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OCCURRENCE OF EARLY CARBONIFEROUS HIGH-Zr RHYOLITES, COBEQUID HIGHLANDS, NOVA SCOTIA: TEMPERATURE EFFECT OF A CONTEMPORANEOUS MAFIC MAGMA[§]

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ABSTRACT

The Fountain Lake Group of the Cobequid Highlands is a bimodal rhyolite–basalt volcanic unit that was extruded during the earliest Carboniferous along the southern margin of the Maritimes Basin in northern Nova Scotia. In the eastern Cobequid Highlands, up to 4 km of felsic lava flows and pyroclastic deposits are overlain by 1.5 km of continental tholeiitic basalt. A distinctive high-Zr rhyolite (>900 ppm Zr) occurs as ignimbrites near the top of the felsic volcanic sequence, as dykes cutting the main extrusive rhyolite succession (but not younger units), and as linear intrusive bodies along the northern margin of the Wentworth pluton. In the western Cobequid Highlands, the volcanic succession is less than 1 km thick and comprises rhyolite with lesser basalt. Rhyolites have abundances of trace elements (*i.e.*, Zr, Nb, Y, Ga and Rb) typical of A-type, within-plate granitic magma. Older rhyolites have low ε_{Nd} ($< +1$), low Ga/Al and high Th/La, similar to early phases of coeval granite plutons in the region. Low-Zr rhyolites in the west show either a progressive increase in Zr with fractionation or no systematic pattern, whereas those in the east show a slight decrease. Younger high-Zr rhyolites show a rapid increase in Zr with fractionation, and Zr is almost entirely in the groundmass. These high-Zr rhyolites are only slightly enriched in other high-field-strength elements and *REE* compared with the low-Zr rhyolites. Their Nd isotopic composition is close to that of contemporaneous large gabbroic plutons, suggesting that the felsic magma may in part be derived from fractionation of mafic magma. The high Zr content is the result of high-temperature suppression of zircon crystallization by ambient mafic magmas correlative with the thick continental tholeiite basalts.

Keywords: rhyolite, Carboniferous, Nova Scotia, zirconium.

SOMMAIRE

Les roches du groupe de Fountain Lake, qui affleure sur le plateau de Cobequid, dans le nord de la Nouvelle-Ecosse, constitue une association bimodale rhyolite–basalte mise en place au début de l'ère carbonifère le long de la bordure sud du bassin des Maritimes. Dans la partie orientale du plateau, jusqu'à 4 km de laves et de roches pyroclastiques felsiques sont recouvertes par 1.5 km de basalte tholéiitique d'affinité continentale. Une unité rhyolitique se distingue par sa teneur élevée en Zr (>900 ppm Zr); elle se présente en ignimbrites près du haut de la séquence felsique, en filons recoupant cette séquence, mais non les roches plus jeunes, et en massifs intrusifs linéaires le long de la bordure nord du pluton de Wentworth. Dans la partie occidentale du plateau, la stratigraphie des roches volcaniques est inférieure à 1 km, et les rhyolites sont prédominantes par rapport aux basaltes. Les rhyolites possèdent des teneurs en éléments traces (*i.e.*, Zr, Nb, Y, Ga et Rb) typiques de magmas granitiques de type A, formés dans un contexte intra-plaques. Les rhyolites plus anciennes possèdent une faible valeur de ε_{Nd} ($< +1$) et de Ga/Al, et une valeur Th/La élevée, ressemblant ainsi aux phases précoces des plutons granitiques contemporains de la région. Les rhyolites à faible teneur en Zr dans l'ouest montrent soit une augmentation progressive en Zr due au fractionnement ou bien un comportement non systématique du Zr. Celles du secteur oriental font preuve d'un léger enrichissement. Les rhyolites à Zr élevé, plus jeunes, montrent un enrichissement marqué en Zr avec le fractionnement progressif du magma, et le Zr se trouve presqu'entièrement dans la matrice. Ces rhyolites enrichies en Zr ne le sont que légèrement dans le cas des autres éléments à champ électrostatique élevé et les terres rares, par rapport au rhyolites à faible teneur en Zr. Leur composition isotopique en Nd ressemble à celle de plutons contemporains de composition gabbroïque, ce qui fait penser que le magma felsique pourrait être issu du fractionnement d'un magma mafique. La teneur élevée en Zr résulterait de la suppression du zircon à température élevée à cause de la présence de magma mafique nourissier des épaisses coulées de basalte tholéiitique.

(Traduit par la Rédaction)

Mots-clés: rhyolite, carbonifère, Nouvelle-Ecosse, zirconium.

