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LATE PROTEROZOIC HIGH-TITANIUM BASALTS IN THE AVALON ZONE OF NOVA SCOTIA

GEORGIA PE-PIPER
Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3

J. BRENDAN MURPHY
Department of Geology, St. Francis Xavier University, Antigonish, Nova Scotia B2G 1C0

Abstract

Basalts with high contents of Ti are widespread in Late Proterozoic basins in the Avalon zone of northern Nova Scotia. These basins also contain thick andesites and rhyolites, with subduction-related geochemical signatures, that are overlain by turbidites. The high-Ti basalts geochemically resemble some continental tholeiites that are enriched in high-field-strength elements such as Zr, Ti and Y. They are associated with minor basalt of ocean-island-tholeiite and alkaline compositions. A comparison with similar rocks from Africa and the margin of Iapetus suggests that the high-Ti basalts formed by partial melting of mantle similar to that which is the source for enriched MORB. All these enriched continental tholeiites tend to show some depletion in Nb_N and Ta_N relative to La_N: this phenomenon therefore cannot be used as an indicator of a subduction-related origin. The co-occurrence of such enriched mantle and of subduction in northern Nova Scotia appears to be coincidental.

Keywords: basalt, continental tholeiite, subduction, Proterozoic, Avalon zone, Nova Scotia.

Sommaire

Les basaltes à teneur élevée en titane sont répandus dans les bassins d'âge protérozoïque précoce de la zone avalonnienne du nord de la Nouvelle-Ecosse. Ces bassins contiennent aussi d'épais amas d'andésite et de rhyolite possédant une affiliation géochimique à une zone de subduction; ces amas sont recouverts de turbidites. Ces roches basaltiques ressemblent à certaines tholéites continentales enrichies en Zr, Ti et Y; ils sont associés à des quantités moins importantes de basalte typique des îles océaniques et de basalte alcalin. Une comparaison avec des roches semblables d'Afrique et en marge de l'océan Iapétus fait penser que le magma basaltique à teneur élevée en titane a pris naissance dans le manteau dans les mêmes conditions qui favorisent la formation de basalte enrichi des rides océaniques. Toutes ces compositions de basaltes continentaux tholéitiques enrichis ont tendance à montrer un appauvrissement en Nb_N et Ta_N comparé à La_N. C'est donc dire que cet indicateur ne pourrait pas servir pour démontrer une affiliation à une zone de subduction. La juxtaposition de manteau enrichi et de zone de subduction dans le nord de la Nouvelle-Ecosse nous paraît une coïncidence.

(Traduit par la Rédaction)

Mots-clés: basalte, tholéite continentale, subduction, protérozoïque, zone d'Avalon, Nouvelle-Ecosse.

Introduction

In the Avalon zone of Nova Scotia, Late Proterozoic volcano-sedimentary sequences are found in the Antigonish and Cobequid Highlands (Murphy 1988, Pe-Piper & Piper 1989, Pe-Piper & Murphy 1989). The volcanic rocks include a series of andesite, dacite and rhyolite flows and pyroclastic units that appear geochemically related, and geochemically distinct Fe–Ti-rich basalts. These basalts occur as both flows and hypabyssal intrusive bodies. Murphy *et al.* (1990) and Pe-Piper & Piper (1989) have compared these basalts with continental tholeiites, although chemically they have higher concentrations of incompatible minor and trace elements such as P, Zr, Y and light rare-earth elements (*REE*) than do most continental tholeiites described in the literature.

In this paper, we describe the particular distinctive geochemical features of these Fe–Ti-rich mafic rocks, compare them with published data on continental tholeiites elsewhere, and evaluate petrogenetic evidence for their origin.

Geological Setting

Late Proterozoic rocks of the Avalon zone outcrop in the Cobequid and Antigonish Highlands of northern mainland Nova Scotia (Fig. 1). In both areas, the geology

