04
FeO	16.86	17.04	18.07	18.50	18.49	18.50	19.63	19.08	18.12	17.13	18.79	19.00	14.88	14.96	15.01	15.09	14.03	13.98
MnO	0.32	0.33	0.44	0.41	0.42	0.42	0.56	0.53	0.52	0.52	0.60	0.57	0.42	0.46	0.69	0.66	0.58	0.61
MgO	9.66	9.79	9.77	9.61	9.72	9.73	8.59	8.54	10.02	10.70	9.89	9.68	12.89	12.62	12.49	12.66	13.20	13.63
CaO	11.82	11.91	11.61	11.76	12.07	11.98	12.02	11.84	11.90	11.83	11.55	11.75	12.12	12.20	12.02	12.01	11.99	12.00
Na_2O	1.52	1.45	1.41	1.51	1.56	1.60	1.49	1.54	1.08	1.16	1.34	1.28	1.33	1.24	0.97	0.98	1.19	0.97
K_2O	0.86	0.71	1.48	1.25	1.57	1.50	1.40	1.28	1.02	0.90	1.34	1.37	0.95	0.94	0.60	0.64	0.71	0.58
Total	97.82	98.21	98.02	98.31	97.46	98.37	97.29	96.83	98.28	98.17	97.16	97.44	98.08	98.01	97.19	97.43	96.92	97.29
NUMBER OF CATIONS ON THE BASIS OF 23 OXYGEN ATOMS																		
Si	6.21	6.31	6.31	6.31	6.27	6.39	6.23	6.27	6.31	6.40	6.33	6.31	6.72	6.70	6.95	6.93	6.92	7.00
^{IV}Al	1.79	1.69	1.69	1.69	1.73	1.61	1.77	1.73	1.69	1.60	1.67	1.70	1.28	1.30	1.05	1.07	1.08	1.00
^{VI}Al	0.69	0.67	0.47	0.44	0.27	0.34	0.40	0.50	0.41	0.41	0.26	0.27	0.27	0.29	0.24	0.20	0.18	0.17
Cr	0.01	0	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Fe^{3+}	0.45	0.43	0.50	0.50	0.46	0.34	0.54	0.45	0.67	0.60	0.68	0.66	0.40	0.40	0.30	0.34	0.25	0.34
Ti	0.09	0.08	0.08	0.09	0.14	0.12	0.07	0.07	0.11	0.11	0.10	0.11	0.07	0.08	0.11	0.12	0.14	0.11
Mg	2.14	2.16	2.18	2.14	2.20	2.18	1.95	1.95	2.21	2.35	2.23	2.18	2.82	2.76	2.75	2.78	2.91	2.98
Fe^{2+}	1.64	1.67	1.76	1.81	1.89	1.99	1.97	1.99	1.58	1.52	1.70	1.74	1.42	1.43	1.56	1.52	1.49	1.38
Mn	0.04	0.04	0.06	0.05	0.05	0.05	0.07	0.07	0.07	0.07	0.08	0.07	0.05	0.06	0.09	0.08	0.07	0.08
Ca	1.88	1.89	1.86	1.88	1.97	1.93	1.97	1.94	1.89	1.87	1.87	1.90	1.91	1.92	1.90	1.90	1.90	1.89
Na	0.44	0.42	0.41	0.44	0.46	0.47	0.44	0.46	0.31	0.33	0.39	0.38	0.38	0.35	0.28	0.28	0.34	0.28
K	0.16	0.13	0.28	0.24	0.30	0.29	0.27	0.25	0.19	0.17	0.26	0.26	0.18	0.18	0.11	0.12	0.13	0.11

Abbreviations: KRDS Kathy Road Dioritic Suite, TLDS Timber Lake Dioritic Suite, GFQD Gisborne Flowage Quartz Diorite, IRT Ingonish Tonalite, WCDS Wreck Cove Dioritic Suite, IBG Indian Brook Granodiorite. Analyses at Dalhousie University by JEOL-733 electron microprobe with four wavelength-dispersion spectrometers and a Tracor Northern 145-eV energy dispersion detector. Operating conditions were 15 kV at 5 na beam current. Geological standards were used. A Tracor Northern ZAF matrix correction programme was utilized for data reduction. Formulae were calculated using the programme AMPHIBOL (Richard & Clarke 1990).

TABLE 2. CALCULATED PRESSURES AND TEMPERATURES BASED ON HORNBLENDE

						Pressure (MPa)			Temp. (°C)
PLUTON	SAMPLE	n	Al[t]	Si	Ab	H&Z	H et al	J&R	B&H
KRDS	SB-84-49	6	2.40	6.26	0.51	815	878	669	855
	SB-84-42	1	2.64	6.23	0.51	936	1013	771	843
	SB-84-41	3	2.37	6.27	0.51	800	861	657	853
	SB-84-134	6	2.13	6.32	0.51	679	725	551	858
	SB-84-124	5	1.41	6.90	0.51	317	319	260	769
TLDS	AM-84-53	1	1.95	6.39	0.55	589	624	479	837
GFQD	K10-S21	3	2.16	6.27	0.64	694	742	568	816
	CF-88-14	2	2.29	6.20	0.64	760	816	623	823
	RR-84-8	4	2.19	6.22	0.64	710	759	580	825
IRT	K09-S103	1	2.01	6.40	0.50	619	958	504	852
	K09-S89	1	2.31	6.33	0.50	770	827	631	847
	K10-S8	2	1.95	6.56	0.50	589	624	479	818
	SB-86-3184	2	1.81	6.55	0.50	518	545	420	830
	AM-84-52	3	1.81	6.49	0.50	518	545	420	844
WCDS	K10-S14	4	1.80	6.56	0.52	513	539	416	820
	CF-88-409	3	1.58	6.67	0.52	403	477	322	809
IBG (West)	AM-84-7	6	1.46	6.71	0.65	342	347	272	763
	RR-87-5503	4	1.25	7.04	0.65	237	229	183	703
	AM-84-36A	7	1.30	6.91	0.65	262	257	204	729
	AM-84-35	7	1.30	6.90	0.65	262	257	204	732
	AM-84-74	7	1.60	6.68	0.65	413	426	331	761
	AM-84-75	4	1.40	6.82	0.65	312	305	246	743
IBG (East)	AM-84-86	7	0.87	7.16	0.65	46	15	22	697
	AM-84-16	5	0.89	7.10	0.65	56	26	30	710
	IBG-1	4	1.09	6.91	0.65	156	139	115	742