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INTRODUCTION

The mid-Devonian to lower Permian Maritimes Basin (Fig. 1) is a major post-tectonic extensional basin in Atlantic Canada (Bradley 1982). Most of the volcanic rocks in the basin are continental tholeiitic basalts (Blanchard *et al.* 1984, Pe-Piper & Piper 1998). However, extrusive and hypabyssal rhyolites also are widespread along the Cobequid crust-scale shear zone at the southern margin of the basin, where the Fountain Lake Group consists locally of as much as 3–3.5 km of felsic volcanic rocks overlain by 1–1.5 km of basalt. The Fountain Lake Group outcrops in several areas of the Cobequid Highlands (Fig. 2), where it has been dismembered by later faulting. Palynology (Utting *et al.* 1989) indicates a Tournaisian age for at least the upper part of the Fountain Lake Group, and preliminary U–Pb zircon dating (Dunning *et al.* 1997) indicates that the felsic volcanic rocks are mostly 358–354 Ma and thus of earliest Carboniferous age according to the time scale of Tucker *et al.* (1998). These volcanic rocks are thus somewhat younger than the main granite and gabbro plutons of the Cobequid Highlands (360–363 Ma: Doig *et al.* 1996). Within the Maritimes Basin, both older volcanic successions, such as the late Devonian Fisset Brook Formation of western Cape Breton Island (Barr & Peterson 1998), and younger rocks, such as the Visean–Westphalian volcanic rocks of New Brunswick (Fyffe & Barr 1986), have thinner rhyolite sequences and a higher proportion of basalt to rhyolite. The thick sequences of felsic volcanic rocks in the Cobequid Highlands are thus regionally unusual.

The thick rhyolite sequences in the Cobequid Highlands show considerable geochemical variation. Both whole-rock geochemistry (Pe-Piper *et al.* 1991) and Pb and Nd isotopic data (Pe-Piper & Piper 1998) of coeval granites suggest that the felsic magmas result from anatexis in the lower crust, with heat derived from coexisting mafic magma. The chronology of emplacement of magma pulses is well known from volcanic stratigraphy, cross-cutting relationships and radiometric dating. In this paper, we attempt to constrain i) the petrogenetic history of the felsic magma, ii) the evolution of distinctive Zr-rich phases, and iii) the relationship between the felsic and mafic flows of the Fountain Lake Group. We establish a comparison with the minor rhyolite sequences elsewhere in the Maritimes Basin.

GEOLOGICAL SETTING

The Cobequid Highlands lie on the southern margin of the Late Paleozoic Maritimes Basin (Fig. 1). This

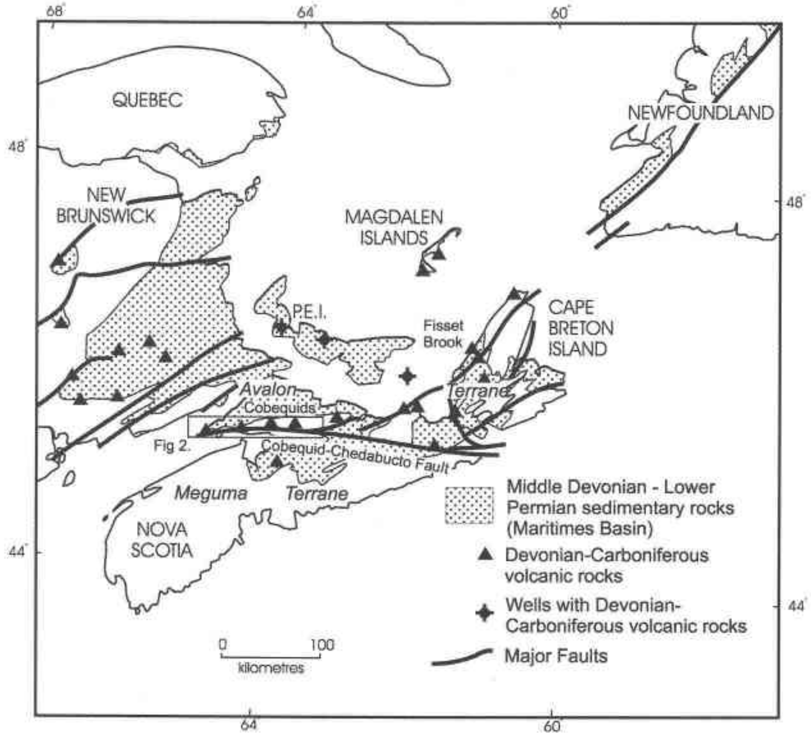

FIG. 1. The Maritimes Basin, Atlantic Canada, showing location of the Cobequid Highlands and Devonian–Carboniferous volcanic rocks.

