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Article abstract

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Geochemistry of Ordovician volcanic rocks of the Tetagouche Group of southwestern New Brunswick

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The Lower to Middle Ordovician volcanic suite of the Tetagouche Group from the southwestern part of the Miramichi Terrane in the Woodstock-Meductic area in southwestern New Brunswick is composed of a bimodal basalt-rhyolite association. The basalts have calc-alkalic characteristics and were emplaced on the continental crust in a volcanic arc or back-arc environment. The rhyolites were probably derived by melting of an amphibolite-facies crust. The basalts differ from those of the Tetagouche Group from the Bathurst area which include within-plate basalts and MORB. However, they both may be part of a single Ordovician arc-back-arc system.

Le cortège volcanique du Groupe de Tétagouche (Ordovicien médian à inférieur) dans la portion sud-ouest de la Lanière de Miramichi (région de Woodstock-Meductic, sud-ouest du Nouveau-Brunswick) se compose d'une association bimodale de basalte et rhyolite. Les basaltes présentent des caractères calco-alcalins et ils se sont mis en place sur la croûte continentale dans un milieu d'arc insulaire ou de rétro-arc. Les rhyolites proviennent probablement de la fonte d'une croûte de faciès à amphibolites. Les basaltes diffèrent de ceux du Groupe de Tétagouche dans la région de Bathurst, qui comprennent des basaltes intra-plaques et des MORB, quoique tous deux puissent faire partie d'un système arc:rétro-arc ordovicien unique.

[Traduit par le journal]

INTRODUCTION

The Miramichi Terrane (or Miramichi Anticlinorium of Rodgers, 1970) of the Canadian Appalachians is one of the distinct tectonostratigraphic zones of pre-Carboniferous strata in New Brunswick (Ruitenberg *et al.*, 1977; Fyffe and Fricker, 1987). It constitutes a northeast-trending belt, usually 10-40 km wide, across New Brunswick (Fig. 1). The Miramichi Terrane is composed predominantly of the Cambro-Ordovician Tetagouche Group, a volcano-sedimentary sequence containing a voluminous bimodal suite of basaltic and rhyolitic rocks. In northern New Brunswick, the volcanic rocks have been used previously for interpreting the tectonic setting of the Miramichi Terrane and formulating various plate tectonic models of the early evolution of the northern Appalachians (Rast and Stringer, 1974; Pajari *et al.*, 1977; Whitehead and Goodfellow, 1978; van Staal, 1987). The sequence has been correlated with comparable units in Maine (Neuman, 1968, 1984; Roy and Mencher, 1976; van Staal, 1987) and Newfoundland (Rast *et al.*, 1976; Fyffe, 1982; van Staal, 1987) and with amphibolite-facies metamorphic rocks of the Miramichi Highlands in New Brunswick (Fyffe *et al.*, 1988). In the Bathurst area of northeastern New Brunswick, volcanic rocks of the Tetagouche Group host many massive sulphide deposits including one of the world's largest lead-zinc producers, the Brunswick No. 12 orebody.

Rocks considered to be Tetagouche correlatives crop out in the southern part of the Miramichi Terrane. However, no geochemical data are available on the volcanic rocks from this

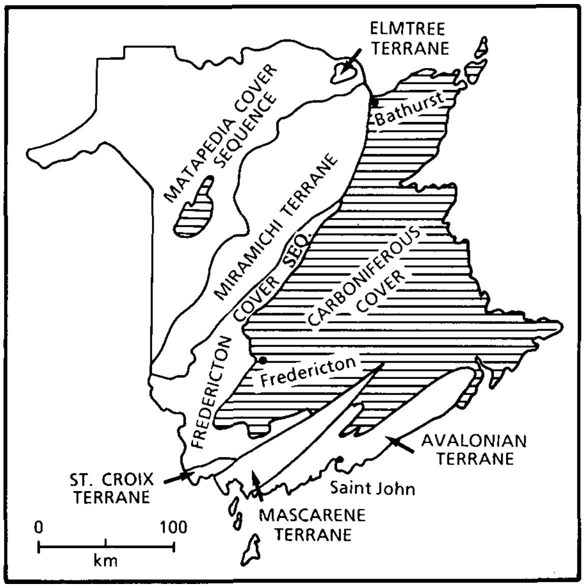

Fig. 1. Generalized map of tectonostratigraphic zones of New Brunswick (modified from Fyffe *et al.*, 1983).

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area, although such information may indicate if their characteristics are the same as those in the Bathurst area and they thus might be considered to be a suitable environment for stratiform sulphide mineralization. The purpose of this paper is to present geochemical data for the Ordovician volcanic rocks of the Tetagouche Group from the southwestern part of the Miramichi Terrane in the Meductic-Woodstock area of southwestern New Brunswick and to discuss their petrogenetic and geodynamic significance.

GEOLOGICAL SETTING

The lower part of the Tetagouche Group in northeastern New Brunswick is composed of a sequence of alternating Cambrian to Lower Ordovician quartzites and semipelites considered to be quartzose turbidites (Skinner, 1974; Fyffe, 1982) deposited on a continental margin off the Avalon Platform (Ruitenberg *et al.*, 1977). The sequence is locally conformably overlain by calcareous phyllites that contain Arenigian shallow water fauna (Fyffe, 1976; Nowlan, 1981; Fyffe *et al.*, 1983; Neuman, 1984). The upper part of the Tetagouche Group is composed of felsic volcanic rocks and overlying mafic volcanic rocks intercalated with hematitic and manganiferous slates and cherts. The volcanic sequence is overlain by graywackes containing debris from the underlying volcanic rocks (Helmstaedt, 1971; Skinner, 1974). The fossiliferous strata indicate that the upper part of the group is of Middle Ordovician age (Kennedy *et al.*, 1979; Nowlan, 1981).

The tectonic setting of the basalts of the Tetagouche Group has been a matter of controversy. In the Bathurst area, the basalts were interpreted by Rast and Stringer (1974) and Pajari *et al.* (1977) to have been formed in an ensialic island arc environment with a subduction zone dipping to the southeast. On the other hand, Whitehead and Goodfellow (1978) argued that two types of basaltic rocks are present: tholeiitic basalts that resemble ocean-floor basalts and alkali basalts comparable to those of oceanic islands. The recent study of van Staal (1987) has demonstrated that the Ordovician basaltic rocks include mid-ocean ridge basalts and within-plate basalts that were both emplaced in a marginal-sea or back-arc basin environment.