*Pluton abbreviations as in Table 1. Pressures were calculated using the equations of Hammarstrom & Zen 1986 (H&Z), Hollister et al. 1987 (H et al.), and Johnson and Rutherford 1989 (J&R). Calculated pressures of hornblende crystallization are multiplied by 100 to give values in MPa. Temperatures were calculated using the equations of Blundy & Holland (1990) with the calculated pressures from the equation of Johnson & Rutherford (1989). n = number of hornblende rim analyses used to calculate average total aluminum (Al[t]) and average silicon (Si) per formula unit. Ab is the co-existing plagioclase composition.

three equations for comparison (Table 2); the patterns displayed by the data are the same in all three cases, but the pressures calculated using the equation of Johnson & Rutherford (1989) seem most compatible with adjacent metamorphic units and are cited in the following discussion and shown on Figure 2.

The application of the hornblende geobarometer has been questioned, on the basis that the Al content of hornblende is more sensitive to temperature than to pressure, and a geothermometer has been proposed for hornblende coexisting with plagioclase in silica-saturated rocks (Blundy & Holland 1990). Temperatures have been calculated for the units of this study (Table 2) using the equation of Blundy & Holland (1990) and utilizing the pressures calculated by the equation of Johnson & Rutherford (1989).

The calculated pressures are highest for samples from the northern part of the Kathy Road Dioritic Suite, and they generally decrease to the east and south (Table 2, Fig. 2). The pressures suggest that the northern part of the Kathy Road Dioritic Suite, as well as the adjacent Gisborne Flowage Quartz Diorite, crystallized at mesozonal to catazonal depths, whereas the southernmost part of the Kathy Road Dioritic Suite formed at a much shallower depth. This variation is broadly consistent with a change in metamorphic grade documented in the adjacent McMillan Flowage Formation from amphibolite facies in the north to greenschist facies in the south, although the pressures indicated by mineral assemblages in the northern part of the McMillan Flowage Formation are not as high as those indicated by the hornblende geobarometer for adjacent parts of the Kathy Road Dioritic Suite and Gisborne Flowage Quartz Diorite (Raeside & Barr 1986, 1990).

The Timber Lake, Ingonish River, and Wreck Cove units yield intermediate pressures of crystallization, and the lowest pressures are from the southeastern part of the Indian Brook Granodiorite; these results indicate crystallization at a pressure less than 100 MPa (epizonal). The latter is consistent with the preservation in that area of subgreenschist-facies volcanic rocks of the Price Point Formation (Fig. 1) (Raeside & Barr 1990).

In contrast to pressures, the temperatures calculated using the equation of Blundy & Holland (1990) show a relatively small range within each pluton that does not exceed the reported uncertainty for their calibration (± 75°C). As would be expected, higher temperatures are generally indicated for the dioritic plutons compared to the Indian Brook Granodiorite.

EPIDOTE CHEMISTRY

Chemical compositions

Epidote grains of inferred magmatic origin from the Kathy Road, Gisborne Flowage, and Ingonish River plutons commonly show a decrease in Al and increase in Fe contents from core to rim (Table 3). This is attributed to replacement of Al by Fe^{3+} near the margins of magmatic epidote crystals and subsequent growth of more Fe-rich epidote. Similar compositional differences are apparent between magmatic and secondary epidote, with compositions of secondary epidote similar to rim compositions on magmatic epidote grains. Secondary epidote also tends to be lower in Ti; Cr, Mg, Mn, and Na contents are variable, whereas Ca content is relatively constant (Table 3).

The average proportion of the pistacite component ranges from 24.5% in the Kathy Road Dioritic Suite to 26.8% in the Ingonish River Tonalite. These values are slightly lower than those of epidote with textural relationships (*e.g.*, replacement of plagioclase) that indicate a secondary origin; such epidote generally contains between 26 and 27% (Table 3). However, both types of epidote have pistacite components within the range 25 to 29 that has been reported to be typical of magmatic epidote (Tulloch 1979, 1986, Vyhnal *et al.* 1991).

The epidote compositions documented in this study differ markedly from those analyzed by Vyhnal *et al.* (1991) from monzogranitic plutons in the southern Appalachian Orogen. The latter typically have a higher proportion of the pistacite component, lower Si, Al, and Ca, and higher Fe.

Pressure implications

Naney (1983) showed that epidote is stable in synthetic H_2O-saturated tonalitic and granodioritic melts at $f(O_2)$ values between the nickel–bunsenite (NB) and hematite–magnetite (HM) buffers, at temperatures between the solidus (600°C) and approximately 700°C, and at pressures at least in the 600 to 800 MPa range. Zen & Hammarstrom (1984a) proposed that magmatic epidote forms near the solidus of the crystallizing magma according to the following schematic reaction:

2 hornblende + 2 alkali feldspar + 1 magnetite + nH_2O + mO_2 = 3 epidote + 3 biotite + 6 quartz.