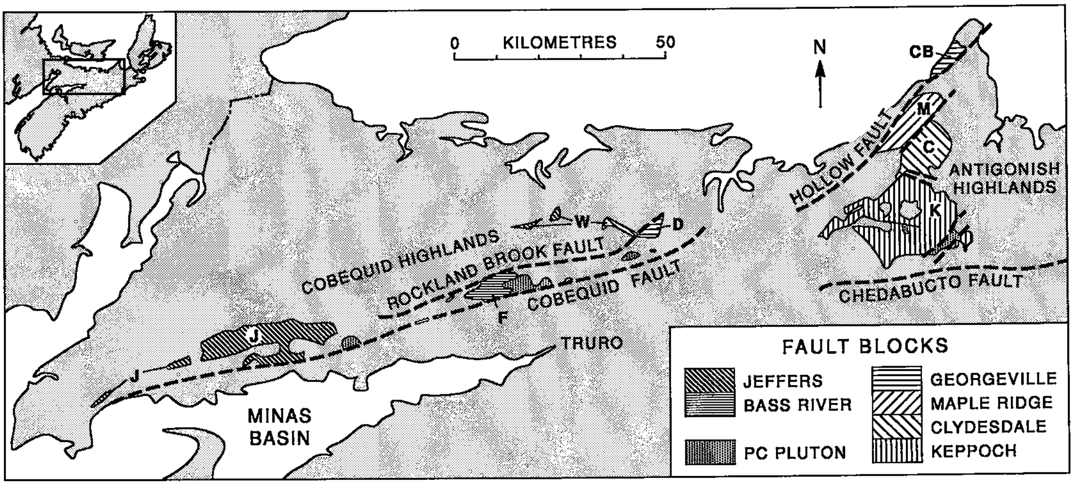


FIG. 1. General geological map of the Precambrian rocks of northern mainland Nova Scotia (modified from Williams 1979, Donohoe & Wallace 1982, Murphy *et al.* 1982, Murphy 1986, and Pe-Piper & Piper 1987). Rocks of the Antigonish Highlands (the Georgeville Group) comprise Clydesdale Formation (C), Chisholm Brook Formation (CB), Keppoch Formation (K), and Maple Ridge Formation (M). Rocks of the Cobequid Highlands comprise Dalhousie Mountain volcanic unit (D), Folly River Formation (F), Jeffers Group (J) and Warwick Mountain Formation (W) (part of Jeffers Group).

is complicated by a long history of strike-slip faulting, dating from the Late Proterozoic to the Carboniferous. The Late Proterozoic rocks in these two highland areas show many similarities and may have originally accumulated in the same basin.

In the Antigonish Highlands, the Late Proterozoic Georgeville Group consists of interbedded volcanic rocks and turbidites up to 3.3 km thick that indicate the formation of a sedimentary basin in which shallow-marine volcanic rocks are overlain by thick turbidites. The northern and possibly the southern margins of the basin are preserved. The Georgeville Group was polydeformed and post-tectonically intruded by granodiorite (Benson 1974, Murphy 1982) in the latest Precambrian and is unconformably overlain by Lower Cambrian strata.

In the northern part of the basin, the Georgeville Group consists of voluminous subaerial to shallow marine basaltic andesites (Chisholm Brook Formation). In the southern part of the basin are interlayered basalts, basaltic andesites and rhyolites (Keppoch Formation). The central part of the basin contains a thick sequence of turbidites and minor basalts (Clydesdale Formation) that overlie the Keppoch Formation (Murphy & Keppie 1987). Two main groups of volcanic rocks are distinguished on the basis of geochemistry (Murphy *et al.* 1990). Basaltic andesites and rhyolites show calc-alkaline chemistry; the basalts of the Clydesdale and Keppoch Formations are rich in Fe and Ti and resemble continental tholeiites. A few basalts in the Clydesdale Formation show alkaline geochemistry (Murphy *et al.* 1990).

In the western Cobequid Highlands (Pe-Piper & Piper 1989), the Jeffers Group (several hundred meters thick) consists of volcanic rocks (Gilbert Hills Formation) that pass upward into turbidites (Cranberry Lake Formation). The entire Group consists of a series of thrust slices; the original extent of the basin is unclear. As in the Antigonish Highlands, there are two geochemically distinct assemblages of volcanic rocks (Pe-Piper & Piper 1989): calc-alkaline andesites, with minor dacites and rhyodacites (Harrington River facies), and Fe–Ti rich basalt and diabase associated with felsic pyroclastic rocks (Lakelands facies). The Jeffers Group was deformed and intruded by latest Proterozoic granodioritic plutons having a calc-alkaline geochemical affinity (Pe-Piper 1988).

In the eastern Cobequid Highlands, the Folly River Formation is probably of the same age as the Georgeville and Jeffers Groups (Pe-Piper & Murphy 1989), and may correlate with the Clydesdale Formation. The formation consists of an entirely marine sequence of basalt flows, very abundant feeder dykes, and interbedded distal turbidites and cherts. It unconformably overlies a previously deformed sequence of shelf orthoquartzites. The lavas and dykes are Fe–Ti-rich basalts geochemically similar to those in the Jeffers and Georgeville Groups (Pe-Piper & Murphy 1989).

The calc-alkaline character of the voluminous andesites to rhyolites of the Georgeville and Jeffers Groups, and of the granodioritic plutons that intrude them, has been accepted as evidence for a subduction-related origin for this cycle of volcanism (Pe-Piper & Piper 1989, Murphy *et al.* 1990). The presence of thick turbidites suggests extensional basins. Using principally paleogeographic criteria, Murphy *et al.* (1990) interpreted the basin of the Georgeville Group as lying within a volcanic arc. Using principally geochemical criteria, Pe-Piper & Piper (1989) interpreted the basin of the Jeffers Group as a back-arc basin.

The Fe–Ti-rich basalts are intimately associated with the calc-alkaline rocks. They are intercalated with andesites in both the Keppoch and Gilbert Hills formations. Furthermore, geochemically similar Fe–Ti-rich mafic bodies occur within the Frog Lake diorite, one of the latest Proterozoic calc-alkaline plutons of the Cobequid Highlands (Hubley 1987).