The geology of the Tetagouche Group in the Meductic-Woodstock area of southwestern New Brunswick has been described by Venugopal (1978, 1979). The Tetagouche Group extends for more than 10 km between two tectonostratigraphic zones, the Matapedia Cover Sequence on the west and the Fredericton Cover Sequence on the east (Figs. 1, 2). The stratigraphic column of the group is closely comparable to the type sections in the Bathurst area (Fyffe, 1976). The lower part of the Tetagouche succession in the Meductic area is represented by the quartzites and slates. They are overlain by black slates with graptolites of an early Ordovician age (middle- to late-Arenigian; Fyffe *et al.*, 1983). The volcanic sequence (Pocomoonshine volcanics of Venugopal, 1978, 1979), which is more than 3,000 m thick, conformably (Venugopal, 1979) overlies the black slates. The sequence is distinctly bimodal; subordinate felsic rocks are probably older than the mafic unit (Venugopal, 1979; Fyffe, 1982). The former are predominantly composed of volcanic tuffs containing beds of red ferromanganiferous slates and cherts (Poole, 1963; Venugopal, 1978, 1979) similar to the iron formation associated with massive stratiform sulphide deposits in the Bathurst area. Compared to the Bathurst area, the felsic volcanic rocks in the Woodstock-Meductic part of the Miramichi Terrane occur in rather limited amounts. Venugopal (1979) has estimated the thickness of the felsic unit to be in the range of about 600 m. The overlying mafic volcanic rocks are represented by lava flows, tuffs and breccias. The rocks were affected by sub-greenschist regional metamorphism of prehnite-pumpellyite grade (Venugopal, 1978, 1979). The volcanic sequence, in turn, underlies the sedimentary unit composed of intercalated slates, greywackes and limestones with graptolites and conodonts of early Caradocian age (Nowlan, 1981; Fyffe *et al.*, 1983). In summary, volcanism in southwestern New Brunswick started in the Arenigian, reached its peak in the Llanvirnian to early Caradocian and ended by the middle-Caradocian (Fyffe *et al.*, 1983). As detailed structural studies in the Woodstock-Meductic area are lacking, it is unclear whether the basaltic suite is autochthonous or allochthonous like that in the Bathurst area (van Staal, 1987).

PETROGRAPHIC NOTES AND CLINOPYROXENE COMPOSITION

Relict primary minerals and igneous textures are commonly preserved in the volcanic rocks. The mafic lava flows are typically porphyritic with phenocrysts of clinopyroxene and plagioclase set in a fine-grained groundmass containing microlites of plagioclase and microphenocrysts of clinopyroxene and Fe-Ti oxides. Several samples have amygdules filled with chlorite and rarely carbonate. Plagioclase is generally albitized or saussuritized. Clinopyroxene is mostly fresh although in some samples it is altered mainly to chlorite and carbonate. Clinopyroxene phenocrysts commonly exhibit distinct zoning. Clinopyroxenes are predominantly low-Al and low-Ti augites, typical of basaltic rocks of orogenic zones (Table 1, Fig. 3). They display some variations in composition; Ca and Al decrease while Si, Fe and Mn increase with decreasing Mg/Fe. Venugopal (1978, 1979) reported the occurrence of pumpellyite and prehnite in regional metamorphic assemblages of some of the mafic volcanic rocks.

The felsic volcanic rocks are mainly tuffs composed of plagioclase, K-feldspar and embayed quartz crystal fragments enclosed in matrix material containing chlorite, sericite, calcite and opaque.

GEOCHEMISTRY

Sampling and Analytical Methods

Due to poor exposure over a large part of the studied area, most samples of mafic rocks were collected from the vicinity of Oak Mountain, whereas the majority of felsic samples are from road-cuts along the Trans-Canada Highway (Fig. 2). Twenty-three samples (19 basalts and basaltic andesites and 4 rhyolites) devoid of amygdules and secondary veins were selected for