Minimum pressures of crystallization lower than

TABLE 3. REPRESENTATIVE COMPOSITIONS OF MAGMATIC AND SECONDARY EPIDOTE

	Magmatic Epidote						Secondary Epidote		
	KRDS		GFQD		IRT		KRDS	IRT	WCDS
	Core	Rim	Core	Rim	Core	Rim			
SiO_2	38.02	37.68	37.74	38.28	37.80	37.61	37.84	37.69	37.36
TiO_2	0.15	0.15	0.11	0.10	0.37	0.12	0.05	0.12	0.07
Al_2O_3	25.18	23.77	24.89	24.54	24.11	22.93	22.92	22.56	23.19
Cr_2O_3	0.04	0.08	0	0.03	0.07	0.06	0.05	0.02	0.08
FeO^t	10.57	12.63	11.53	12.23	11.36	13.09	13.23	12.97	12.11
MnO	0.32	0.08	0.23	0.24	0.36	0.23	0.32	0.16	0.48
MgO	0.07	0.03	0	0	0.05	0	0.05	0	0.19
CaO	23.31	23.54	25.55	23.71	23.44	23.46	23.25	23.88	23.25
Na_2O	0.07	0.09	0.01	0	0.09	0.05	0.03	0.09	0.08
Total	97.74	98.05	98.05	99.12	97.65	97.55	97.74	97.49	96.80
NUMBER OF CATIONS ON THE BASIS OF 25 OXYGEN ATOMS									
Si	3.06	3.06	3.05	3.07	3.07	3.09	3.10	3.10	3.08
Al	2.39	2.28	2.37	2.32	2.31	2.22	2.21	2.19	2.25
Fe^t	0.75	0.86	0.78	0.82	0.77	0.90	0.91	0.89	0.83
Cr	0.003	0.01	0	0.002	0.004	0.004	0.003	0.001	0.01
Ti	0.01	0.01	0.01	0.01	0.02	0.01	0.003	0.01	0.004
Mg	0.01	0.004	0	0	0.01	0	0.01	0	0.02
Mn	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.03
Ca	2.01	2.05	2.04	2.04	2.04	2.06	2.04	2.10	2.05
Na	0.01	0.01	0.002	0	0.01	0.01	0.005	0.01	0.01
Ps%	22.95	27.37	24.73	26.12	25.05	28.82	29.05	28.97	27.03

Epidote analyses by electron microprobe as in Table 1.
Ps% = pistacite component.
Pluton abbreviations as in Table 1.

600 MPa were suggested for more silica-rich rocks such as calc-alkaline granite, whereas pressures higher than 800 MPa were proposed for less silica-rich rocks, including quartz diorite and diorite (Zen & Hammarstrom 1986). Magmatic epidote in two-mica granite commonly is more pistacite-rich and formed at considerably lower pressure than is indicated by the hornblende–epidote association (Zen & Hammarstrom 1988).

More recently, the high-pressure origin of magmatic epidote in hornblende-bearing rocks has been questioned, because epidote with features that suggest magmatic origin occur in rocks for which the calculated pressures of crystallization for coexisting hornblende are as low as 280 ± 50 MPa (Vyhnal *et al.* 1990). However, the bulk compositions of the rocks are monzogranitic rather than tonalitic and granodioritic, and a high-pressure origin for epidote in rocks of the latter compositions appears still to be valid.

The occurrence of magmatic epidote in the Kathy Road Dioritic Suite, Gisborne Flowage Quartz Diorite, and Ingonish River Tonalite is consistent with the high calculated pressures of hornblende crystallization (Fig. 2). The Timber Lake and Wreck Cove dioritic suites and the Indian Brook Granodiorite lack magmatic epidote, and in these plutons, hornblende geobarometry has yielded pressures of crystallization too low to be compatible with crystallization of magmatic epidote in rocks of quartz dioritic and granodioritic composition.

Whole-Rock Chemistry

General characteristics

Means and standard deviations for major and trace element concentrations are compiled in Table 4. Results of the analyses and sample locations for the dioritic and tonalitic units are presented by Farrow (1989). Data for the Indian Brook Granodiorite are given in Table 5.

The Timber Lake, Wreck Cove, and Kathy Road dioritic plutons have average silica contents typical of mafic rocks (less than 52%), with the lowest average in the Timber Lake Dioritic Suite. The lowest silica values are from samples with high concentrations of mafic minerals (mainly hornblende), and each unit has a range in silica contents and corresponding variations in other elements, as illustrated in Figure 3, consistent with the variation in modal composition of the samples that range from diorite through to quartz diorite and tonalite. The Gisborne Flowage Dioritic Suite has generally higher silica content than the other three dioritic suites, averaging about 55%, although some samples have SiO_2 values as low as 50% (Fig. 3).

The Ingonish River Tonalite has a higher average

TABLE 4. MEANS AND STANDARD DEVIATIONS OF CHEMICAL COMPOSITIONS OF PLUTONS[1] OF THE STUDY AREA

PLUTON (n)	TLDS (n=5)		WCDS (n=9)		KRDS (n=15)		GFQD (n=10)		IRT (n=20)		IBG (n=11)	
SiO_2	47.31	± 4.45	51.49	± 6.19	51.91	± 4.41	55.15	± 2.58	59.21	± 2.72	64.10	± 4.37
TiO_2	0.76	0.24	0.81	0.25	0.82	0.27	0.81	0.15	0.53	0.09	0.48	0.15
Al_2O_3	18.34	2.97	16.16	1.43	17.47	1.43	17.76	0.62	17.08	0.67	15.27	1.50
$Fe_2O_3^t$	10.42	1.62	10.09	2.61	9.70	1.55	8.03	1.12	6.94	1.11	4.87	1.64
MnO	0.19	0.02	0.17	0.03	0.18	0.03	0.17	0.02	0.14	0.02	0.10	0.04
MgO	6.64	2.04	5.89	1.81	5.34	0.77	3.63	0.52	3.39	0.57	2.10	0.98
CaO	10.11	1.77	9.02	2.40	9.26	1.45	7.48	1.40	6.69	1.25	4.07	1.57
Na_2O	2.10	0.79	2.24	0.67	2.62	0.39	3.27	0.31	2.83	0.21	3.33	0.42
K_2O	1.43	0.21	1.45	0.46	0.88	0.43	2.16	0.77	1.71	0.42	3.24	1.02
P_2O_5	0.35	0.38	0.18	0.10	0.16	0.05	0.25	0.09	0.15	0.02	0.16	0.06
LOI	2.22	0.65	2.32	0.95	1.24	0.60	0.97	0.44	1.38	0.43	1.81	0.86
Total	99.86	0.42	99.82	0.59	99.58	0.42	99.61	0.39	100.04	0.52	99.53	0.83
Ba	224	57	215	97	166	76	491	132	326	86	439	106
Rb	55	9	43	20	28	17	62	26	49	18	95	37
Sr	439	97	385	70	368	61	588	115	426	57	343	132
Y	21	7	21	7	22	6	25	3	18	2	22	4
Zr	62	16	93	56	82	30	173	56	93	18	164	27
Nb	5	1	7	2	6	1	9	2	7	2	10	2
Cu	78	23	132	71	91	38	44	30	61	24	38	35
Pb	16	16	9	2	10	<1	10	1	8	3	10	3
Zn	104	20	94	24	91	17	90	12	79	8	64	17
Ni	31	25	30	21	25	12	10	2	6	3	8	3
Cr	72	77	45	45	55	51	14	9	24	9	39	14
V	297	124	302	125	301	63	209	40	198	39	123	66
Ga	18	3	18	3	18	2	18	2	18	2	16	2
Th	10	0	8	3	9	3	9	3	4	3	15	13

[1]Pluton abbreviations as in Table 1. Analytical data for TLDS, WCDS, KRDS, GFQD and IRT from Farrow (1989), and for IBG from Table 5. Analyses by X-ray fluorescence as described by Farrow (1989).