Petrography and Geochemistry

All the basaltic rocks studied have undergone low-grade greenschist-facies metamorphism, as shown by the presence of chlorite, epidote, actinolite and albite, although relics of primary igneous textures and minerals (including olivine, clinopyroxene, biotite and plagioclase) are commonly observed (Pe-Piper & Piper 1989, Pe-Piper & Murphy 1989).

Representative results of geochemical analyses of the Fe–Ti-rich continental tholeiites of the Cobequid and Antigonish Highlands are shown in Table 1. The rocks analyzed lack macroscopic features of alteration and veins, and have relatively low loss on ignition (LOI). Calculation of norms and Mg number are based on partitioning of iron so that $Fe^{3+}/Fe_t = 0.15$.

Previous regional studies (Pe-Piper & Piper 1989, Pe-Piper & Murphy 1989, Murphy *et al.* 1990) have shown that in individual suites of rocks with varying degrees of alteration, the elements Na, Ca, K, Rb, Ba and Sr show erratic distributions, but other elements, including Fe, Ti, P, Zr, Y and the *REE*, show a regular variation. Although abundances of large-ion lithophile elements (*LILE*) should therefore be treated with caution, fresher samples (*e.g.*, Figs. 2A, B) show consistent abundances of the *LILE*. Abundances of most other elements seem largely unaffected by the low-grade metamorphism. Despite the susceptibility of normative calculations to the effects of alteration, these northern Nova Scotia rocks have normative compositions corresponding to those of continental tholeiites (Thompson *et al.* 1983).

The abundance of selected incompatible trace elements from representative samples of each formation are shown in Figure 2 plotted as "spidergrams" (Thompson *et al.* 1984) of element abundances normalized to chondrite abundances. On the basis of abundance of

TABLE 1. CONCENTRATION OF MAJOR AND TRACE ELEMENTS IN REPRESENTATIVE HIGH-Ti BASALTS FROM NORTHERN NOVA SCOTIA

Strat. unit	Clydesdale Formation		Folly River Formation				Keppoch Formation	Jeffers Group	
Rock type	cont. thol.	alk. bas.	cont. thol.	cont. thol.	ocean isl. thol.	cont. thol.	cont. thol.	cont. thol.	alk. bas.
Sample	1	2	3	4	5	6	7	8	9
	10156	10147	9-5-1	10-4-8	10-4-1	6-2-3	14245	C1211	C1159
Major elements (wt%) by XRF									
SiO_2	46.90	48.40	49.73	49.51	47.47	47.52	45.80	45.64	42.29
TiO_2	3.00	2.60	1.96	1.76	2.13	3.41	2.42	2.40	2.70
Al_2O_3	14.70	17.80	13.12	13.13	12.65	12.51	15.10	14.80	17.04
Fe_2O_3t	16.80	10.70	13.00	11.13	15.07	15.00	14.10	13.93	13.62
MnO	n.d.	n.d.	0.22	0.23	0.25	0.23	0.66	0.27	0.10
MgO	6.10	7.50	6.43	7.21	7.02	5.22	6.48	7.47	7.99
CaO	7.20	6.20	10.40	9.89	10.00	10.07	7.26	8.84	4.78
Na_2O	2.80	3.40	3.62	3.29	2.50	2.55	2.38	2.55	1.69
K_2O	1.40	2.70	0.20	0.17	0.13	0.87	1.63	1.01	6.53
P_2O_5	0.90	0.70	0.17	0.12	0.17	0.49	0.33	0.31	0.34
L.O.I.	n.d.	n.d.	0.50	3.10	2.00	0.60	2.62	2.50	1.77
Total	99.80	100.00	99.35	99.54	99.39	98.47	98.78	99.72	98.85
Normative minerals									
ne	-	2.0	-	-	-	-	-	-	8.1
ol	17.1	23.3	15.1	9.1	10.2	5.5	18.8	13.0	28.6
di	5.8	0.9	26.9	24.0	22.3	23.3	7.4	16.2	1.9
hy	12.7	-	1.7	11.2	16.1	14.7	9.7	8.8	-
qz	-	-	-	-	-	-	-	-	-
[Mg] number	46	62	54	60	52	45	52	56	58