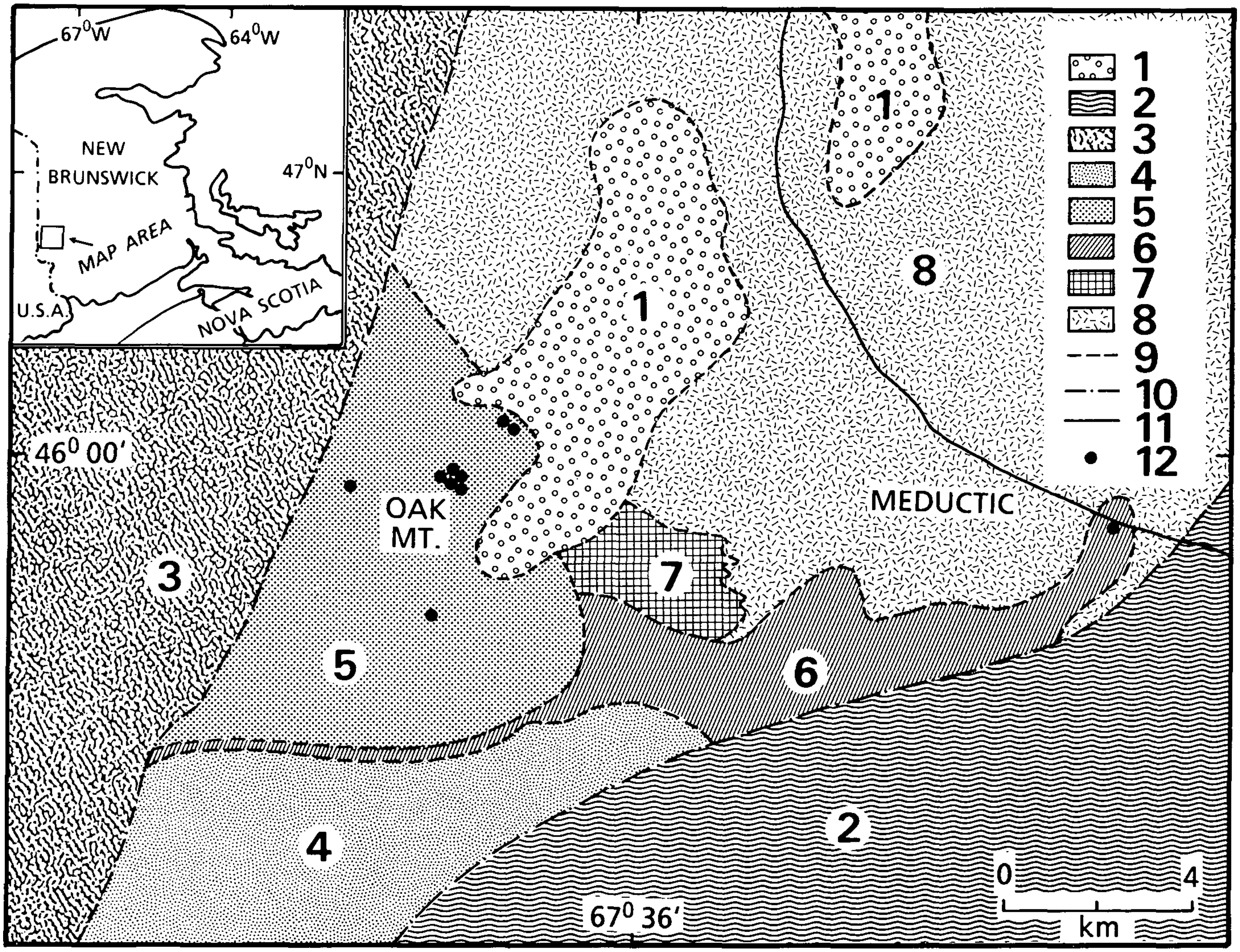

Fig. 2. Generalized geological map of the Meductic-Woodstock area (after Venugopal, 1978, 1979). Legend: (1) Devonian granite; (2) Silurian and Devonian sedimentary and minor granitic rocks; (3) Silurian sedimentary rocks; (4) Ordovician Belle Lake slate; (5) mafic members of Ordovician Pocomoonshine volcanic suite; (6) felsic members of Ordovician Pocomoonshine volcanic suite; (7) Ordovician black slate and minor sandstone; (8) Cambro-Ordovician quartzite; (9) geologic contact; (10) fault; (11) Trans-Canada Highway; (12) sample location for chemical analysis given in Table 2.

analysis from a set of over 50 specimens. Major and some trace elements (Rb, Sr, Ba, Ga, Zr, Y, Nb, Cr, Ni, V, Zn and Cu) were analyzed by X-ray fluorescence using fused discs (for the major elements) and pressed powder pellets (for the trace elements). Other trace elements (Sc, Hf, Ta, Co, Th, La, Ce, Nd, Sm, Eu, Tb, Yb and Lu) were analyzed by instrumental neutron activation on thirteen samples. The precision and accuracy of the data are given by Dostal *et al.* (1986). Briefly, the precision of the trace element data is usually better than 10%. The analyses of the samples are given in Table 2.

Alteration

Because the volcanic rocks have suffered low-grade metamorphism, the original chemical composition may have been modified. Several mafic rocks have high loss-on-ignition (LOI), up to 4.5%. Some major elements in the mafic rocks, particularly Na and K, are highly variable (Table 2). The significant scatter of the abundances of these elements as well as of Ca is probably due to alteration. Several trace elements, including Rb and Ba that display positive correlation with K, seem to be also redistributed in some basalts. Thus to limit the effect of secondary processes, the discussion is based mainly on the less mobile elements such as high-field-strength elements (HFSE) and rare earth elements (REE), which are usually considered to be relatively immobile during secondary processes (e.g., Winchester and Floyd, 1977; Condie, 1982).

Whole-Rock Geochemistry

The volcanic rocks are distinctly bimodal. The mafic rocks have SiO_2 contents (on LOI-free basis) ranging from 48 to 57% while the felsic members have >70% SiO_2. The mafic rocks have major element compositions typical of volcanic arc lavas as is also shown by the FeO-MgO-Al_2O_3 diagram (Fig. 4; Pearce *et al.*, 1977, 1988). They are high in Al_2O_3 and CaO but low in TiO_2 and

Table 1. Average composition of clinopyroxene from basalts of the Tetagouche Group from the Woodstock-Meductic area.

SiO_2	Al_2O_3	FeO_t	Mno	MgO	CaO	Na_2O	TiO_2	Cr_2O_3
50.39 (0.54)	3.84 (0.85)	8.42 (1.53)	0.21 (0.10)	15.75 (0.45)	20.71 (0.91)	0.25 (0.05)	0.39 (0.09)	0.04 (0.07)

Number of Cations per 6 oxygens

Si	Al^{iv}	Al^{vi}	Cr	Ti	Mn	Fe^{2+}	Mg	Ca	Na
1.856	0.144	0.022	0.001	0.011	0.007	0.259	0.865	0.817	0.018

Analyses were done using an energy dispersive microprobe. The values were obtained from 15 analyses of 3 samples. Standard deviations are given in parentheses. FeO_t is total Fe recalculated as FeO.

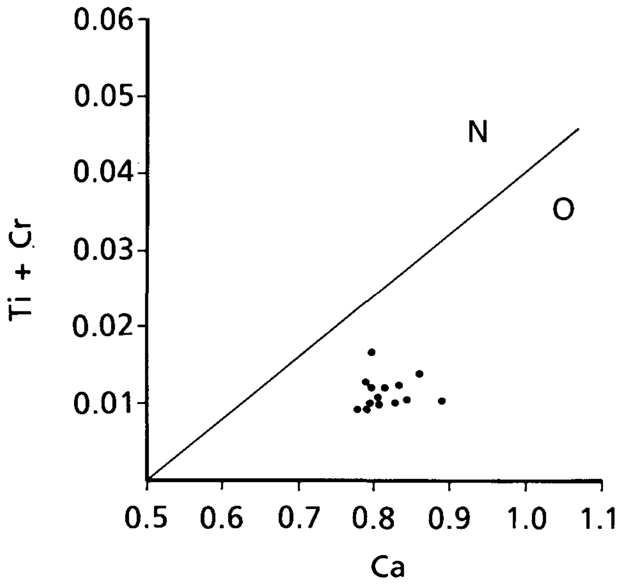

Fig. 3. (Ti + Cr) vs Ca (number of cations per 6 oxygens) diagram for clinopyroxenes of the basaltic rocks of the Tetagouche Group from the Woodstock-Meductic area. Dividing line between fields for clinopyroxene from orogenic (O) and non-orogenic basalts (N) after Leterrier *et al.* (1982).

