Geochemistry of Carboniferous peralkaline felsic volcanic rocks, central New Brunswick, Canada: examination of uranium potential

Taryn R. Gray[1]*, Jaroslav Dostal[1], Malcolm McLeod[2], Duncan Keppie[3], Yuanyuan Zhang[4]

1. Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada
2. New Brunswick Department of Natural Resources and Energy, Geological Surveys Branch,
P.O. Box 5040, Sussex, New Brunswick E4E 5L2, Canada
3. Instituto de Geología, Universidad Nacional Autónoma de México, 04510, México
4. Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education,
School of Earth and Space Sciences, Peking University, Beijing, China 100871
*Corresponding author <Taryn.Gray@smu.ca>

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ABSTRACT

Felsic volcanic rocks from the ca. 335 Ma Cumberland Hill Formation of southern New Brunswick consist of peralkaline rhyolite and trachyte. These rocks are interpreted to have undergone extensive fractional crystallization from an alkali basaltic magma, although their different geochemical signatures indicate that the rhyolite was not derived from the trachyte via continuous fractional crystallization. The rhyolite is highly enriched in incompatible trace elements including uranium (up to ca. 20 ppm). Cumberland Hill peralkaline rhyolite suggests that a potentially economic source of uranium exists in the basin, based on the elevated uranium concentrations and high potential for remobilization into surrounding sedimentary units.

RÉSUMÉ

Les roches volcaniques felsiques de la Formation de Cumberland Hill, au sud du Nouveau-Brunswick, dont l'origine remonte à quelque 335 Ma se composent de rhyolite et de trachyte hyperalcalines. On estime que ces roches ont subi une cristallisation fractionnée intense à partir d'un magma de basalte alcalin, même si leurs diverses signatures géochimiques indiquent que la rhyolite n'est pas issue de la trachyte par un processus permanent de cristallisation fractionnée. La rhyolite est fortement enrichie d'éléments traces incompatibles, au nombre duquel se trouve de l'uranium (concentration qui peut atteindre environ 20 ppm). Si l'on se fie aux fortes concentrations d'uranium et à la grande possibilité de remobilisation dans les unités sédimentaires environnantes, la présence de la rhyolite hyperalcaline dans la Formation de Cumberland Hill porte à croire que le bassin pourrait contenir une source d'uranium vraisemblablement rentable.

[Traduit par la redaction]

INTRODUCTION

Igneous rocks are sparsely distributed throughout the Middle Devonian–Permian Maritimes Basin (Fyffe and Barr 1986; Dunning *et al.* 2002). They appear to decrease in volume through time from: (i) Middle to Late Devonian tholeiite, minor alkali basalt, bimodal gabbro and A-type to evolved I-type granite; (ii) Lower Carboniferous bimodal igneous rocks, and most sparsely, (iii) Upper Carboniferous bimodal igneous rocks (New Brunswick Department of Natural Resources 2010a). The felsic igneous rocks, as well as the interbedded lithic sandstone, conglomerate, and feldspathic sandstone of the Cumberland Hill Formation, the topic of this paper, were considered part of the Late Wesphalian Pictou Group, and consequently associated with the latter episode of magmatism based on stratigraphic relationships (Fyffe and Barr 1986). However, recent mapping indicated that these volcanic rocks lie within the Visean to early Namurian Mabou Group, and therefore are associated with the middle episode of volcanic activity (St. Peter 1997; New Brunswick Department of Natural Resources 2010a). A mid-Visean U-Pb zircon date of 335 ± 2 Ma substantiates this interpretation (New Brunswick Department of Natural Resources 2010a). Hence the felsic volcanic rocks in the Cumberland Hill Formation appear to

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have approximately the same age as several alkali mafic units in New Brunswick (e.g., the Hardwood Ridge, Royal Road, and Queenstown basalts), and the tholeiitic-alkali mafic rocks of the Cap aux Diables Formation in the Magdalen Islands (Barr *et al.* 1985; Fyffe and Barr 1986; LaFleche *et al.* 1998; New Brunswick Department of Natural Resources 2010a).

The mafic rocks have continental within-plate characteristics (Barr *et al.* 1985), and HIMU-OIB Pb-isotopic signatures that have been related either to a mantle plume (Pe-Piper and Piper 1998) or to decompression melting below a pull-apart rift (LaFleche *et al.* 1998). However, the plume model (Murphy *et al.* 1999; Keppie and Krogh 1999) appears inconsistent with U-Pb chronology of Devonian to early Carboniferous volcanic rocks within the southern Magdalen Basin (Dunning *et al.* 2002).

In this paper, we selected key samples from the Cumberland Hill Formation in order to petrologically and geochemically characterize the rocks and compare the rhyolite and trachyte to similar rocks elsewhere in the Maritimes Basin. This work is critical when assessing uranium potential in the Cumberland Hill Formation, as similar rocks in the Maritimes Basin have been identified as hosts of economic uranium mineralization (e.g., Dahlkamp 1993; Plant *et al.* 1999; Cuney 2009; Nash 2010).

GEOLOGICAL SETTING

Late Devonian to Early Permian rocks of New Brunswick comprise the western part of the Maritimes Basin of Atlantic Canada. The Maritimes Basin is a successor basin within which there are a number of sub-basins separated by fault-bounded ridges of basement (Fig. 1a). In New Brunswick, these rocks occur within deep depositional centres or subbasins, or on shallowly buried or partially exposed basement uplifts and platforms (e.g., St. Peter and Johnson 2009).

The volcanic rocks of the Cumberland Hill Formation crop out as several inliers and are unconformably overlain by the Upper Carboniferous Pictou Group on the New Brunswick Platform (Fig. 1b). The outcrops are likely related to a single volcanic centre partially hidden beneath Pictou Group rocks, because the area incorporating the inliers clearly defines a circular area of high magnetic response on aeromagnetic maps (Thomas and Kiss 2005).

Fyffe and Barr (1986) examined some of the felsic volcanic rocks in the vicinity of Cumberland Hill, including lava flows and tuffs in a rhyolitic unit and underlying trachytic unit. Subsequently, St. Peter (1997) delineated the distribution of these units in more detail, depicting the trachyte as mostly underlying, but in part interdigitating with, the rhyolite (Fig.2). There is also one massive intrusive porphyry plug with several smaller dykes/pipes, interpreted by Thomas and Kiss (2005) as volcanic feeder dykes, based on their bulls-eye positive magnetic anomalies (50–375 nT) within the magnetically anomalous area. The exact thickness of these units is unknown as they are poorly exposed; however, both trachyte and rhyolite units are believed to be tens of metres thick (St. Peter 1997).

PETROGRAPHY

The rhyolite occurs as aphanitic to porphyritic flows and ignimbritic tuffs with flow banding and microporphyritic to porphyritic textures (Fig. 3a). Flow-aligned phenocrysts of feldspar (mainly anorthoclase; Fyffe and Barr 1986; 0.1–0.5 mm in length) and quartz (0.3–1 mm) are enclosed in a quartzofeldspathic groundmass with rare green clinopyroxene (hedenbergite; Fyffe and Barr 1986). The groundmass is composed of quartz, feldspar, devitrified glass, minor magnetite, ilmenite, pyrite, rare galena, fluorite and accessory minerals similar to those in trachyte samples (i.e., microlites of zircon, apatite, monazite, and allanite). The rhyolite is also extensively altered, although to a lesser degree than the trachyte, with most primary magmatic phases replaced by a secondary assemblage (i.e., carbonate, sericite, albite, and chlorite).