Trace elements (ppm) by XRF									
Ba	925	888	93	89	60	258	520	279	1170
Rb	35	60	1	2	-	19	60	55	328
Sr	372	293	102	157	208	261	500	291	186
Y	54	30	35	27	37	38	30	33	23
Zr	249	293	143	110	133	240	150	148	160
Nb	11	88	5	5	5	16	22	12	26
Pb	-	-	-	-	-	3	-	11	16
Ga	22	21	16	14	25	29	-	21	27
Zn	-	-	127	90	132	127	-	114	46
Ni	-	105	61	69	53	44	40	72	128
V	53	329	413	369	468	400	270	298	291
Cr	335	387	107	219	87	56	44	113	215
REE and other trace elements (ppm) by INAA									
La	27	70	n.d.	n.d.	5.7	20.9	26	11.2	16.1
Ce	61	132	n.d.	n.d.	17	52	48	25.1	31.5
Nd	30	50	n.d.	n.d.	14	27	24	17.1	18.9
Sm	6.50	8.60	n.d.	n.d.	4.88	7.63	6.30	4.72	3.97
Eu	2.80	2.20	n.d.	n.d.	1.70	2.46	2.40	1.83	1.56
Tb	n.d.	n.d.	n.d.	n.d.	1.30	1.40	2.4	0.73	0.57
Yb	4.40	3.00	n.d.	n.d.	4.64	4.09	0.4	2.51	1.42
Lu	0.60	0.40	n.d.	n.d.	0.67	0.59	n.d.	0.41	0.22
Cs	n.d.	n.d.	n.d.	n.d.	0.50	1.90	n.d.	6.86	12.52
Hf	5.0	6.0	n.d.	n.d.	3.1	4.9	n.d.	2.9	2.6
Sb	n.d.	n.d.	n.d.	n.d.	0.20	0.20	n.d.	-	0.66
Sc	47	35	n.d.	n.d.	50.1	40.2	32	29.1	23.6
Ta	n.d.	n.d.	n.d.	n.d.	0.50	0.80	n.d.	0.57	1.26
Th	n.d.	n.d.	n.d.	n.d.	0.30	1.70	n.d.	0.87	1.46
U	n.d.	n.d.	n.d.	n.d.	0.2	0.5	n.d.	0.13	0.6

n.d. not determined; - not detected. Analyses by X-ray fluorescence using a Philips PW 1400 sequential X-ray fluorescence spectrometer with a Rh-anode X-ray tube. Major-oxide determinations were carried out on fused glass discs, whereas concentrations of trace elements were determined from pressed powder pellets. International reference rocks, with recommended values from Abbey (1983), as well as in-house standards, were used for calibration. Analytical precision, as determined from replicate analyses, is generally better than 2%, except for MgO, Na_2O and Nb, which are better than 5%, and Th, which is better than 10%. Loss on ignition (L.O.I.) was determined by treating the sample for 1.5 hr at 1050°C in an electric furnace. The rare-earth-element concentrations were determined by neutron activation analysis, with at least two standard reference materials chosen so as to roughly correspond to the composition of the unknowns. Values of the concentration of elements in the rock standards are those reported by Govindaraju (1989). The precision of the results, as determined on replicate analyses, is generally better than 5% for La, Ce, Eu, Tb, Yb, Lu, Th, Sc, and Co, and better than 10% for Nd, Sm, Cs, Hf, Ta, and U. Calculation of norms and Mg number are based on a partition of iron so that Fe^{3+}/Fe_t = 0.15.

incompatible minor and trace elements, three groups of basalts are distinguished in the Late Proterozoic volcanic sequences of northern Nova Scotia (in addition to basaltic andesites of calc-alkaline affinity).

Enriched continental tholeiites

Trace-element patterns typical of continental tholeiites [using criteria of Thompson *et al.* (1983) and Dostal & Dupuy (1984)] are found in most samples of the Folly River Formation (illustrated by sample 6 in Fig. 2A) and Clydesdale Formation (Sample 1, Fig. 2B) and in some rocks from the Keppoch Formation. In these rocks, there generally is a slight and gradual decline in normalized abundances of elements from Ba to Yb. Nb and Ta are less enriched than La and Ce, and, in general, Ba shows rather low relative enrichment. The relative enrichment of elements from Nd to Yb in the spidergram is substantially greater than that in most continental tholeiites, even for unfractionated samples with high Mg-number and low normative orthopyroxene (*e.g.*, samples 3, 4 in Fig. 2A and Table 1), but is similar to that in some high-Ti tholeiites described in the literature (see below). We refer to this type of rock as an enriched continental tholeiite.

Rocks from the Jeffers Group (*e.g.*, sample 8, Fig. 2B) and some samples from the Keppoch Formation (*e.g.*, sample 7, Fig. 2B) show similar behavior to the enriched continental tholeiites from the Folly River Formation, except that there is greater enrichment in the *LILE*, La_N and Ce_N are similar to Ta_N and Nb_N, and high-field-strength (*HFS*) elements are not so enriched.