P_2O_5 (Table 2), features which are characteristic of calc-alkalic rocks. Their calc-alkalic nature is also suggested by the relationships of FeO_t vs FeO_t/MgO (Fig. 5; Miyashiro, 1974) and TiO_2-MnO-P_2O_5 (Fig. 6; Mullen, 1983). Although the majority of the basaltic rocks show limited compositional dispersion, some of them are distinctly fractionated and their (Mg) (= mole % MgO/ MgO + FeO_t) values range from 0.63 to 0.51. The low concentrations of Ni(<35 ppm) and Cr (<160 ppm) are also indicative of extensive fractionation of mafic minerals. The decrease of Ni, Cr and Sc with decreasing (Mg) suggests the fractionation of mafic minerals--pyroxenes and possibly olivine. The abundances of Ti, Fe and V remain nearly constant with (Mg), suggesting a subordinate amount of crystallization of Fe-Ti oxides. The rocks also have low Ti/V ratios (usually <15) but high V/Ni and V/Cr, typical of volcanic arc rocks (Ewart, 1982; Shervais, 1982).

The incompatible elements, including Zr, Nb, Y and P, show covariation amongst themselves and also with REE and exhibit negative correlations with compatible elements such as Mg, Ni and Cr suggesting the relative immobility of all these elements during metamorphism. The interrelation of Ti-Zr-Y (Fig. 7; Pearce and Cann, 1973) is indicative of the calc-alkalic character of the basalts. The REE patterns of the basaltic rocks (Fig. 8) display distinct light REE (LREE) enrichment and relatively flat heavy REE (HREE) with La/Yb ranging from 7 to 11. The rocks have rather similar patterns but varying total REE concentrations. The variations mainly reflect low-pressure fractionation of common rock-forming minerals--pyroxene, plagioclase and olivine--a process which leads essentially to the enrichment of total REE in the residual magma with relatively little change of the fractionation patterns. The small negative Eu anomaly in the sample with the highest REE abundances indicates fractionation of plagioclase. The REE patterns are typical of basaltic rocks from volcanic arc regimes (e.g., Gill, 1981; Dostal *et al.*, 1982; Hickey *et al.*, 1984).

The chemical characteristics of the basaltic rocks are summarized in Figure 9, where the composition of the representative samples is normalized to mid-ocean ridge basalts (MORB) (Pearce, 1982). Compared to MORB, the basalts are enriched in large-ion-lithophile-elements (LILE) including Sr, K, Ba, Th and LREE relative to HFSE including Nb, Ta, Zr, Hf and Ti. The concentration of elements less incompatible than Zr is usually below those of MORB. The shape of the pattern is characterized by the depletion of Nb and Ta in relation to Th and Ce, negative anomalies of Zr, Hf and Ti and a sloping of the segment from Ce

Table 2. Representative chemical analyses of volcanic rocks from the Woodstock-Meductic area.

	127	128	130	138	141	142	154	157	166	126	129	131	132	146	156	167	168	169	173	102	103	152	124
SiO_2(%)	50.11	50.52	51.58	47.35	49.32	50.35	48.73	51.49	52.98	50.41	47.09	49.45	48.62	55.54	53.07	53	46.12	54.92	52.76	74.62	77.43	70.98	77.82
TiO_2	0.52	0.44	0.50	0.56	0.74	0.45	0.56	0.79	0.56	0.46	0.46	0.50	0.52	0.39	0.49	0.53	0.59	0.50	0.53	0.12	0.10	0.14	0.11
Al_2O_3	17.76	16.44	17.89	17.44	18.33	18.39	16.62	15.52	18.66	17.19	17.65	18.46	19.06	15.84	17.76	17.61	19	17.21	17.26	13.64	12.33	15.49	11.99
Fe_2O_3	9.32	8.21	8.50	9.30	8.62	7.76	8.93	10.03	8.61	7.81	9.10	8.59	9.05	8.03	8.03	9.19	11.06	7.62	8.11	2.14	1.63	3.15	1.68
MnO	0.17	0.15	0.15	0.19	0.15	0.14	0.17	0.17	0.14	0.12	0.18	0.15	0.16	0.14	0.11	0.16	0.18	0.14	0.17	0.29	0.24	0.27	0.27
MgO	6.38	6.99	5.88	6.37	4.76	5.98	6.76	6.06	4.61	5.67	7.73	4.56	5.43	4.83	4.21	4.76	6.80	4.49	4.82	2.19	1.67	3.04	1.74
CaO	6.54	10.44	8.59	12.57	9.64	9.14	10.58	8.53	5.42	11.39	10.93	10.77	8.83	7.67	10.08	6.30	8.77	7.26	9.63	0.14	0.16	0.02	0.16
Na_2O	4.33	2.39	2.13	1.99	4.06	1.97	3.13	1.89	5.42	2.33	2.50	2.71	2.69	4.16	2.21	3.39	1.96	2.93	2.88	3.46	4.91	1.62	4.15
K_2O	1.18	1.17	1.87	0.24	0.92	3.01	0.76	1.92	0.75	0.44	0.70	1.32	2.22	0.65	1.12	1.54	1.48	1.53	0.92	1.89	0.88	3.30	1.18
P_2O_5	0.14	0.12	0.12	0.15	0.21	0.14	0.15	0.23	0.17	0.15	0.12	0.14	0.14	0.11	0.16	0.15	0.16	0.14	0.13	0.05	0.04	0.05	0.04
LOI	3.00	3.30	3.80	4.50	3.00	3.00	3.90	2.80	2.40	4.50	4.20	3.80	3.80	3.00	3.30	3.10	4.30	3.70	3.00	1.80	1.30	2.80	1.50
Total	99.45	100.17	100.61	100.66	99.75	100.33	100.29	99.43	99.72	100.47	100.66	100.45	100.52	100.36	100.54	99.73	100.42	100.44	100.21	100.34	100.69	100.86	100.64
Rb (ppm)	37	30	61	5	16	84	20	34	19	11	15	33	57	15	34	46	39	41	23	58	25	98	33
Sr	512	369	323	221	403	317	287	631	268	131	409	642	466	174	812	326	625	511	276	117	159	44	137
Ba	165	216	301	14	254	707	95	603	199	81	117	265	542	179	122	244	297	280	167	664	248	1118	366
Sc	33.5	35.9	32.3	37.6	31.8	28.9	37.0	33.6	27.5											9.44	6.80	11.00	8.05
V	274	231	243	300	313	227	283	291	267	234	252	263	261	269	216	244	283	241	276	8	5	10	5
Cr	91	159	50	114	24	50	118	178	26	103	137	57	59	133	21	21	43	39	52	4	2	4	4
Ni	15	20	17	14	10	22	18	30	9	15	33	9	15	16	10	10	10	9	12	13	14	30	21
Co	40.9	46.6	44.1	51.5	45.8	47.1	44.4	50.6	35.1														
Cu	65	68	35	73	117	51	61	134	44	59	71	57	58	48	52	43	61	33	52	1			11
Zn	76	73	70	82	86	68	72	98	81	67	74	70	73	66	75	92	93	61	74	63	49	85	57
Y	13	12	14	14	18	13	12	20	15	13	12	14	14	18	13	15	15	13	14	30	39	56	46
Zr	69	55	57	60	80	55	59	99	74	57	54	64	64	65	80	73	75	65	63	139	110	139	125
Nb	7	3	4	6	6	5	6	9	4	5	5	5	7	6	7	6	5	6	6	13	11	11	12
Hf	1.39	1.11	1.15	1.28	1.83	1.09	1.28	2.05	1.55											4.72	3.41	4.54	2.09
Ta	0.31	0.20	0.24	0.30	0.36	0.29	0.34	0.52	0.38											1.21	1.26	1.10	1.20
Ga	18	17	21	23	19	15	23	21	22	24	25	19	25	24	22	21	22	18	20	19	18	24	14
Th	3.55	2.57	2.56	3.52	4.08	3.81	3.60	4.63	3.65											9.30	6.46	9.01	7.06
La	10.3	7.70	8.00	11.3	13.7	11.6	11.1	16.7	11.9											53.0	25.2	39.7	33.3
Ce	22.9	17.9	17.7	25.6	31.2	25.0	25.1	36.7	24.8											88.4	57.7	92.4	57.5
Nd	11.6	8.71		12.3	15.8	11.5	12.3	19.0	11.5												27.0	42.2	
Sm	2.50	1.98	2.10	2.76	3.58	2.50	2.69	3.98	2.65											8.69	6.04	9.21	5.97
Eu	0.70	0.55	0.64	0.81	1.02	0.65	0.74	0.99	0.73											0.74	0.58	0.85	0.58
Tb	0.35	0.32	0.34	0.36	0.49	0.34	0.39	0.53	0.39											1.04	1.27	1.79	1.27
Yb	1.27	1.11	1.16	1.30	1.76	1.09	1.42	1.91	1.42											3.95	4.94	6.74	5.38
Lu	0.21	0.19	0.20	0.22	0.28	0.19	0.23	0.31	0.24											0.61	0.78	1.02	0.84