The trachyte occurs in two varieties, porphyritic and aphanitic, the latter of which is dominant. The porphyritic trachyte contains phenocrysts of feldspar (sanidine or anorthoclase) up to 2 mm in size, rare clinopyroxene, and plagioclase (Fig. 3b). The groundmass is largely composed of devitrified glass with phenocrysts of feldspar, clinopyroxene, and quartz, and rare ilmenite, hematite, sphalerite, and galena. Accessory minerals (fine-grained microlitic zircon, apatite, monazite, and allanite) were identified and confirmed using a scanning electron microscope including backscattered electron imaging, energy-dispersive X-ray spectroscopy and X-ray element mapping. The aphanitic variety displays a typical trachytic texture with flow-aligned feldspars (0.1–0.5 mm in length) enclosed in a fine-grained matrix similar to that of the porphyritic type. Both varieties are pervasively altered, with only relicts of primary minerals present, and secondary minerals dominated by calcite, sericite, chlorite, albite, and hematite alteration.

GEOCHEMISTRY

Fifteen samples were collected from the Cumberland Hill Formation, crushed and pulped in a soft iron swing mill, then analyzed for major elements using glass discs by X-ray fluorescence (XRF) spectrometry in the Nova Scotia Regional Geochemical Centre at Saint Mary's University, Halifax. Samples were subsequently analyzed for trace element compositions using a Perkin Elmer Optima 3000 inductively coupled plasma-mass spectrometer in the Activation Laboratories in Ancaster, Ontario. Prior to analysis, samples were digested in nitric acid after lithium metaborate fusion to ensure the complete dissolution of refractory accessory minerals. Precision and accuracy of the XRF data are reported by Dostal *et al.* (1994). The analytical error of the trace element determinations is 2–10%.

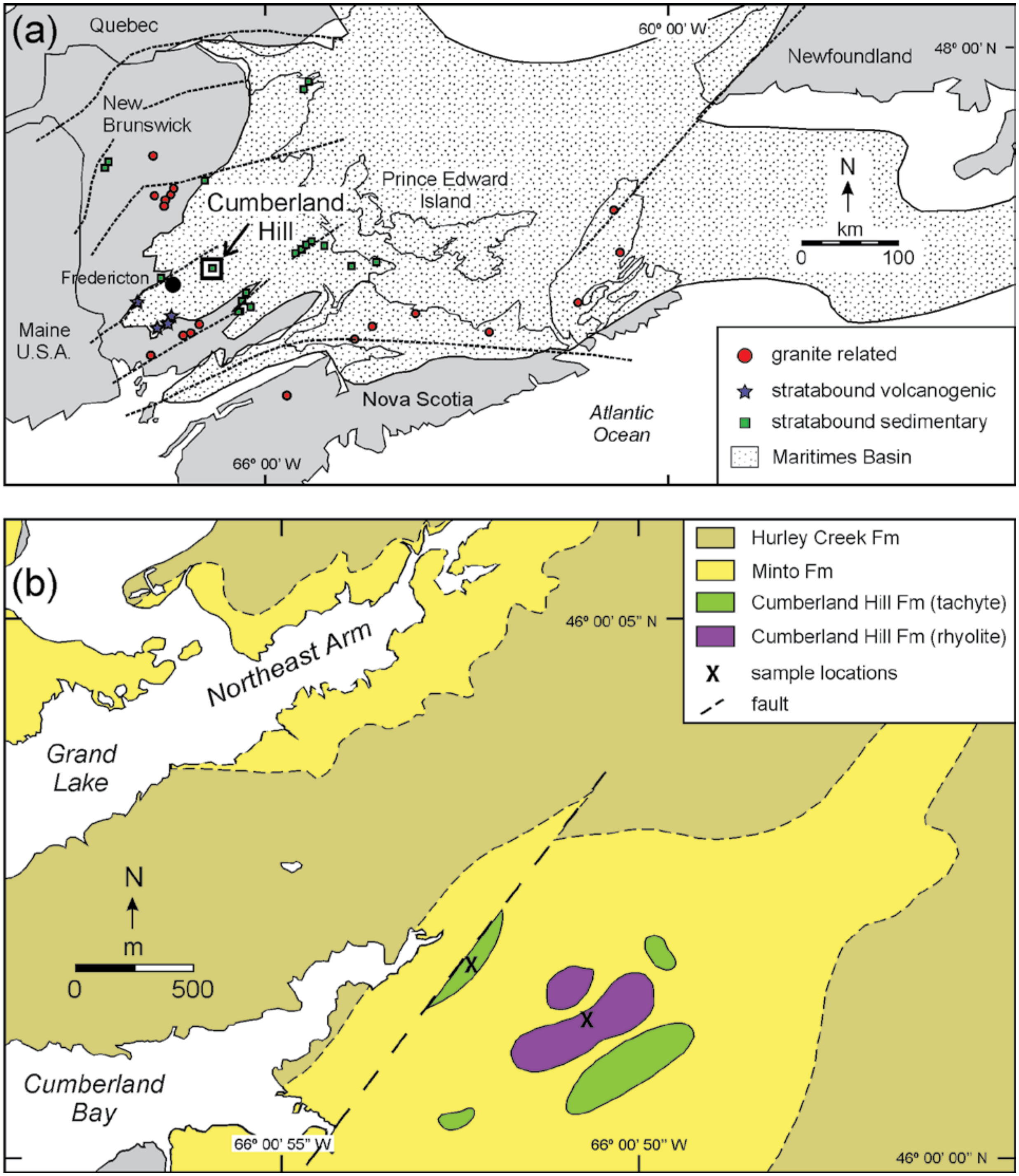

Fig. 1. (a) Map of Atlantic Canada depicting the Maritimes Basin, adapted from Roliff (1962), Williams (1974), Bradley (1982), and Fyffe and Barr (1986). Major faults are indicated as dashed lines; study area is indicated with a box. Red circles, blue stars and green squares represent different types of uranium occurrences within the Maritimes Basin (McLeod and Smith 2010; Dostal *et al.* 1983); (b) Geological map of the Cumberland Hill area, southern New Brunswick (adapted from Smith 2007) indicating the areal extent of the Cumberland Hill trachyte and rhyolite, both of which are interbedded with lithic and feldspathic sandstone and conglomerate, and contain interdigitating feldspar porphyry, rhyolite ash tuff, breccia, and lapilli tuff (New Brunswick Department of Natural Resources 2010a). The Hurley Creek Formation is composed of mudstone, fine-grained sandstone, coarse-grained feldspathic and lithic sandstone and polymictic pebble conglomerate at the top (Muller 1951). The Minto Formation contains feldspathic, pebbly and fine-grained sandstone, polymictic conglomerate and minor laminated mudstone, shale and thin coal seams (Dyer 1926; Muller 1951; St. Peter 2000).