TABLE 5. CHEMICAL COMPOSITION OF INDIAN BROOK GRANODIORITE

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	71.68	67.59	65.15	66.66	63.41	57.55	61.32	64.19	67.01	63.85	56.73
TiO_2	0.37	0.42	0.48	0.16	0.54	0.61	0.53	0.54	0.40	0.54	0.73
Al_2O_3	11.68	13.54	15.98	14.92	15.47	16.53	16.13	15.16	16.10	15.49	16.97
$Fe_2O_3{}^t$	3.50	3.41	4.47	2.52	4.98	7.04	6.06	5.05	3.52	5.08	7.91
MnO	0.06	0.07	0.08	0.05	0.08	0.15	0.13	0.12	0.10	0.11	0.18
MgO	1.14	1.16	1.09	1.63	1.52	3.81	2.79	2.47	1.42	2.44	3.58
CaO	2.07	2.90	3.72	2.52	3.26	7.12	5.65	3.82	3.50	4.18	6.07
Na_2O	2.48	3.43	3.46	3.21	3.05	3.24	3.34	3.24	3.88	3.23	4.10
K_2O	4.42	4.08	3.34	3.89	4.14	1.83	2.73	3.90	2.43	3.57	1.32
P_2O_5	0.10	0.13	0.14	0.06	0.13	0.17	0.17	0.18	0.16	0.17	0.32
LOI	3.06	2.94	1.70	1.56	3.26	1.50	0.99	1.21	0.97	1.10	1.60
Total	100.54	99.67	99.59	97.18	99.84	99.55	99.84	99.86	99.49	99.76	99.51
Ba	267	570	459	487	547	329	308	524	553	514	399
Rb	123	138	108	143	135	46	74	109	60	110	43
Sr	60	242	335	216	288	452	350	356	468	406	500
Y	25	-	25	21	25	18	15	26	17	25	22
Zr	217	-	157	113	177	167	142	161	186	167	155
Nb	10	-	12	11	10	8	13	10	8	10	5
Cu	5	8	78	5	5	38	105	58	11	51	20
Pb	10	9	10	10	10	5	10	14	12	-	-
Zn	62	58	49	36	71	76	72	69	54	57	96
Ni	7	-	14	6	8	9	8	11	5	6	10
Cr	57	-	37	41	51	56	36	35	37	23	14
V	48	-	94	43	137	222	145	140	52	116	228
Ga	14	-	14	14	15	18	16	17	16	18	17
Th	43	-	11	27	10	2	10	12	6	12	-

Analyses by X-ray fluorescence as described by Farrow (1989). Sample locations given in minutes of latitude 46°N and minutes of longitude 60°W; 1, 20.75 & 32.4; 2, 20.7 & 32.5; 3, 20.75 & 33.1; 4, 19.3 & 33.7; 5, 20.55 & 33.8; 6, 30.8 & 28.85; 7, 30.85 & 28.9; 8, 26.95 & 29.95; 9, 25.95 & 32.7; 10, 20.8 & 32.2; 11, 26.5 & 33.4.

SiO_2 content of about 59%, but overlaps in SiO_2 content with more silicic samples from the dioritic units, and with the more mafic samples from the Indian Brook Granodiorite (Fig. 3). The Indian Brook Granodiorite shows a wide range in silica content from about 57 to 72%, with an average value of 64%. This range in chemical composition corresponds with variations in the proportions of feldspar and mafic minerals in the unit; these variations seem to be gradational.

Taken as a group, the plutons range more or less continuously from mafic to felsic (Fig. 3). Most major element oxides display linear trends on silica variation diagrams (*e.g.*, Fig. 3); TiO_2, Al_2O_3, Fe_2O_3t, MnO, MgO, and CaO display definite negative correlations (correlation coefficients more than -0.7) with silica, whereas K_2O and Na_2O display definite positive correlations (correlation coefficients more than +0.7) with silica. P_2O_5 shows only a moderate correlation (correlation coefficient -0.55), mainly because of scatter in mafic samples that appears to correspond to varying apatite content.

Among the trace elements, Zn, V, and Ga show strong negative correlation with silica (*e.g.*, Fig. 3). Ni and Cu show only moderate correlation, with most of the variation in the mafic plutons. Sr shows moderate negative correlation (correlation coefficient about -0.5) with SiO_2, and both Ba and Rb show positive correlation (+0.5 and +0.7, respectively) with SiO_2. Nb contents are low, between about 5 and 10 ppm. Zr values are high in the Gisborne Flowage Quartz Diorite compared to the other dioritic plutons (Fig. 3).

Petrogenesis

Overall, the chemical variations within each pluton and among the plutons as a group suggest a major role for crystal fractionation in magma evolution. Plots of Rb *versus* Sr and Ba *versus* Sr (Fig. 4) show large increases in Rb and Ba with little change in Sr in going from more mafic to more felsic samples, consistent with fractionation of dominantly hornblende combined with some plagioclase; the latter appears to become more significant in the Indian Brook Granodiorite. The very low Rb and Ba values in some mafic dioritic samples may reflect hornblende accumulation.