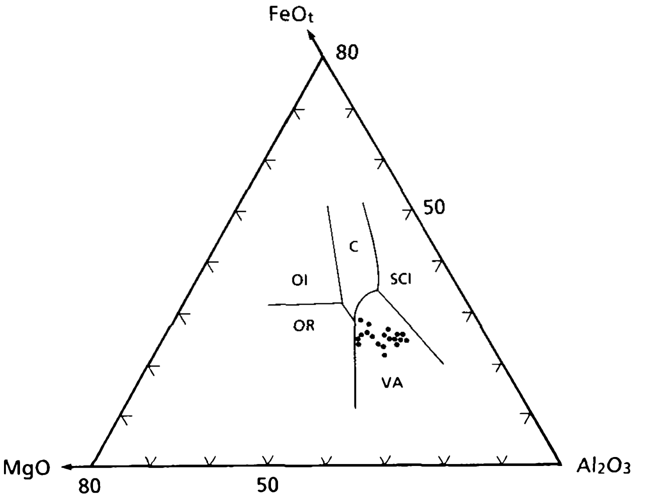

Fig. 4. FeO_t-MgO-Al_2O_3 discrimination diagram of Pearce *et al.* (1977, 1988) for the mafic rocks of the Tetagouche Group from the Woodstock-Meductic area. OI - ocean-island basalts; OR - ocean-ridge and ocean-floor basalts; VA - volcanic arc basalts; SCI - spreading-centre island basalts; C - continental basalts.

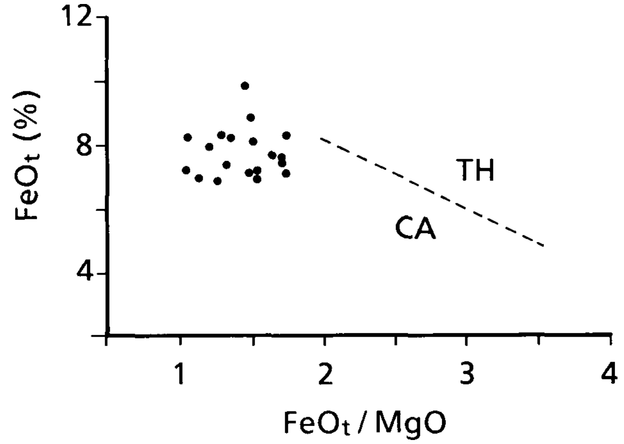

Fig. 5. FeO_t vs FeO_t/MgO diagram for mafic rocks of the Tetagouche Group from the Woodstock-Meductic area. Dividing line between tholeiitic (TH) and calc-alkalic (CA) fields after Miyashiro (1974).

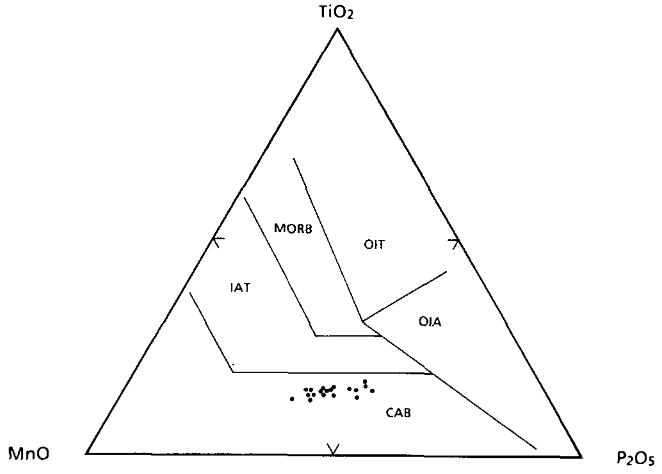

Fig. 6. TiO_2-MnO(X10)-P_2O_5(X10) discrimination diagram of Mullen (1983) for the mafic rocks of the Tetagouche Group from the Woodstock-Meductic area. Fields: OIT - ocean-island tholeiites; OIA - ocean-island alkali basalts; MORB - mid-ocean ridge basalts; IAT - island arc tholeiites; CAB - calc-alkalic basalts.