According to the $Na_2O + K_2O$ vs SiO_2 classification of LeMaitre *et al.* (1989; Fig. 4a) and the Zr/TiO_2 vs SiO_2 diagram (Fig. 4b) of Winchester and Floyd (1977), the rocks can be subdivided into two groups, trachyte and peralkaline rhyolite, analogous to comendite/pantellerite fields according to Winchester and Floyd (1977). Most rocks are peralkaline with a high agpaitic index (AI = mole (Na+K)/Al; Shand 1951) and acmite in their CIPW normative mineralogy. Considering loss on ignition-free analyses (Table 1), the trachyte on average (n = 7, 1σ) has moderate SiO_2 (65 ± 2.48 wt. %) accompanied by high total alkalis (9.5 ± 1.81 wt. %), low CaO (2.5 ± 1.21 wt. %), high FeO^t/MgO (ca. 25) and elevated concentrations of high field

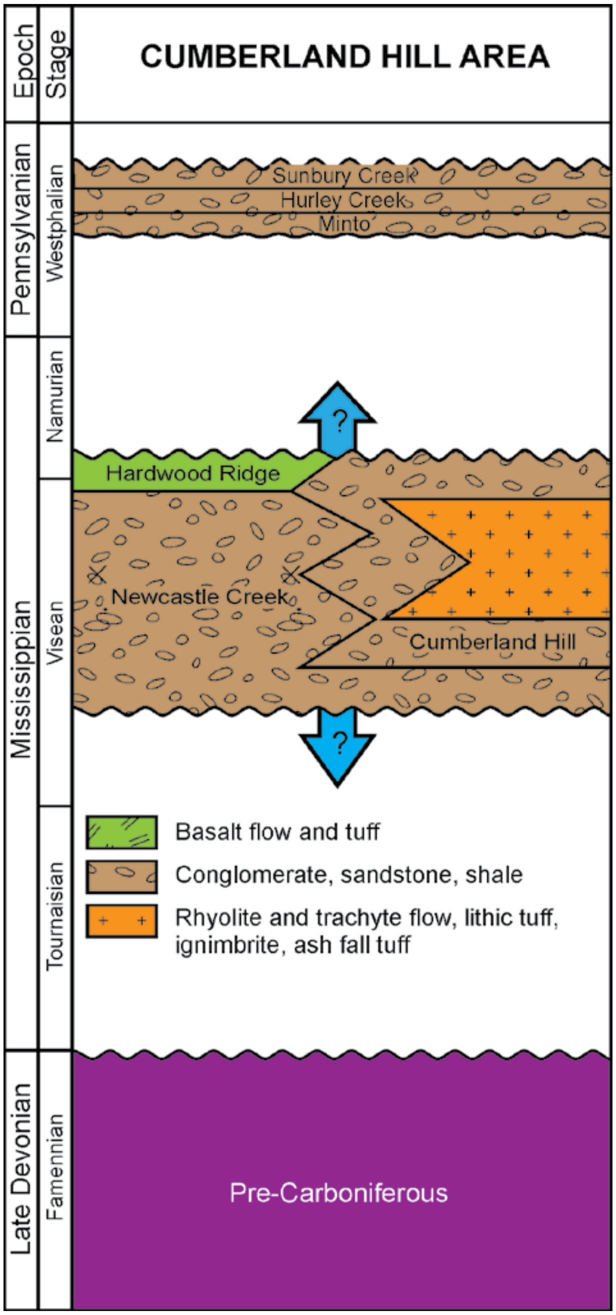

Fig. 2. Carboniferous stratigraphy in the central New Brunswick Basin (adapted from St. Peter 1997). The Cumberland Hill and Hardwood Ridge formations are part of the Mabou Group, whereas the Minto Formation, Hurley Creek Formation and Sunbury Creek Formation belong to the Pictou Group.

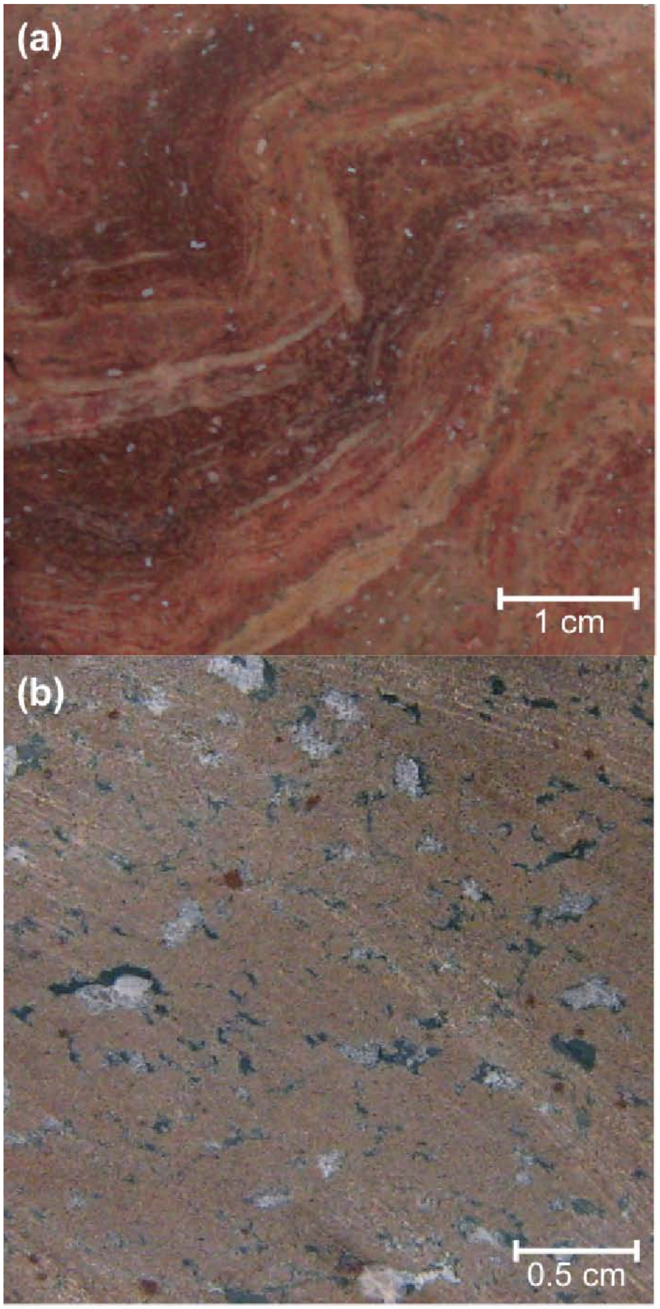

Fig. 3. Slab photographs indicating (a) flow-banded rhyolite with a quartzofeldspathic groundmass, and (b) vuggy trachyte with chlorite infillings.

Table 1. Major and trace element concentrations in trachyte and rhyolite from the Cumberland Hill Formation.