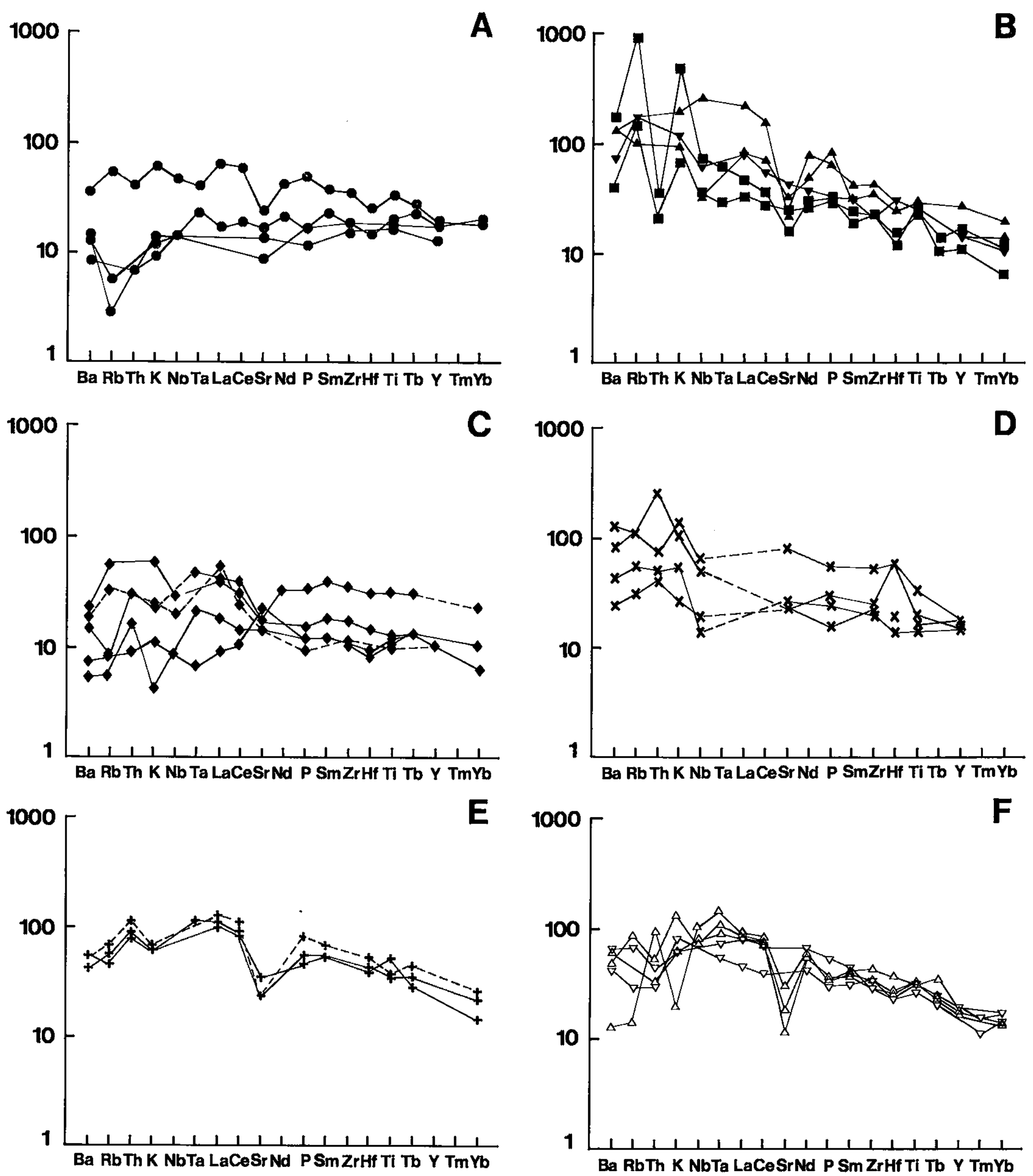


FIG. 2. Abundances of incompatible trace elements in representative samples normalized to chondrite (method of Thompson *et al.* 1984). A. Folly River Formation and Jeffers Group (numbers refer to Table 1). B. Keppoch Formation, Clydesdale Formation, Jeffers Group (numbers refer to Table 1). C. Representative continental tholeiites from the literature. Typical continental tholeiites: 1 North Mountain Basalt (Dostal & Dupuy 1984), 2 Avalon Dyke (Papezik & Hodych 1980), 3 feldspar-phyric tholeiites, west Greenland (O'Nions & Clarke 1972), 4, 5 olivine tholeiites, west Greenland (O'Nions & Clarke 1972). D. Enriched continental tholeiites from north Karoo (Duncan *et al.* 1984). E. Enriched continental tholeiites from Liberia (Dupuy *et al.* 1988). F. Enriched continental tholeiites from the Late Precambrian margin of Iapetus (Coish *et al.* 1985, Ratcliffe 1987).

Oceanic island tholeiite

Some samples (*e.g.*, 5 from the Folly River Formation) show variations in concentration of incompatible elements more like what is found in olivine (oceanic island) tholeiites (Fig. 2A), with an increase in normalized abundance from Ba to Ta, followed by a decrease, so that La and Ce are less enriched than Nb and Ta. The elements Ba to Nb are less enriched than Yb. *HFS* elements are less abundant than in the enriched continental tholeiites.

Alkaline rocks

A few samples from the Clydesdale Formation (*e.g.*, sample 2, Fig. 2B) show systematically high enrichment of elements from Ba to Ce, characteristic of alkaline rocks, although they show high values of La and Ce as well as Nb. Some Jeffers Group rocks (*e.g.*, sample 9, Fig. 2B) also show alkaline tendencies, with enrichment in Nb and Ta.