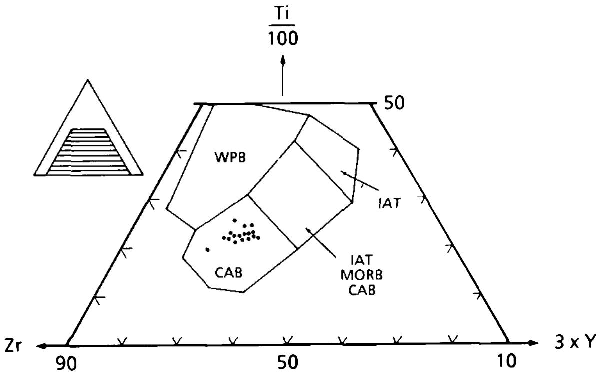

Fig. 7. Ti-Zr-Y discrimination diagram of Pearce and Cann (1973) for the basaltic rocks (SiO_2 <56%) of the Tetagouche Group from the Woodstock-Meductic area. Fields: WPB - within-plate basalts; IAT - island-arc tholeiites; MORB - ocean-floor basalts; CAB - calc-alkalic basalts.

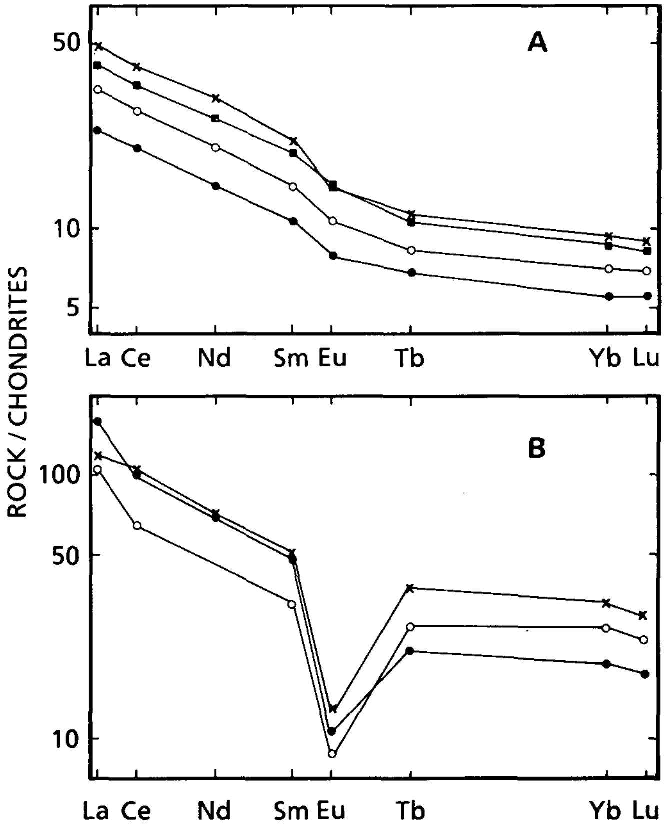

Fig. 8. Chondrite-normalized REE abundances in the Tetagouche Group of the Woodstock-Meductic area. (A) Basaltic rocks, ● - sample 128; ■ - 141; ○ - 154; X - 157. (B) Rhyolitic rocks, ● - sample 102; ○ - 124; X - 152.

to Yb, typical of calc-alkalic basalts (Pearce, 1982, 1983). The enrichment of K, Rb, Sr and Ba as well as Th relative to Ta and Nb are those generally observed in calc-alkalic rocks.

The felsic rocks are rhyolites with >70% SiO_2 and low contents of Al_2O_3 and K_2O (usually <2%). Compared to similar rocks from the Bathurst area (Whitehead and Goodfellow, 1978), they are lower in Ti, P and Zr. There are also differences in the abundances of the mobile elements. The Bathurst rocks have higher contents of K and Rb but lower Na than most felsic rocks

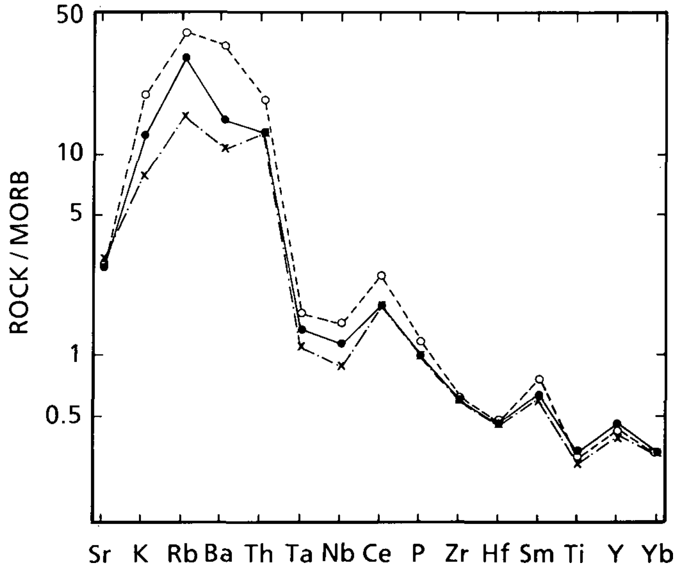

Fig. 9. MORB-normalized incompatible element patterns (Pearce, 1982, 1983) of the basaltic rocks of the Tetagouche Group from the Woodstock-Meductic area. X - sample 128;● - 130;○ - 142.

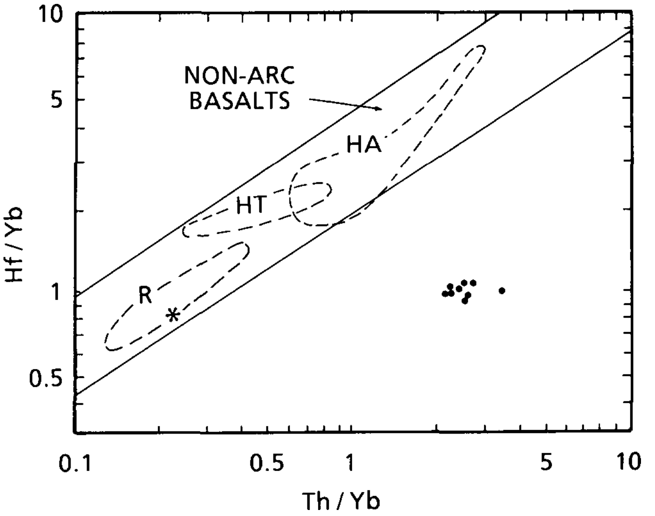

Fig. 10. Hf/Yb vs Th/Yb diagram (after Okamura, 1987) for the basaltic rocks of the Tetagouche Group from the Woodstock-Meductic area. Two parallel lines outline the 'mantle' array of the basalts from non-arc settings (Pearce, 1983; Okamura, 1987). The dashed lines show the fields of the Hawaiian alkali basalts (HA), Hawaiian tholeiites (HT) and Reykjanes Ridge basalts (R) whereas the star represents primordial mantle (Okamura, 1987).

from the Woodstock-Meductic area. Although K is variable in the felsic rocks, the K/Rb and K/Ba ratios remain relatively constant (~285 and ~25, respectively). The positive correlation of these elements might be due to secondary processes. The REE of the felsic rocks display patterns that are found in some high-silica rhyolites and high-level silicic plutons (e.g., Ewart, 1979; Izett, 1981; Cullers *et al.*, 1981). Chondrite-normalized patterns (Fig. 8) show only moderate light REE enrichment and a flat segment of heavy REE with La/Sm between 4 and 6 and La/Yb in the range of 5 to 14. The rocks have high abundances of HREE with Yb_n (n = chondrite-normalized) ~20-35. Large negative Eu anomalies and low concentrations of Sr are consistent with significant feldspar fractionation.