Although both Fe and Mg show negative correlation with silica content (Fig. 3, Table 4), the FeO^t/MgO ratio stays approximately constant (Fig. 5), indicative of calc-alkaline affinity (Miyashiro 1974). However, the wide variation in Cr with approximately constant V in the dioritic and tonalitic plutons (Fig. 6) is not typical of calc-alkaline suites. Electron-microprobe analyses of hornblende in these plutons indicate that minor amounts of Cr (up to 0.4% Cr_2O_3) are present (Farrow 1989), and hence Cr variation may have resulted from hornblende fractionation in these plutons. In addition, relict pyroxene cores are present in some hornblende grains, suggesting that earlier fractionation of Cr-bearing pyroxene also may have contributed to the range in Cr values. The lack of change in V suggests that magnetite fractionation was not significant in the dioritic-tonalitic plutons; in contrast, decrease in V with less change in Cr indicates that magnetite may have played a significant role in producing variation in the Indian Brook Granodiorite (Fig. 6).

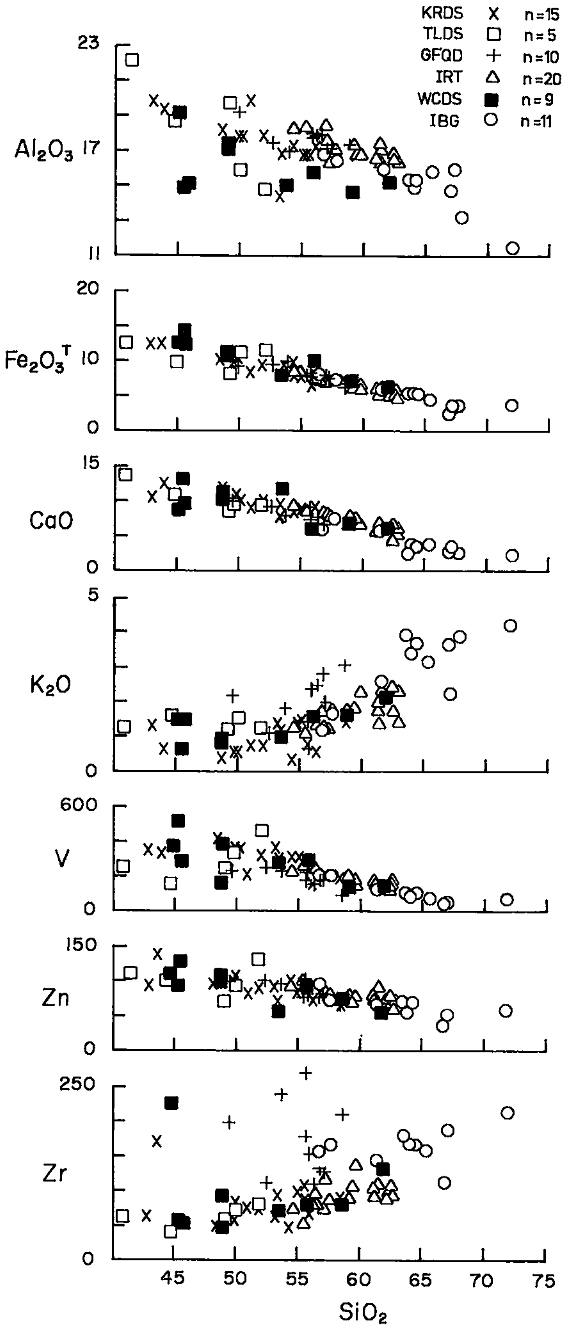

FIG. 3. Silica variation diagrams for selected major element oxides and trace elements in plutons of this study. Data from Farrow (1989) and Table 5.

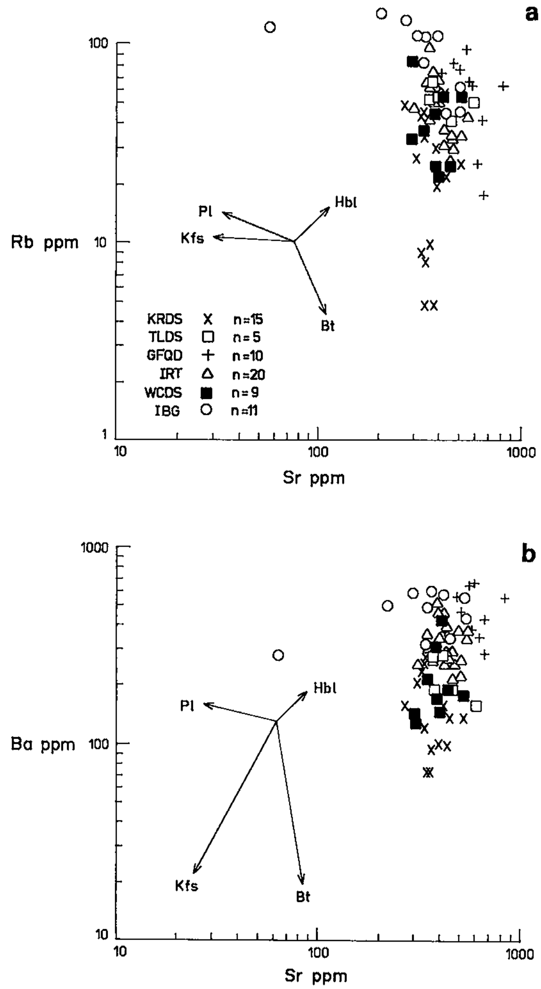

FIG. 4. Plots of (a) Rb–Sr and (b) Ba–Sr for plutons of this study. Vectors show trends for Rayleigh fractionation of 30% plagioclase (Pl), K-feldspar (Kfs), biotite (Bt), and hornblende (Hbl), calculated using the following K_D values (from McCarthy & Hasty 1976, Tindle & Pearce 1981) for plagioclase, K-feldspar, biotite, and hornblende, respectively: Ba: 0.4, 6, 6.36, 0.35; Rb: 0.04, 0.8, 3.26, 0.011; Sr: 3.35, 3.6, 0.12, 0.058.

Distribution in large separate intrusions that in some cases appear to have crystallized over a range of depths does not suggest direct genetic links among the plutons; they are unlikely to be related to one another by differentiation processes. Instead, each pluton may represent an individual evolving batch of magma, perhaps generated from similar source-rocks by varying degrees of partial melting and then subject to fractional crystallization. The similarity in chemical trends displayed by the plutons (Fig. 3) probably represents similarity in both source rocks and subsequent evolution of the batches of magma.