Comparative Geochemistry of Continental Tholeiites

Although the enriched continental tholeiites of northern Nova Scotia are more enriched in the elements Sr, Nd and the high-field-strength elements P to Yb compared with most continental tholeiites (such as those illustrated in Fig. 2C), some similar high-Ti rift-related tholeiites have been reported. These include:

(1) Ti-rich tholeiites from the northwestern margin of Iapetus (Coish *et al.* 1985, Ratcliffe 1987), illustrated in Figure 2F and by open triangles in Figure 3. These show similar concentrations of incompatible trace elements to the Folly River Formation, except that Nb and Ta are generally enriched relative to K, La and Ce (Fig. 3D). Coish *et al.* (1985) compared these rocks with e-type MORB and continental tholeiites.

(2) Ti-rich tholeiites from the northern Karoo (Duncan *et al.* 1984), which show similar or slightly higher abundances of both *HFS* and *LIL* elements compared with the Nova Scotian rocks (Fig. 2D). The Karoo tholeiites, however, are more highly fractionated (lower Mg-number and higher proportion of normative quartz) than all but the most fractionated Nova Scotian rocks. Their Ba/La ratio (x in Fig. 3A) is almost MORB-like, and Th content is high (Fig. 3F). The Karoo rocks were interpreted as derived from enriched mantle (Duncan *et al.* 1984).

(3) Ti-rich tholeiites from the early Mesozoic dykes of Liberia (group II of Dupuy *et al.* 1988) (Fig. 2E, + in Fig. 3) also are similar to the Nova Scotian tholeiites except that, like the Karoo rocks, they are more highly fractionated. On the basis of trace element and Sr and Nd isotopic data, Dupuy *et al.* (1988) proposed that the high degree of enrichment is the result of a low degree of partial melting of mantle without significant modification by either continental crust or "subduction-related" subcontinental lithosphere.

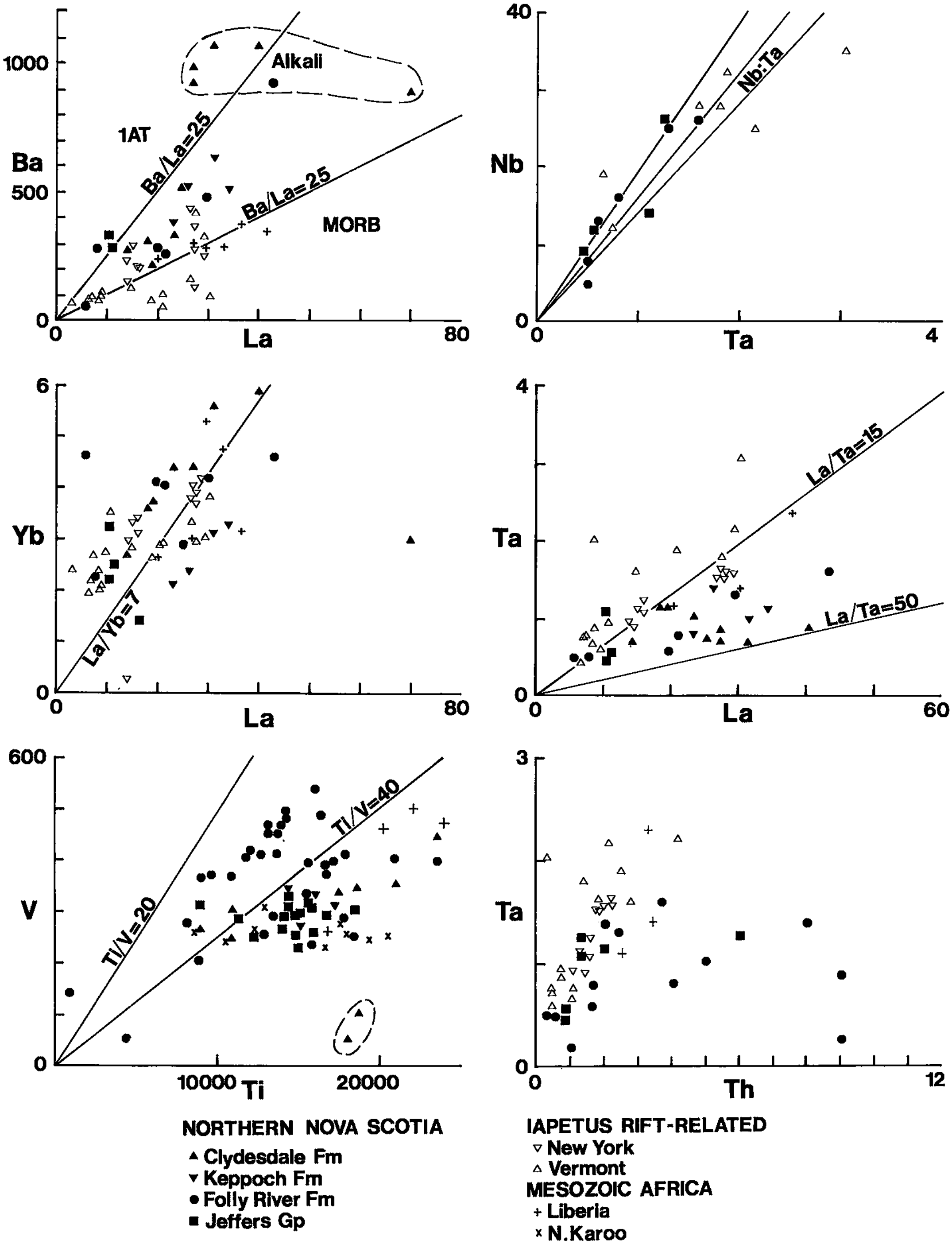
In general, high-Ti tholeiites of the Jeffers Group and Keppoch Formation rocks tend to be slightly enriched in *LILE* and the *LREE* compared with Folly River Formation rocks and other enriched continental tholeiites, such as the Iapetus rift-related rocks (Figs. 3A, E, F). Although *LILE* abundances must be treated with caution, it is noteworthy that in the Jeffers Group and Keppoch Formation, unlike the Folly River Formation, the enriched continental tholeiites are intercalated with calc-alkaline rocks.