PETROGENESIS

Basaltic Rocks

The basaltic rocks have undergone extensive fractional crystallization involving the separation of pyroxene, plagioclase, olivine and Fe-Ti oxides. In fact, most compositional differences among the mafic rocks can be accounted for by this process.

Like other mafic calc-alkalic volcanic rocks of the orogenic zones, the basaltic rocks of the Woodstock-Meductic area were probably derived from an upper mantle source overlying the subduction zone. Some further information on the composition of the source can be obtained from interelement ratios such as Hf/Yb - Th/Yb (Okamura, 1987) plotted in Figure 10. The field of "non-arc" basalts in Figure 10 outlines the range observed for the heterogeneous source compositions of MORB and within-plate basalts. Mantle processes which are not related to subduction as well as partial melting and fractional crystallization produce vectors with a slope of unity, parallel to this mantle field because they enhance Hf and Th equally (Pearce 1983; Okamura, 1987). On the other hand, as the experiments of Tatsumi *et al.* (1986) confirmed, the subduction-related processes preferentially affect LILE including Th relative to HFSE (Pearce, 1983; Okamura, 1987) thus producing subhorizontal vectors on Figure 10. The basalts plot away from the non-orogenic basalt field, indicating the presence of a subduction-related component in their mantle source which originally had a composition, at least as far as the Hf/Yb ratio is concerned, comparable to the primordial mantle (Fig. 10). However, the subhorizontal trends can also reflect crustal contamination as the crustal rocks also plot in the Th/Yb enriched field (Pearce, 1982, 1983). There are indications that both subduction-related enrichment and crustal contamination played a role during the genesis of these basalts. The negative Ta-Nb anomalies on the MORB-normalized trace element patterns accompanied by high Sr/Ce (Pearce, 1982) observed in the basalts are characteristic of a subduction zone component in the source. On the other hand the Th/La ratio, which is considered to be a good indicator of crustal contamination (Hildreth and Moorbath, 1988), is high in the basalts (~0.30) relative to the mantle values (~0.12; Sun, 1982) suggesting that the rocks were affected by crustal contamination.

The high Zr/Y (>3) of the Woodstock basalts suggests that they were emplaced on the continental crust (Pearce, 1982), a conclusion consistent with the occurrence of abundant rhyolitic rocks in the Tetagouche Group. However, the relatively low HFSE abundances imply that the continental crust was thin. Likewise, the moderate La/Yb and Th/Yb ratios which overlap those from evolved island arcs and continental margins (Fig. 11) differ from the low values characteristic of primitive arcs or the high ratios typical of Andean arcs.

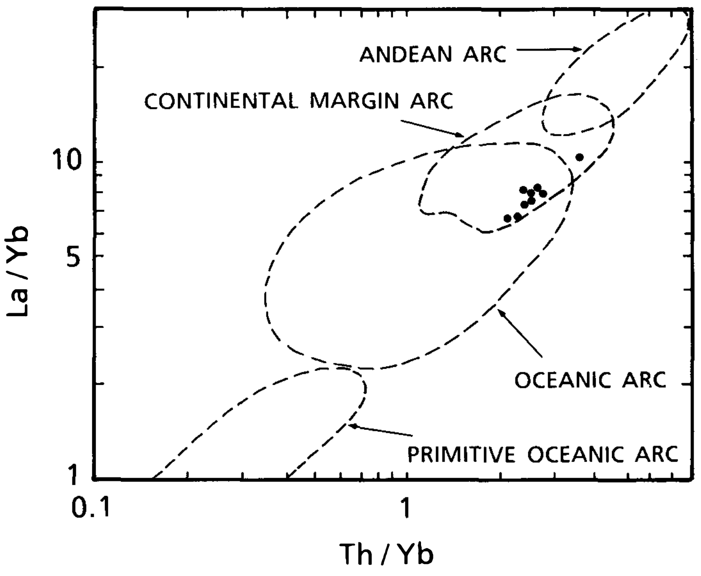

Fig. 11. La/Yb vs Th/Yb diagram for the mafic rocks of the Tetagouche Group from the Woodstock-Meductic area. Fields for modern arc-related mafic lavas (after Crow and Condie, 1987).

Felsic Rocks

Two hypotheses which may be invoked for the origin of the felsic rocks are fractional crystallization of mafic magma and partial melting of the crust. There are several arguments against the derivation of the felsic rocks from the basalts by simple fractional crystallization. They include the lack of intermediate rocks and significant differences between the felsic and basaltic rocks in the ratios of incompatible elements that are not modified by fractional crystallization.