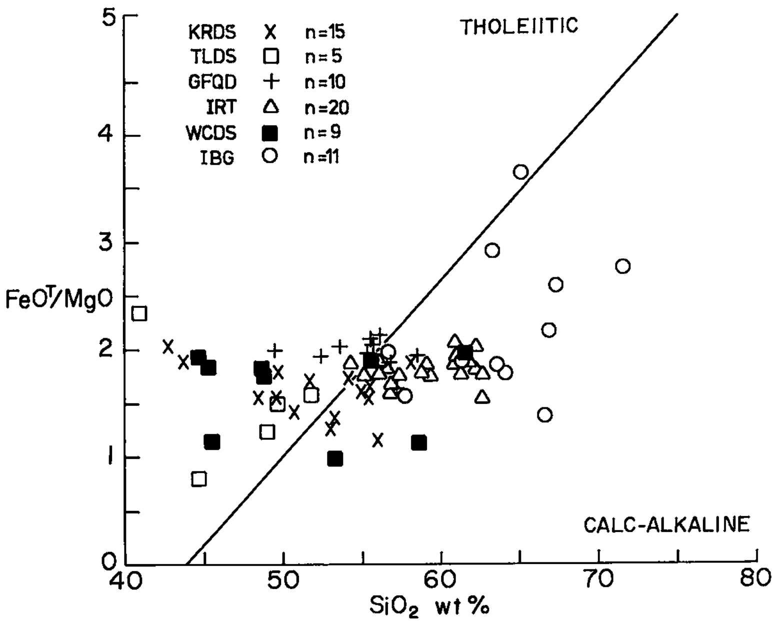

FIG. 5. Plot of FeO^T/MgO against SiO_2, with dividing line between tholeiitic and calc-alkaline rocks after Miyashiro (1974).

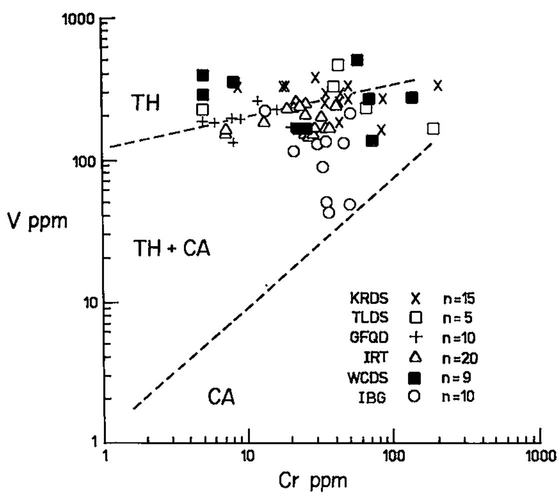

FIG. 6. Plot of V against Cr, with tholeiitic (TH) and calc-alkaline (CA) fields after Miyashiro & Shido (1975).

Rare-earth elements

Rare-earth element (*REE*) data are available for a total of nine samples representing the Kathy Road Dioritic Suite, Gisborne Flowage Quartz Diorite, Ingonish River Tonalite, and Indian Brook Granodiorite (Table 6). Total *REE* abundance is low in the Kathy Road and Ingonish River samples, and much higher (especially in the case of the light *REE*) in samples from the Gisborne Flowage Quartz Diorite and Indian Brook Granodiorite (Fig. 7). This difference is consistent with the abundance of accessory phases (epidote, allanite, zircon, titanite) in the latter two units.

The Kathy Road and Ingonish River samples have essentially identical chondrite-normalized *REE* patterns, with slightly lower heavy *REE* in the Ingonish River Tonalite (Fig. 8). The three samples from Kathy Road Dioritic Suite represent a range of silica contents from low to moderate to high. The low-silica sample has the lowest concentrations of *LREE*, but *HREE* patterns are similar in all three samples, and very flat.

The Gisborne Flowage and Indian Brook samples also have similar *REE* patterns, with a high abundance of heavy *REE* compared to the Kathy Road and Ingonish River samples (Fig. 8).

Overall, the flat *HREE* patterns in all these units are most consistent with an origin by partial melting of source rocks in which neither garnet nor hornblende was present in the residue. The presence of garnet in the residue generally leads to depletion in *HREE*, whereas the presence of hornblende tends to result in concave-upward *HREE* patterns (Hanson 1980), neither of which is indicated by these data (Fig. 8). A mafic granulitic source, with

TABLE 6. RARE-EARTH ELEMENT DATA[1]

	1 KRDS	2 KRDS	3 KRDS	4 IRT	5 IRT	6 GFQD	7 GFQD	8 IBG	9 IBG
La	9.94	10.74	7.94	10.70	9.08	26.59	24.79	31.26	27.57
Ce	23.22	24.78	17.28	25.03	17.63	54.68	55.13	69.18	62.54
Pr	3.12	3.00	2.38	3.38	2.65	6.75	6.89		
Nd	13.25	11.70	10.15	14.36	11.30	25.86	27.35	30.87	24.85
Sm	3.23	2.72	2.73	3.46	2.79	5.19	5.83	6.15	4.13
Eu	0.81	0.63	0.79	0.79	0.62	1.21	1.38	1.44	1.54
Gd	2.95	2.37	2.57	2.77	2.23	3.55	4.34		
Tb	0.50	0.42	0.46	0.45	0.39	0.57	0.69	0.71	0.47
Dy	3.35	2.69	2.94	2.66	2.37	3.46	3.93		
Ho	0.67	0.57	0.65	0.54	0.47	0.64	0.80		
Er	2.05	1.60	1.84	1.64	1.38	1.82	2.22		
Tm	0.28	0.24	0.26	0.23	0.21	0.26	0.31		
Yb	1.99	1.61	1.82	1.65	1.47	1.82	2.17	2.49	1.74
Lu	0.31	0.26	0.28	0.24	0.22	0.28	0.32	0.36	0.28

[1] Analyses 1-7 by ICP-MS at Memorial University, St. John's, Newfoundland. Analyses 8 & 9 by Instrumental Neutron Activation at St. Mary's University, Halifax, Nova Scotia. Sample locations given in minutes of latitude 46°N and minutes of longitude 60°W: 1, 15.5 & 45.5; 2, 23.7 & 42.4; 3, 25.3 & 43.6; 4, 33.1 & 30.8; 5, 23.3 & 39.1; 6, 32.1 & 37.4; 7, 31.5 & 38.0; 8, 20.8 & 32.2; 9, 30.85 & 28.9. Samples 8 and 9 are numbers 10 and 7, respectively, in Table 5.