	Trachyte							Rhyolite							
	46°01'56"N, 65°51'57"W to 46°01'50"N, 65°52'04"W							46°01'11"N, 65°51'15"W to 46°01'13"N, 65°51'14"W							
	1-202	1-203	1-206	1-207	1-01	1-12	1-14	2-01	2-8A	2-8B	2-09	2-10	2-11	2-12	2-13
SiO_2 (wt. %)	61.71	59.93	66.95	63.63	64.15	62.39	62.30	74.22	72.81	73.40	72.72	71.69	71.85	72.42	74.29
TiO_2	0.48	0.47	0.63	0.37	0.60	0.63	0.38	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18
Al_2O_3	14.29	14.14	13.87	14.94	13.75	13.51	14.43	11.64	11.23	11.44	11.25	11.60	11.71	11.65	11.93
$Fe_2O_3^T$	9.30	8.80	4.07	7.83	6.11	5.10	7.84	3.39	4.16	4.13	4.13	4.37	4.22	4.36	3.38
MnO	0.18	0.25	0.11	0.22	0.19	0.17	0.22	0.04	0.10	0.10	0.12	0.10	0.10	0.09	0.03
MgO	0.13	0.37	0.20	0.08	0.37	0.29	0.07	0.02	0.02	-	0.02	0.02	0.05	0.02	0.03
CaO	1.52	2.36	2.30	1.69	3.13	4.50	1.38	0.11	0.15	0.15	0.22	0.31	0.26	0.23	0.34
Na_2O	4.78	4.43	3.73	5.77	3.03	2.21	6.17	3.65	3.93	4.21	3.67	3.81	4.26	4.50	5.33
K_2O	4.93	5.02	4.97	5.16	4.85	3.87	5.68	4.59	4.96	4.84	5.56	4.97	4.53	4.18	3.46
P_2O_5	0.14	0.13	0.23	0.09	0.17	0.19	0.08	-	0.01	-	0.01	-	-	-	-
LOI	1.84	2.48	2.84	0.66	4.02	6.31	0.62	0.96	1.31	1.17	1.99	1.80	2.06	1.03	1.40
Total	99.30	98.37	99.89	100.44	100.37	99.17	99.17	98.79	98.85	99.61	99.85	98.84	99.22	98.66	100.37
Pb (ppm)	26.0	13.0	18.0	21.0	9.00	16.0	90.0	15.0	62.0	21.0	37.0	28.0	82.0	24.0	17.0
Zn	250	150	110	210	90.0	60.0	210	390	280	300	360	300	300	310	290
W	1.60	1.40	1.80	1.40	1.10	3.50	0.70	3.20	6.60	8.20	2.90	3.50	3.40	22.9	9.40
Rb	81.0	79.0	92.0	104	98.0	91.0	124	308	290	299	347	306	262	244	192
Cs	0.60	0.20	1.30	0.70	1.70	1.70	0.70	1.90	1.70	1.90	1.90	2.10	1.50	1.70	1.10
Ba	384	403	552	259	664	398	280	15.00	4.00	-	12.0	6.00	9.00	-	9.00
Sr	107	281	100	42.0	93.0	96.0	39.0	25.0	16.0	17.0	37.0	39.0	38.0	21.0	28.0
Ga	36.0	34.0	26.0	40.0	30.0	28.0	39.0	56.0	54.0	58.0	57.0	57.0	56.0	58.0	55.0
Ta	6.72	6.68	3.67	8.09	3.70	4.33	8.29	15.1	18.4	18.9	18.4	18.2	18.4	19.4	18.7
Nb	95.5	92.6	51.5	118	51.1	65.6	118	281	235	287	222	249	223	306	208
Hf	22.3	21.9	11.7	24.9	14.4	16.0	31.0	57.3	51.1	55.5	53.0	50.4	51.7	54.5	55.0
Zr	991	944	557	1150	679	755	1550	2640	2190	2420	2290	2300	2280	2380	2450
Y	86.90	83.3	51.7	101	54.4	62.3	88.8	177	179	175	179	184	162	187	191
Th	11.5	11.1	11.3	12.2	12.6	13.6	14.8	29.6	31.2	30.8	38.7	32.9	29.2	33.1	35.0
U	2.36	2.35	4.81	3.71	4.65	5.79	3.99	20.80	9.27	11.70	18.50	13.80	16.10	10.20	13.80
La	114	116	93.0	139	86.0	88.3	120	164	150	151	144	142	146	148	146
Ce	239	243	195	286	183	189	259	337	331	334	330	327	315	319	322
Pr	25.9	26.3	20.7	30.5	21.7	22.1	30.6	39.3	39.1	39.5	37.7	37.5	38.3	38.7	38.7
Nd	92.5	94.8	70.3	110	86.6	88.8	122	152	155	155	147	147	151	152	152
Sm	20.8	20.7	14.9	23.7	17.1	17.5	24.8	35.6	36.6	37.3	35.3	35.5	36.1	36.3	36.4
Eu	5.33	5.40	3.62	5.40	3.40	3.55	4.85	3.06	3.17	3.17	3.11	3.08	3.18	3.12	3.20
Gd	19.3	19.6	13.3	22.2	14.0	14.7	21.5	33.2	34.9	35.9	34.6	34.7	34.8	35.5	36.0
Tb	3.12	3.04	2.02	3.49	2.10	2.26	3.38	6.08	6.04	6.11	6.12	6.12	6.00	6.27	6.35
Dy	16.9	16.6	10.8	19.7	11.3	12.6	18.4	33.3	34.5	34.3	35.1	35.1	33.0	35.9	36.1
Ho	3.15	3.12	2.00	3.66	2.17	2.46	3.56	6.62	6.67	6.67	7.16	6.97	6.24	7.13	7.20
Er	8.85	8.61	5.61	10.0	5.91	6.78	9.72	18.2	18.1	17.8	19.5	19.0	16.6	19.4	19.6
Tm	1.27	1.24	0.81	1.42	0.88	1.02	1.45	2.85	2.64	2.63	2.95	2.93	2.55	3.01	2.97
Yb	8.35	7.98	5.29	9.07	5.61	6.50	9.37	17.6	17.7	15.5	17.0	17.9	15.7	18.1	17.7
Lu	1.30	1.30	0.80	1.42	0.89	1.03	1.48	2.54	2.68	2.23	2.36	2.63	2.30	2.60	2.56

Note: - symbol indicates no data available, or value below detection limits strength elements (HFSE) and other incompatible elements (e.g., Zr + Nb + Ce + Y = 1334 ± 409.70; Whalen *et al.* 1987). The average of the rhyolitic rocks (n = 8, 1σ) has higher SiO_2 (75.0 ± 0.66 wt. %), equivalent total alkali concentrations (9.0 ± 0.29 wt. %), very low CaO (0.23 ± 0.08 wt. %), high FeO^t/MgO (ca. 140), and high HFSE and other incompatible elements (e.g., Zr + Nb + Ce + Y = 3126 ± 161.75; Whalen *et al.* 1987).