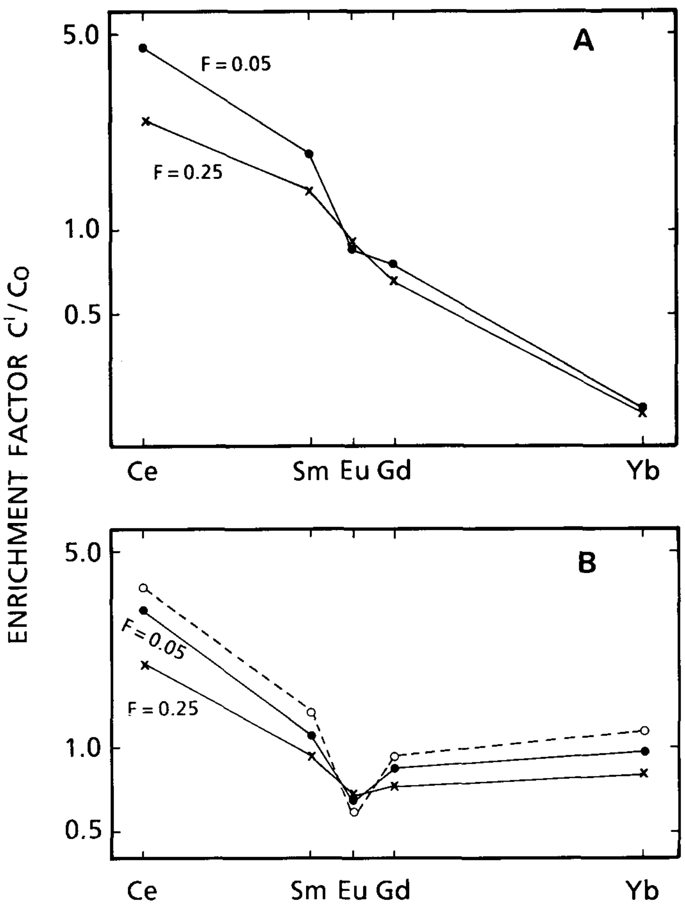

Fig. 12. Enrichment factors C^1/Co (concentration in melt/concentration in rock source) for REE in melts produced by partial melting of granulite - (A) and amphibolite-facies (B) crustal rocks. Non-modal batch melting equation and partition coefficients of Arth (1976) and Henderson (1984) were used. F - fractions of melt produced. Mineral proportions of the source (X) as well as melting proportions (P) are after Stern and Gottfried (1986). (A) Garnet granulite: Phases (and their values for X and P): K-feldspar 0.1 and 0.35; plagioclase 0.35 and 0.4; quartz 0.35 and 0.25; garnet 0.1 and 0.0; clinopyroxene 0.1 and 0.0. (B) Amphibolite-facies source: K-feldspar 0.1 and 0.35; plagioclase 0.35 and 0.4; quartz 0.35 and 0.25 and amphibole 0.2 and 0.0. Dashed line in B - calculated REE abundances in the liquid produced by fractional crystallization of 20% feldspars (K-feldspar 0.5 and plagioclase 0.5) from the partial melt with F = 0.05. The partition coefficients used are the same as for the melting model.

An alternative to the crystal fractionation model is generation of the felsic suite by partial melting. The anatectic model can account for the silicic composition of the rocks without necessitating large amounts of intermediate magmas. Petrological experiments exclude a direct partial melting of upper mantle ultramafic rocks (Wyllie *et al.*, 1976) as a viable mechanism for the generation of silicic liquids. The trace element abundances of the felsic volcanics are similar to those of many granitic and rhyolitic rocks which are considered to be generated by partial melting of lower crust with intermediate composition (e.g., Crecraft *et al.*, 1981; Cullers *et al.*, 1981). The mineral assemblages of such a source probably include garnet and/or amphibole and could occur in either the granulite or amphibolite facies. The model calculations for REE during the melting of garnet granulite and amphibolite-facies crust are given in Figure 12 together with the parameters used. Low-silica I-type granites are formed by about 25% melting of the intermediate lower crust (Compston and Chappell, 1979; Stern and Gottfried, 1986); a smaller degree of melting would be required for the more silicic liquids. Melts formed by crustal melting are predominantly composed of feldspars and quartz (Wyllie, 1977). Since the analyzed felsic rocks contained more than 90% of normative felsic constituents, the trace element modelling assumed melting only of feldspars and quartz. The results of the calculation show that the liquids derived from garnet granulite by 25% or lesser degree of melting have much more fractionated REE patterns than the analyzed felsic rocks. The presence of zircon in the residue (Watson and Harrison, 1983) would generate an even steeper slope of the REE pattern. Thus, it appears that the felsic rocks cannot be readily produced by anatexis of garnet granulites. Calculated enrichment of the REE patterns of liquids formed by the melting of amphibolite-facies rocks are similar to those of the felsic rocks. Subsequent fractional crystallization of a feldspar-dominated assemblage would increase the REE content of the magma and increase the size of the negative Eu anomaly (Fig. 12). Considering the uncertainties inherent in these calculations, the results are consistent with the derivation of the felsic rocks by partial melting of amphibolite-facies sources. The REE data show that the source had a pattern with only slight LREE enrichment and relatively high abundances of HREE with a La/Yb ratio significantly smaller than that given by Taylor and McLennan (1985) for the average crust.

The close spatial and temporal association of compositionally distinct magmas, characteristic of bimodal suites, suggests separate but related sources for the two magma types. A currently favored model (e.g., Bacon *et al.*, 1980; Crecraft *et al.*, 1981) assumes that the intrusion of mantle-derived basalts into the lower crust provides additional heat and leads to the anatexis of more silicic crustal rocks. Such a model is applicable to the studied volcanic sequence.

TECTONIC IMPLICATIONS

The basaltic rocks of the Tetagouche Group from the Woodstock area have compositions typical of rocks which were erupted in an ensialic orogenic environment (arc or back-arc setting). The basalts differ from those of the Tetagouche Group from the Bathurst area which include within-plate basalts and MORB (van Staal, 1987). The Ordovician sequences from the Woodstock and Bathurst areas, however, have rather similar stratigraphy and lithology, including comparable ages and the presence of an iron formation and graptolite-bearing shale (Fyffe, 1982) suggesting that they both may be part of a single Ordovician arc-back-arc system.

The occurrences of these volcanic sequences in the Tetagouche Group are consistent with a general tectonic model for the northern Appalachians (e.g., Strong, 1977; Hatch, 1982; van Staal, 1987; van der Pluijm and van Staal, 1988). The model envisages the presence of an Ordovician volcanic arc with an eastward-dipping subduction zone and a back-arc basin located east of the arc. Thus, the volcanic rocks of the Woodstock area probably represent remnants either of the Ordovician arc or the back-arc basin. The calc-alkalic volcanism of Ordovician age in Grand Pitch and Bronson Hill in New England (Loiselle, 1985; Keppie, 1989) might be an extension of this volcanic belt.

The tectonostratigraphic subdivision of New Brunswick is usually compared with that of Newfoundland. Rast *et al.* (1976) have correlated the Miramichi Terrane with the Gander Zone. However, due to the absence of the Ordovician volcanic sequences and black shales in the Gander Zone, Fyffe (1976) disagreed with such a comparison. The stratigraphy of the upper part of the Tetagouche Group better correlates with the Dunnage Zone (Fyffe, 1982; van Staal, 1987). The Ordovician sequences of the Dunnage Zone include volcanic arc suites (e.g., Strong, 1977; Swinden and Thorpe, 1984) as well as within-plate basalts and MORB (e.g., Jenner and Fryer, 1980; Wasowski and Jacobi, 1985) similar to those of the Tetagouche Group.

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