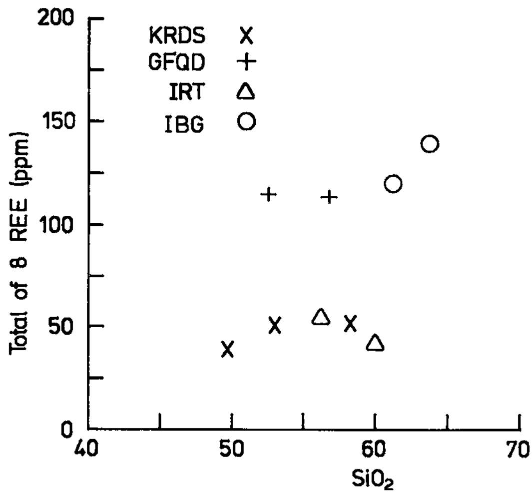

FIG. 7. Total *REE* against SiO_2 for samples from Kathy Road Dioritic Suite, Ingonish River Tonalite, Gisborne Flowage Quartz Diorite, and Indian Brook Granodiorite. Total includes La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu from Table 6.

plagioclase and pyroxene in the residue, could generate melts with *REE* patterns like those displayed by these units. The lack of strong Eu anomalies in most samples suggests either that feldspar fractionation was not a major process or, more likely, given the evidence from other major and trace element data for fractionation of plagioclase and mafic minerals within each unit, that feldspar fractionation was balanced by hornblende fractionation so as to minimize Eu anomalies (Hanson 1980). Fractionation of both feldspar and mafic minerals probably led to enhancement of *LREE* and depletion in *HREE.*

Tectonic setting

Overall, the plutons of the southeastern Cape Breton Highlands are typical of compositionally expanded calc-alkaline I-type suites formed in association with continental-margin subduction zones (*e.g.*, Pitcher 1982, 1987, Brown *et al.* 1984). They are compositionally equivalent to subalkaline basaltic to dacitic volcanic suites formed in such settings (Fig. 9). On diagrams suited for the discrimination of tectonic settings of mafic volcanic rocks, the mafic dioritic samples (SiO_2 less than 52%) generally plot in the volcanic arc fields, although with considerable overlap with ocean-floor fields (Figs. 10a, b).

Further support for origin of these units in a subduction-related setting is their high Al contents; the Gisborne Flowage Quartz Diorite is very similar in average major-element composition to the average high-K, low-SiO_2 orogenic andesite of Gill (1981), and the Ingonish River Tonalite is like the average moderate-K, high-SiO_2 orogenic andesite (Table 7). These similarities to moderate- and high-K arc rocks indicate the presence of thick continental crust. We interpret these units to be the plutonic equivalents of volcanic-arc basalts and andesites and their differentiation products, formed in a late Precambrian subduction zone. The calc-alkaline volcanic rocks of the Price Point Formation (Macdonald & Barr 1985) may be relics of the cogenetic volcanic arc suprastructure, most of which has been removed by erosion farther to the northwest, where deeper crustal levels are exposed.

The apparent difference in age may be related to more rapid cooling and crystallization of the high-level magmas. However, the Ingonish River

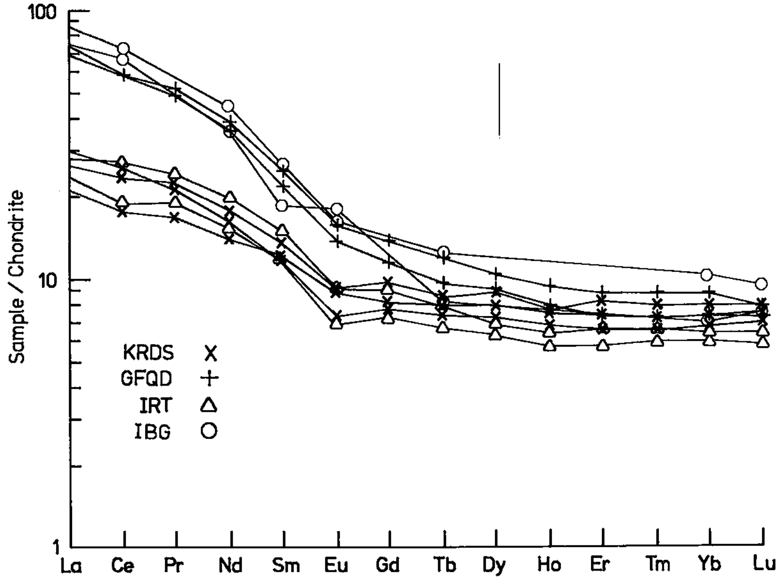

FIG. 8. Chondrite-normalized *REE* patterns for samples from Kathy Road Dioritic Suite, Ingonish River Tonalite, Gisborne Flowage Quartz Diorite, and Indian Brook Granodiorite. Normalization to the chondrite values of Evensen *et al.* (1978).