The major and trace element signatures of the volcanic rocks of the Cumberland Hill Formation are interpreted to vary predominantly due to the degree of fractionation. Conversely, a heterogeneous magma source could also contribute to the variations exhibited. In order to determine the fractionation trends, Nb was utilized as a differentiation index following White *et al.* (2006; Fig. 5). With increasing concentration of Nb, the trachyte samples display positive correlation with Al_2O_3, and negative correlation with TiO_2. The reduction in TiO_2 concentration can most likely be attributed to crystallization of Fe-Ti oxides. Rhyolite samples, in contrast, have relatively constant Al_2O_3 (Fig. 5a) and TiO_2 (Fig. 5b). Trace elements also display different fractionation trends in trachyte and rhyolite samples. Trachyte samples show marked decreases in Ba with increasing Nb (Fig. 5c), reflecting the crystallization of feldspars, as well as an increase in incompatible trace elements including Zr, La, and Ga (Fig. 5d, e, f). However, the abundances of these trace elements in the rhyolite remain virtually unchanged with increasing Nb. The contrast in fractional crystallization trends between trachyte and rhyolite is highlighted by the $CaO-K_2O-Na_2O$ ternary diagram (Fig. 6), which illustrates that trachyte samples plot in a trend away from the CaO apex, whereas rhyolite sample variation is parallel to the K_2O-Na_2O join. This difference is most readily explained by the crystallization of Ca-bearing plagioclase and clinopyroxene in the trachyte magma, and alkali feldspar crystallization in the rhyolite magma.

The chondrite-normalized rare earth element (REE) patterns for each suite (Fig. 7a) are strongly enriched in light REE (LREE). The rhyolite has higher LREE contents with La_n values of ca. 440–510 compared to the trachyte with La_n ca. 270–430. The trachyte shows steeper LREE to heavy rare earth element (HREE) profiles, with La_n/Yb_n ratios ca. 8–11 compared to ca. 4–6 in rhyolite. A similar relationship is observed for La_n/Sm_n, which in the trachyte is ca. 2.6–3.4 and in the rhyolite is ca. 2.2–2.6. The shape of the REE patterns in the trachyte does not change significantly, although the absolute abundances are escalating with the increasing degree of differentiation. The REE patterns of the rhyolite are characterized by a pronounced negative Eu anomaly (average Eu/Eu* = 0.08), consistent with low-pressure fractional crystallization of alkali and/or plagioclase feldspar. Primitive mantle-normalized trace element patterns in both rock types (Fig. 7b) are fairly similar. Both are highly fractionated and peak at Th-Nb; however, the rhyolite displays strong, negative Ba, Sr, and moderately negative Eu anomalies, whereas the trachyte contains only slightly negative anomalies in these elements. The Nb/Ta ratios of the trachyte (14.27 ± 0.47) and rhyolite (13.91 ± 2.48) are the same,

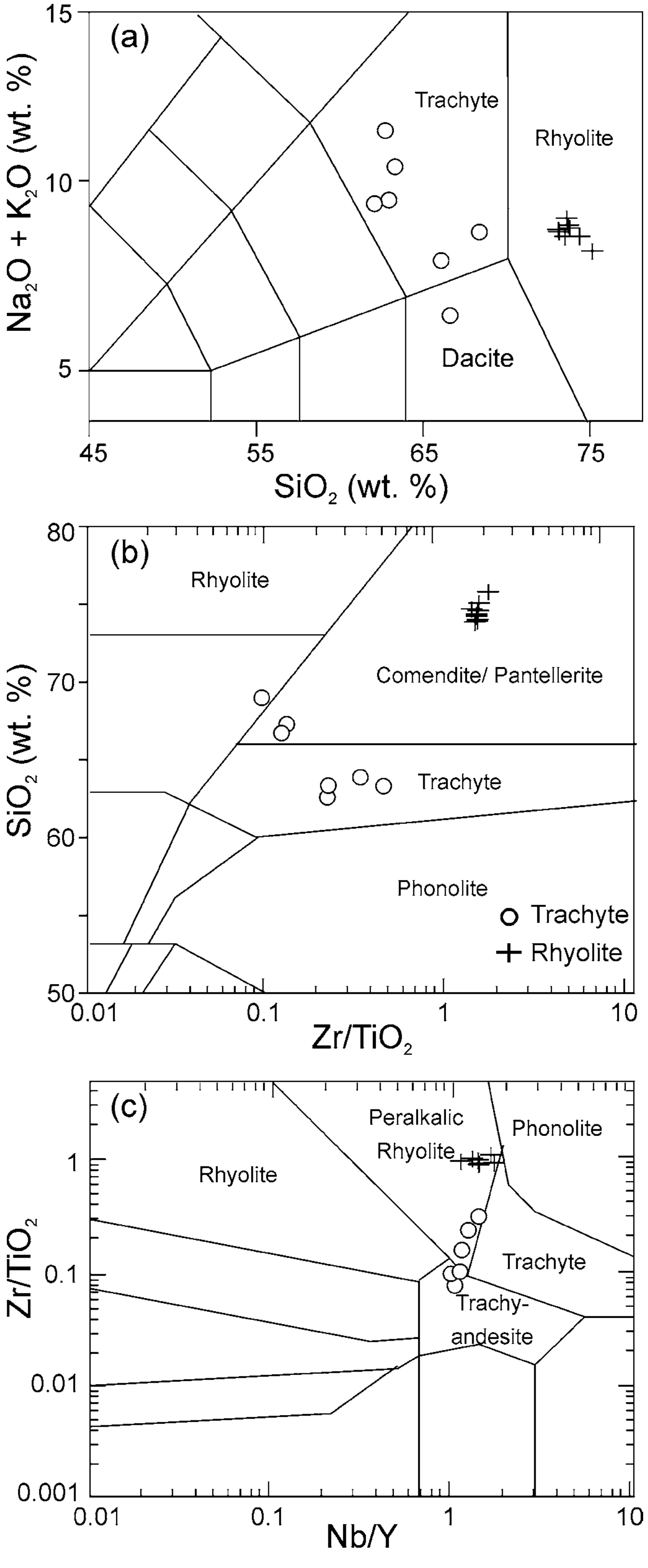

Fig. 4. Plots of (a) $Na_2O + K_2O$ versus SiO_2 (wt. %; Le Maitre et al. 1989); (b) SiO_2 versus Zr/TiO_2 (wt. %; Winchester and Floyd 1977); and (c) Zr/TiO_2 versus Nb/Y (Winchester and Floyd 1977) for volcanic samples from the Cumberland Hill Formation.