Discussion

Suites of continental flood basalt suites include: (1) alkaline rocks, (2) olivine tholeiites that resemble ocean island basalt in their trace element signature, and (3) continental tholeiites, showing *LILE* enrichment and Nb and Ta depletion (Thompson *et al.* 1983). A number of mechanisms have been proposed for the enrichment of continental tholeiites in *LIL* elements: trace element and isotopic studies indicate that there is contamination by crustal material, either within the continental crust, or within inhomogeneous subcontinental lithosphere (*e.g.*, Dostal & Dupuy 1984, Duncan 1987).

The general association of the *LILE*-enriched continental tholeiites of the Antigonish and Cobequid Highlands with less voluminous rocks of both olivine (ocean island) tholeiite and alkaline character is similar to that found generally in rift associations dominated by continental tholeiites (Thompson *et al.* 1983). The possible

FIG. 3. Variation in concentrations of trace elements in selected enriched continental tholeiites from northern Nova Scotia, the Late Precambrian margin of Iapetus [Vermont: Coish *et al.* (1985), New York: Ratcliffe (1987)], and in the Mesozoic of Africa [Liberia, Group II of Dupuy *et al.* (1988), northern Karoo from Duncan (1987)]. Approximate range of ratios of trace elements in MORB, ocean-island tholeiites (OIT) and island-arc tholeiites (IAT) from Dupuy *et al.* (1988). (A) Ba *versus* La: Ba/La = 10 is the maximum value in a typical MORB; Ba/La the minimum value in typical IAT. (La not determined for Karoo). (B) Nb *versus* Ta: Nb/Ta = 16 is normal value for alkaline rocks (Green & Pearson 1987). Ta is concentrated relative to Nb in titanite, rutile and ilmenite (Nb not determined for Liberia, Ta not determined for Karoo). (C) Yb *versus* La: La/Y = 7 is maximum value in typical IAT. (La not determined for Karoo). (D) Ta *versus* La: La/Ta = 50 is minimum value for IAT, La/Ta = 15 is maximum value for OIT and MORB (La, Ta not determined for Karoo, Ta for Clydesdale and Keppoch estimated as Ta = Nb/16). (E) V *versus* Ti: Ti/V = 20 approximately separates IAT from MORB, Ti/V = 40, MORB from OIT. (F) Ta *versus* Th (Ta for Keppoch, Clydesdale and Karoo estimated as Ta = Nb/16).


Ba
La
1AT
Alkali
Ba/La=25
Ba/La=25
MORB
Nb
Ta
Nb:Ta
Yb
La
La/Yb=7
Ta
La
La/Ta=15
La/Ta=50
V
Ti
Ti/V=20
Ti/V=40
Ta
Th
NORTHERN NOVA SCOTIA
▲ Clydesdale Fm
▼ Keppoch Fm
● Folly River Fm
■ Jeffers Gp
IAPETUS RIFT-RELATED
▽ New York
△ Vermont
MESOZOIC AFRICA
+ Liberia
× N.Karoo

olivine tholeiites and alkaline rocks of the Antigonish and Cobequid Highlands (2 and 5, Figs. 2A, B) are not particularly enriched in either *LIL* or *HFS* elements compared with continental analogues elsewhere.

The origin of the enrichment in Ti and the various incompatible trace elements has been variously ascribed to one or more of the following processes: (1) the effects of crustal contamination (Fodor 1987); (2) contamination by (subduction-related) subcontinental lithosphere (Duncan 1987, Murphy 1988), and 3) derivation from enriched mantle either of the type that produces enriched MORB or kimberlitic mantle. Enrichment in Ti and incompatible trace elements is also favored by a low degree of partial melting (Dupuy *et al.* 1988) or a high degree of fractionation (Wilband & Wasuwanich 1980, Fodor 1987).