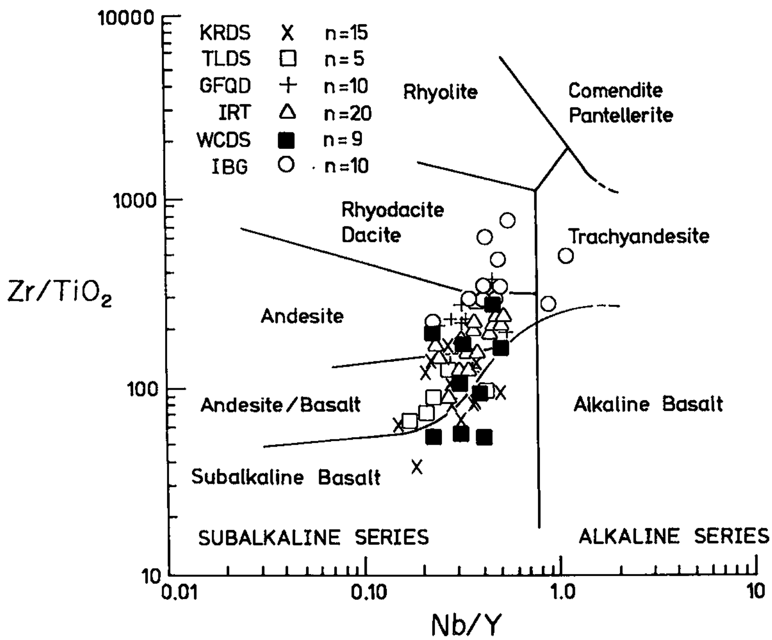

FIG. 9. Plot of Zr/TiO_2 against Nb/Y. Names of volcanic fields after Winchester & Floyd (1977).

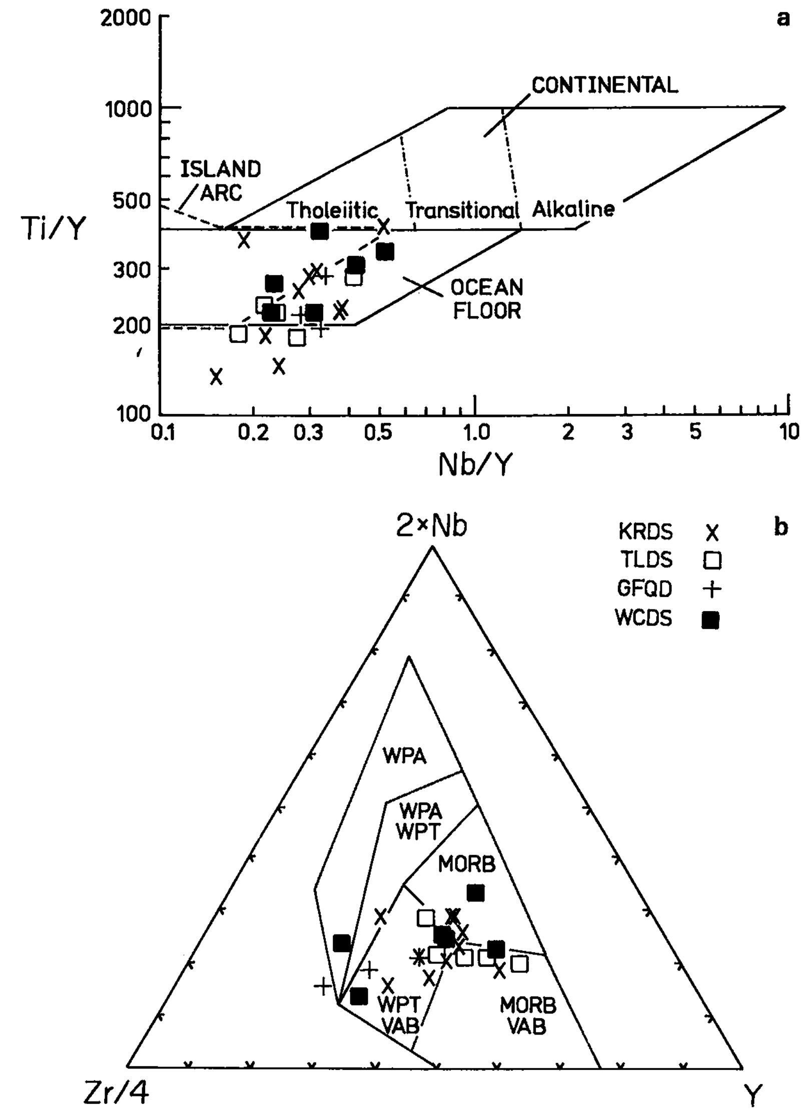

FIG. 10. Mafic samples (SiO_2 less than 52%) plotted on the (a) Ti/Y against Nb/Y diagram of Pearce (1982) and (b) the Nb–Zr–Y triangular diagram of Meschede (1986).

TABLE 7. COMPARISON WITH HIGH-K AND MEDIUM-K OROGENIC ANDESITES*

	GFQD	High-K	IRT	Med-K
SiO_2	55.87	55.7	60.01	60.5
TiO_2	0.82	0.93	0.54	0.71
$Al2O_3$	17.99	18.1	17.31	17.3
FeO^t	8.13	7.6	7.03	6.4
MnO	0.17	0.18	0.14	0.12
MgO	3.68	4.0	3.44	3.2
CaO	7.58	7.8	6.78	6.7
Na_2O	3.31	3.4	2.87	3.3
K_2O	2.19	2.1	1.73	1.5
P_2O_5	0.25	0.31	0.15	0.19

*High-K basic andesite and medium-K acid andesite are from Gill (1981), recalculated to total 100% volatile-free. Average Gisborne Flowage Quartz Diorite (GFQD) and Ingonish River Tonalite (IRT) are from Table 4, recalculated to 100%, volatile-free.

Tonalite appears to be significantly younger, and may represent a later pulse of magmatism.

CONCLUSIONS

Dioritic, tonalitic, and granodioritic plutons of the southeastern Cape Breton Highlands are interpreted to be the roots of a volcanic arc, formed by late Precambrian subduction. The occurrence of high-Al hornblende and magmatic epidote in the northwestern part of the area, the systematic decrease in calculated pressures of hornblende crystallization toward the southeast, and the preservation of volcanic rocks in the southeastern part of the area are consistent with the interpretation that progressively deeper crustal levels are preserved from southeast to northwest across the area. The hornblende geobarometer may not be sufficiently precise to determine the level of exposure in the northwest, but the co-occurrence of high-Al hornblende and magmatic epidote, combined with the nature of the mineral assemblages in adjacent metamorphic units, suggest that the rocks formed at depths equivalent to *ca.* 600 MPa (*ca.* 20 km). More detailed studies of the associated metamorphic units are in progress to further constrain the P–T conditions and tectonic evolution of this area.

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