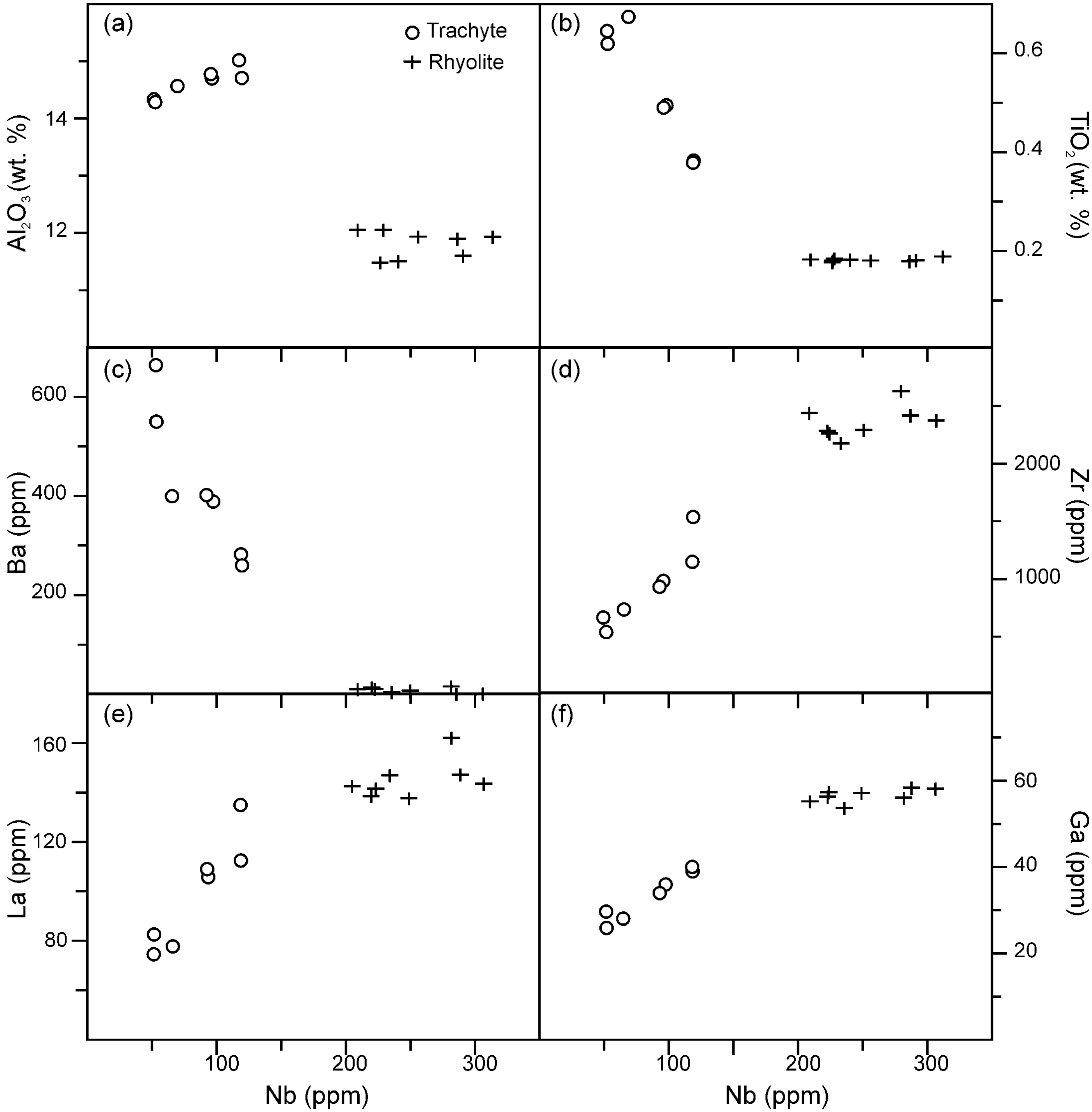

Fig. 5. Plots of Nb (ppm) versus (a) Al_2O_3 (wt. %), (b) TiO_2 (wt. %), (c) Ba (ppm), (d) Zr (ppm), (e) La (ppm), and (f) Ga (ppm) for volcanic samples from the Cumberland Hill Formation.

but slightly lower than that of the mantle (typically ~ 17.5; Sun and McDonough 1989).

The abundances of U and Th in the felsic rocks of the Cumberland Hill Formation are high and variable. Rhyolite display significantly higher contents of U (14.0 ± 4.0 ppm, n = 8), and Th (33.0 ± 3.1 ppm, n = 8) compared to trachyte (U = 2.4 ± 2.4 ppm, n = 7; Th = 12 ± 1.4 ppm, n = 7). The large range in U may be related to devitrification and alteration of the rhyolite groundmass. The rhyolite samples also have a higher U/Th ratio (0.44 ± 0.13, n = 8) than trachyte (0.32 ± 0.09, n = 7), which is comparable to the whole rock or melt inclusion data from non-mineralized peralkaline rhyolite from various

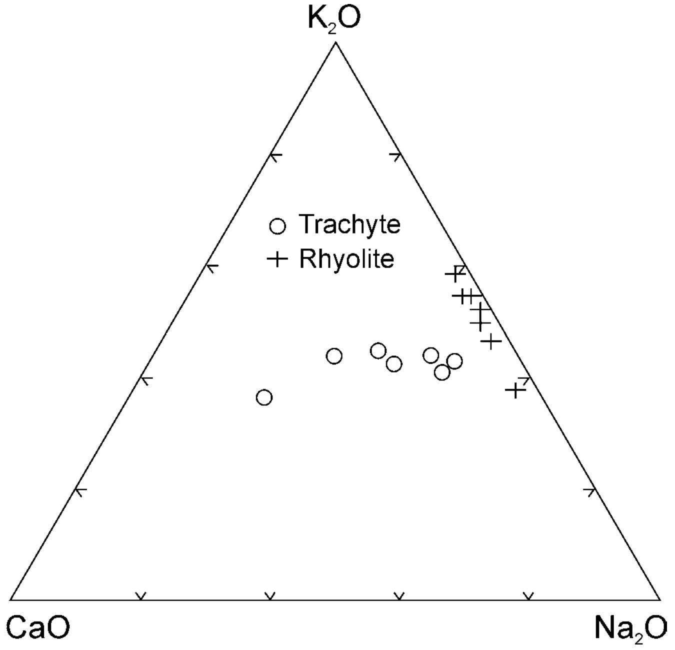

Fig. 6. CaO-K_2O-Na_2O ternary diagram for volcanic samples from the Cumberland Hill Formation. Trends indicate that fractionation of Ca-plagioclase and clinopyroxene could have occurred in trachyte, whereas alkali feldspar fractionation is more likely in rhyolite.

U districts in the world (Cuney and Kyser 2009). The increase of U/Th ratio in the rhyolite compared to trachyte may reflect monazite fractionation. Based on the variability of the U and Th concentrations in the rhyolite and trachyte samples, we interpret that remobilization of these elements has occurred. This remobilization was likely caused by devitrification of the groundmass because zircon is modally insignificant, and not the principal host of these elements based on the lack of correlation of radioactive trace elements with Zr (see Dupuy and Dostal 1983).

PETROGENESIS

Overall the geochemical and mineralogical similarities of the spatially and temporally associated trachyte and rhyolite imply that they are genetically related. However, discontinuous and/or contrasting variation trends and significant differences in incompatible trace element ratios indicate that the rhyolite was not derived from the trachyte via continuous fractional crystallization, although fractional crystallization may be responsible for the variations within the individual suites. The evolution of the trachyte in the melt phase involved crystallization of feldspars, clinopyroxene, and Fe-Ti oxides, whereas the evolution of the rhyolite was dominated by crystallization and fractionation of alkali feldspar.