The particular composition of the Folly River Formation tholeiites, which differ from comparable high-Ti tholeiites in the relatively low concentration of *LILE*, Nb and Ta, and high concentration of *HFS* (*e.g.*, 3, 4, and 6, Fig. 2A), is completely different from that to be anticipated to result from effects of crustal or subcontinental lithospheric contamination. The ratios of Ba/La (Fig. 3A) and Ta/Th (Fig. 3F) in the Folly River Formation are similar to those for enriched tholeiites from Liberia, and Ti/V is strongly MORB-like (Fig. 3E). The high-Ti tholeiites from Liberia, and from northern Karoo, can be distinguished geochemically from associated tholeiites less enriched in *HFS* elements. These low-Ti tholeiites have trace element and isotopic characteristics suggesting the influence of crust or subcontinental lithosphere of subduction origin. In both Liberia and northern Karoo, the high-Ti tholeiites have been interpreted from trace element and isotopic data as derived from enriched mantle (Duncan 1987, Dupuy *et al.* 1988).

The Nova Scotian high-Ti tholeiites are closely associated with subduction-related calc-alkaline rocks. Nevertheless, the enrichment in trace elements is difficult to account for by mantle enrichment through subduction, for several reasons:

a) If the source-mantle enrichment occurred above a subduction zone, enrichment may take place by two processes: by flux of volatiles, which may transport *LILE*, and by emplacement of calc-alkaline magmas, which will show the typical calc-alkaline trend of relative depletion in *HFS* elements. Shallow melting of such mantle would produce normal continental tholeiite with considerable *LILE* enrichment. The presence of volatiles might lead to retention of Nb (Murphy 1988), but the concentrations of *HFS* elements *higher* than in normal continental tholeiites cannot be related to increase in water and other volatiles.

b) If the source mantle were enriched in refractory residues from extraction of a calc-alkaline melt and if the putative refractory minerals included amphibole or phlogopite in significant amounts, then partial melting would result in strong enrichment in K, Rb and the middle *REE*. If the refractory residue included titanite, rutile or ilmenite, which have been postulated as the cause of depletion of Ta and Nb in calc-alkaline magmas, they would have produced a change in the Nb/Ta ratio in the source mantle (Green & Pearson 1987) which, upon melting, would be reflected in a lower Nb/Ta ratio; in fact, the Nb/Ta ratio observed is similar to or a little higher than the mantle norm of 16 (Fig. 3B). Melting of refractory oxides also would be expected to produce a high ratio of Th to other *LILE*; the opposite is observed (Fig. 2).

An origin by partial melting of an enriched MORB-source mantle (Dupuy *et al.* 1988) does not provide an adequate explanation for the intermediate values of the La/Ta ratio (Fig. 3D) for many continental tholeiites, including those described here, between the high values characteristic of island-arc tholeiites and the lower values found in MORB and ocean-island tholeiite, as reviewed in Table 3 of Dupuy *et al.* (1988). The Nova Scotia rocks have a higher La/Ta ratio than the high-Ti tholeiites from Karoo and Liberia. The arguments reviewed above concerning the Nb/Ta ratio, and the observations of Dupuy *et al.* (1988), suggest that the relatively high La/Ta ratio of continental tholeiites does not necessarily require the intervention of subduction processes.

The association of enriched continental tholeiites with subduction-related magmatism in northern Nova Scotia thus appears coincidental. The higher concentrations of *LILE* and *LREE* in continental tholeiites from the Jeffers Group and Keppoch Formation that are intercalated with calc-alkaline rocks probably result from the presence of fluids enriched in *LILE* and *LREE* in the upper mantle or crust traversed by the enriched continental tholeiite magmas (Saunders & Tarney 1984). Enriched continental tholeiites are not a normal feature of back-arc basins. In northern Nova Scotia, the short duration of subduction (and hence the limited volume of subduction products) and the presence of strike-slip faulting and associated extension may have allowed magmas normally trapped beneath subcontinental lithosphere to reach the surface rapidly, with minimal interaction with that lithosphere.

Conclusions

The late Precambrian rock associations in northern Nova Scotia provide evidence of a range of compositions of mantle from which magmas were derived. Calc-alkaline rocks occur in the Keppoch Formation and the Harrington River facies of the Jeffers Group. Enriched continental tholeiites of the Folly River and Clydesdale Formations represent an enriched mantle source. Enriched continental tholeiites in the Lakelands facies of the Jeffers Group and the Keppoch Formation derived from this enriched mantle were modified by *LILE*-enriched fluids. Minor rocks similar to ocean-island tholeiite occur in the Folly River Formation, and some similar to alkali basalt, in the Clydesdale Formation.

The enriched continental tholeiites are similar to those in the northern Karoo, Liberia, and on the northwestern margin of Iapetus. They appear to form from partial melting of mantle similar to that which is the source for enriched MORB. All these continental tholeiites tend to show some depletion in Nb_N and Ta_N relative to La_N; therefore, this phenomenon cannot be used as an indicator of a subduction-related origin. The co-occurrence of such enriched mantle and of subduction in northern Nova Scotia appears to be coincidental.

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