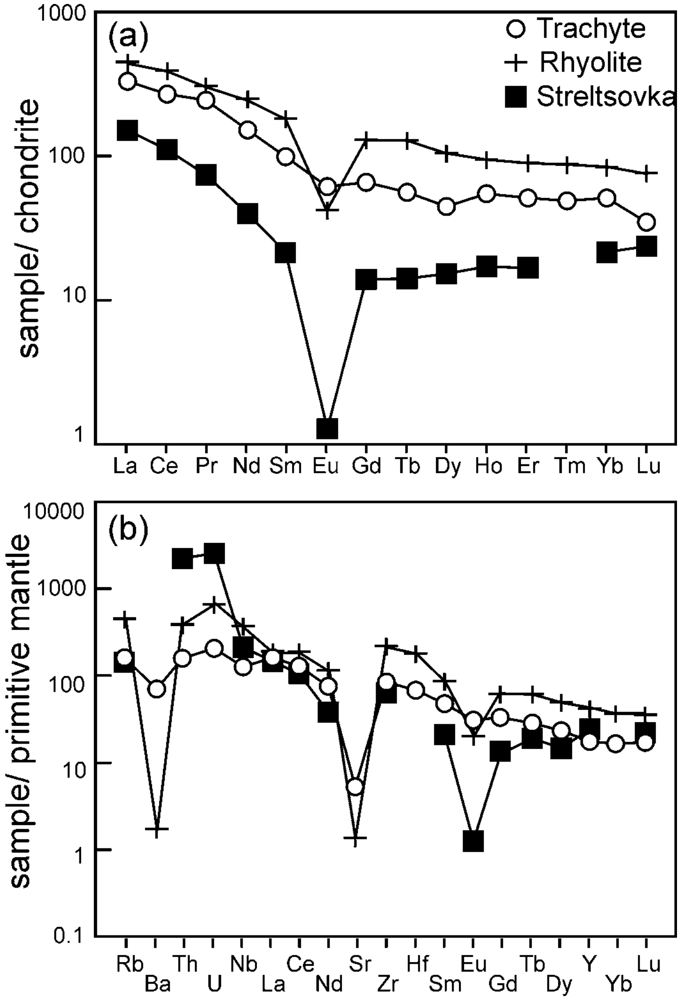

Fig. 7. (a) Chondrite-normalized REE patterns of the averages of trachyte (n = 7) and rhyolite (n = 8) samples from the Cumberland Hill Formation and rhyolite from Streltsovka (n = 1; Chabiron *et al.* 2003); (b) Primitive mantle-normalized multi-element plots of the average of trachyte (n = 7) and rhyolite (n = 8) samples from the Cumberland Hill Formation and rhyolite from Streltsovka (n = 1; Chabiron *et al.* 2003). Normalizing values are after Sun and McDonough (1989).

An alternative model to continuous fractional crystallization for the origin of the rhyolite is assimilation-fractional crystallization. However, the low and overlapping Th/Ta ratio of the trachyte and rhyolite (Fig. 8a), a sensitive indicator of crustal contamination (Gorton and Schandl 2000), demonstrates that assimilation-fractional crystallization and crustal contamination processes cannot solely account for derivation of the rhyolite from the trachyte. In addition, Pe-Piper and Piper (1998) reported an ε_{Nd} value of +3, with an assumed age of ca. 310 Ma from the Cumberland Hill rhyolite. This relatively high value implies that significant assimilation of crustal material is not likely to have taken place.

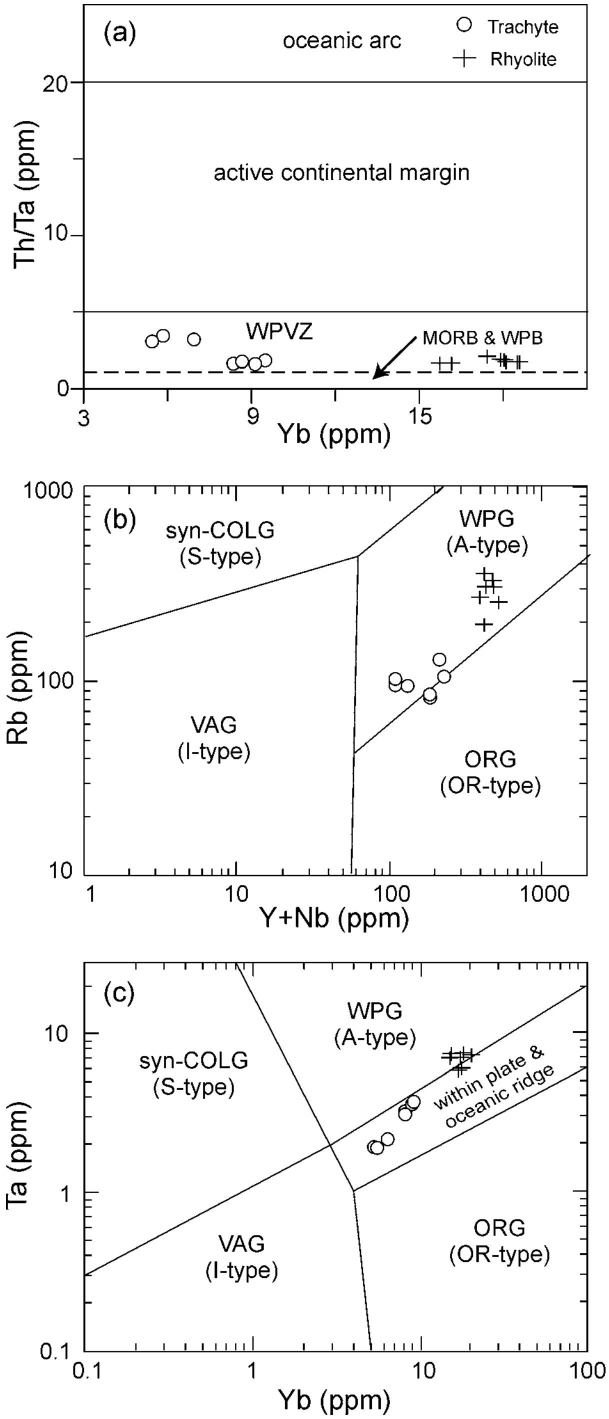

Fig. 8. **Discrimination diagrams for felsic volcanic rocks from the Cumberland Hill Formation. (a) Yb (ppm) versus Th/Ta (Gorton and Schandl 2000). Abbreviations: WPVZ = within plate volcanic zones; MORB = mid-ocean ridge basalt; WPB = within-plate basalt. (b) Rb vs Nb + Y and (c) Ta vs Yb (Pearce *et al.* 1984). Abbreviations: syn-COLG = syn-collisional granite; WPG = within-plate granite; VAG = volcanic-arc granite; ORG = oceanic-ridge granite.**

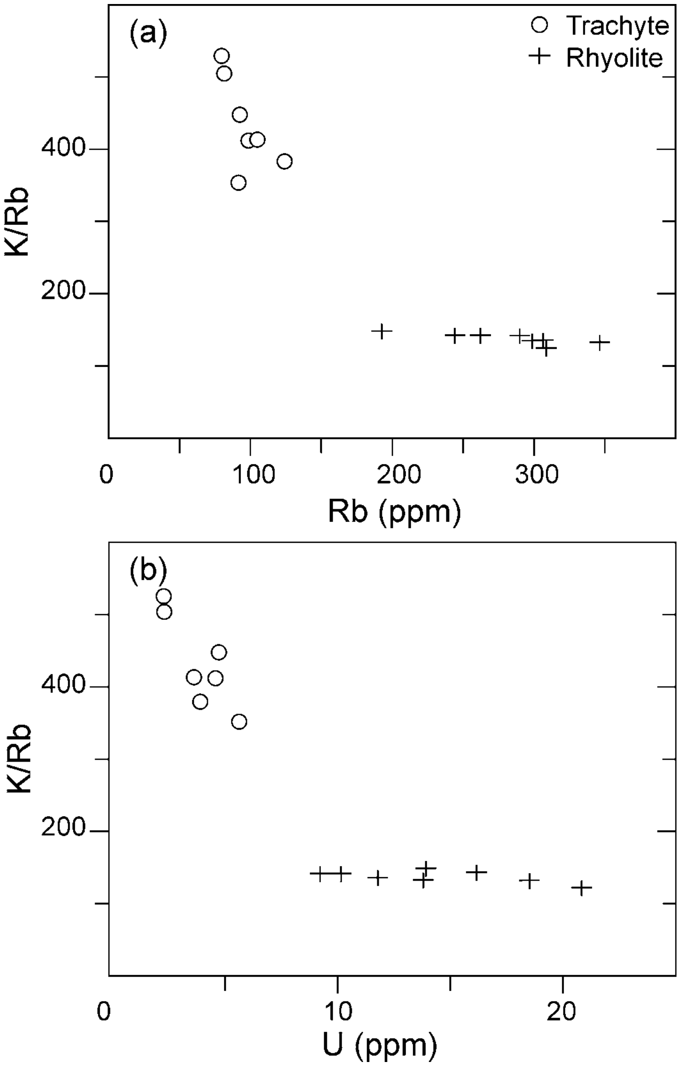

Fig. 9. **Plot of K/Rb versus (a) Rb (ppm) and (b) U (ppm) in felsic volcanic samples from the Cumberland Hill Formation.**

K/Rb ratios in trachyte samples are much higher than in rhyolite samples (Fig. 9a, b), which suggest that the evolution of the rhyolite may have been affected by fluids (Dostal and Chatterjee 1995). Again, this mechanism cannot explain the origin of the rhyolite, but rather indicates that fluids played an important role during the evolution of these rocks and perhaps even led to the mobilization of U (Cuney and Kyser 2009; Nash 2010) in the rhyolite (Fig. 9b).

A comparison with similar rocks elsewhere (e.g., Pecerrillo *et al.* 2003) suggests that the Cumberland Hill trachyte and rhyolite could represent various stages of fractional crystallization in an evolving alkali basaltic magma. The absence of a negative Nb anomaly suggests that the parent magmas were not derived from subcontinental lithospheric mantle, but more plausibly originated from asthenospheric mantle. This interpretation is supported by the rhyolite ε_{Nd} value of +3 (Pe-Piper and Piper 1998), which implies upward migration of enriched asthenospheric magma into a juvenile lithosphere.

LaFleche *et al.* (1998) and Pe-Piper and Piper (1998) described alkali basaltic rocks of comparable age from other parts of the Maritimes Basin. The presence of alkali gabbroic rocks of a similar age (Johnson 2008) in the area suggests that the felsic rocks of the Cumberland Hill Formation could be derived from such parent magma by fractional crystallization. In fact, peralkaline felsic volcanic complexes are typically associated with a shallow-seated alkali intrusions ranging in composition from gabbro to highly fractionated granitic rocks. Although geochemical data are insufficient from the mafic alkali rocks in the vicinity of the Cumberland Hill Formation, chemical analyses of alkali basaltic rocks reported by LaFleche *et al.* (1998) from the Magdalen Islands indicate that similar basalts could have been a parent to trachyte and rhyolite. Trachyte of similar compositions have been documented to evolve from alkali basalt by extensive fractional crystallization (Peccerillo *et al.* 2003) and peralkaline rhyolite could have evolved from such magma by further fractional crystallization in a subvolcanic magma chamber. A likely scenario for the Cumberland Hill felsic rocks is that they are the products of fractional crystallization of alkali basaltic magma, and that the trachyte and rhyolite represent separate magma pulses with the latter being younger having undergone more extensive fractionation prior to emplacement.

ECONOMIC POTENTIAL

Silica-oversaturated peralkaline felsic volcanic rocks, particularly rhyolite, are commonly enriched in U and represent a potential source of uranium for volcanic-related hydrothermal U deposits, such as the Streltsovka caldera (Transbaikalia, Russia: Ischukova 1997; Chabiron *et al.* 2001, 2003; Cuney and Kyser 2009; Nash 2010), sediment-hosted U deposits in siliciclastic sedimentary basins, such as the U deposits in the Tim Mersoi basin in Niger (Forbes *et al.* 1984; Forbes 1989; Plant *et al.* 1999; Pagel *et al.* 2005; International Atomic Energy Agency 2009), and the New Horton mineralization (U-Cu-Ag-Au) within the Carboniferous basin (Boyd 1978; McLeod and Smith 2010; New Brunswick Department of Natural Resources 2010b).

The crystallization of U-bearing accessory minerals in highly depolymerized peralkaline melts is typically suppressed (Cuney 2009; Cuney and Kyser 2009) leading to progressive enrichment of U in residual melts during fractional crystallization and entrapment of U in the glassy groundmass. Subsequently U can be leached during the alteration or devitrification of the glass (Nash 2010). Cuney (2009) and Cuney and Kyser (2009) inferred that ignimbritic tuffs, in which U is hosted in the glass, are the most favourable type of volcanic rock; such rhyolitic pyroclastic rocks are abundant in the Cumberland Hill Formation.

Rhyolite of the Cumberland Hill Formation has relatively high abundances of U compared to associated trachyte and could be a source of U mineralization. The U concentrations in these rhyolite samples are elevated compared to similar felsic and mafic Late Tournaisian–Early Visean deposits of the Maritimes Basin (Magdalen Islands, 0.4–1.9 ppm; Central New Brunswick, 0.8–1.9 ppm and the Cobequid Highland dykes, 0.2 ppm; Pe-Piper and Piper 1998). The abundances of U in the rhyolite are comparable to the non-mineralized U concentrations of the peralkaline rhyolite of the Streltsovka caldera (Fig. 7b), the largest, volcanic-related, U ore field in the world (Cuney 2009). Despite similar U concentration, it is important to consider where U is hosted in rhyolite. When U is hosted in zircon or other resistant accessory minerals it cannot be readily remobilized. Based on current geochemical work, it appears U is present within the glassy groundmass of the rhyolite in the Cumberland Hill Formation and can therefore be released and re-deposited and thus could be a source of U within U- (Cu-V-Ag) deposits within local parts of the Carboniferous basin.

CONCLUSIONS

Felsic volcanic rocks from the Cumberland Hill Formation consist of peralkaline rhyolite and trachyte. Both contain elevated concentrations of incompatible trace elements, with the rhyolite more enriched and fractionated than the trachyte. Although both rock types appear to be genetically related, differences in their geochemical signatures imply the rhyolite was not derived from the trachyte by continuous fractional crystallization. Examination of the Th/Ta ratio also indicated crustal contamination cannot account for the observed compositional contrast. A preferred model is that the trachyte and rhyolite originated from the same or highly similar parent magma, and represent separate magma pulses with the latter being younger, having undergone more extensive fractionation prior to emplacement. The absence of a negative Nb anomaly suggests the parent magma was not derived from subcontinental lithospheric mantle, but more plausibly originated from an asthenospheric mantle source. Lastly, Cumberland Hill rhyolite contains elevated U concentrations, with U hosted within the glassy groundmass. Since U can be leached and re-deposited, the rhyolite could be a source of sediment-hosted U mineralization within the basin.

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