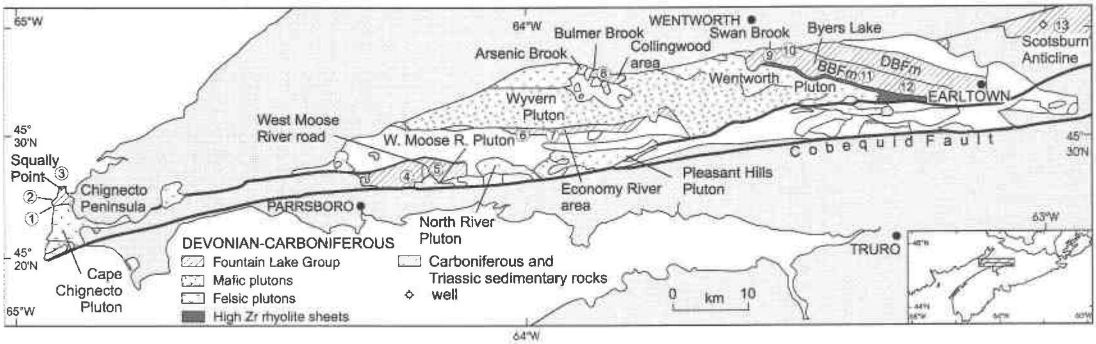

FIG. 2. Devonian–Carboniferous igneous rocks of the Cobequid Highlands, Nova Scotia. Map modified from Donohoe & Wallace (1982). Numbers refer to localities in Figure 3.

basin accumulated several kilometers of middle Devonian to lower Permian strata, following the early to middle Devonian Acadian orogeny (Bradley 1982). Widespread igneous activity accompanied basin formation, which resulted in the emplacement of several mafic and felsic intrusions, as well as the deposition of cogenetic volcanic suites in the Cobequid Highlands. The southern margin of the Cobequid Highlands is marked by the Cobequid–Chedabucto shear zone, which is a dextral strike-slip fault zone separating the Avalon terrane from the Meguma terrane to the south (Keppie 1982). The northern margin of the highlands is unconformably overlain by Carboniferous sedimentary rocks.

In the eastern Cobequid Highlands, the Fountain Lake Group is divided into two formations, the Byers Brook and Diamond Brook formations (Donohoe & Wallace 1982). The earliest volcanic rocks consist principally of rhyolite (Byers Brook Formation) with minor interbedded basalt (Fig. 3). These are overlain by basalts of the Diamond Brook Formation, locally with small rhyolite domes (Dessureau *et al.*, in press). The Byers Brook Formation is from 1 km to >3 km thick in the Earltown – Byers Lake belt of the eastern Cobequid Highlands (Fig. 2), where it outcrops in a series of north-flowing brooks and dips 75°–80°N. The western part of this area was studied in detail by Gower (1988). In the Scotsburn anticline to the east, the Irving Chevron Scotsburn #2 well (Utting *et al.* 1989) intersected 1.5 km stratigraphic thickness of predominantly felsic volcanic rocks. In the western Cobequid Highlands, the Fountain Lake Group is less than 1 km thick and comprises rhyolites and felsic pyroclastic rocks interbedded with lesser basalt flows (Fig. 3; Piper *et al.* 1996a).

On the basis of a reconnaissance study, Dostal *et al.* (1983a) concluded that the rhyolites of the Fountain Lake Group formed in an intraplate setting by crustal anatexis, and U, Th and K were remobilized during secondary processes (Dostal *et al.* 1983b). Pe-Piper *et al.* (1989, 1991) demonstrated that the rhyolites of the Fountain Lake Group were geochemically similar to the early Carboniferous granitic plutons of the Cobequid Highlands. These plutons are subalkaline, and their enrichment in Nb and Y with elevated Ga/Al ratios suggests that they are A-type granites: Pe-Piper *et al.* (1991) interpreted the felsic magmas as produced by anatexis of a halogen-rich anhydrous lower crust. The main gabbro body of the Wentworth pluton (Fig. 2) shows widespread evidence for coexisting mafic and felsic magmas (Pe-Piper *et al.* 1996). Pe-Piper & Piper (1998) reported Pb and Nd isotope determinations for both granites and felsic volcanic and subvolcanic rocks of the Fountain Lake Group.

FIELD OCCURRENCE OF THE FELSIC ROCKS OF THE FOUNTAIN LAKE GROUP

The occurrence of felsic rocks of the Fountain Lake Group is described from west to east through the Cobequid Highlands (Figs. 2, 3). At northern Cape Chignecto, several fault-bound slices preserve segments of a rhyolite – basalt sequence (Piper *et al.* 1996a). Most of the rhyolites are porphyritic and probably intrusive, but at Squally Point (location 1, Figs. 2, 3), an 80-m-thick volcanic sequence is exposed, including thin basalt and a 35-m-thick ignimbrite.

In the West Moose River area, the volcanic sequence lies immediately north of the Cobequid Fault, dipping steeply near the fault and flattening out to the north. On the West Moose River road (5 in Figs. 2, 3), the section consists of 500 m of rhyolite flows with minor pyroclastic flows overlain by alternating basalt and rhyolitic pyroclastic flows, whereas farther west, in McAlese Brook (4 in Figs. 2, 3), basalt is absent.

Thin (< 600 m) east–west-striking belts of the Fountain Lake Group outcrop in fault-bound sections exposed on the New Britain Road and in Economy River (6, 7 in Figs. 2, 3), north of the North River and Pleas-

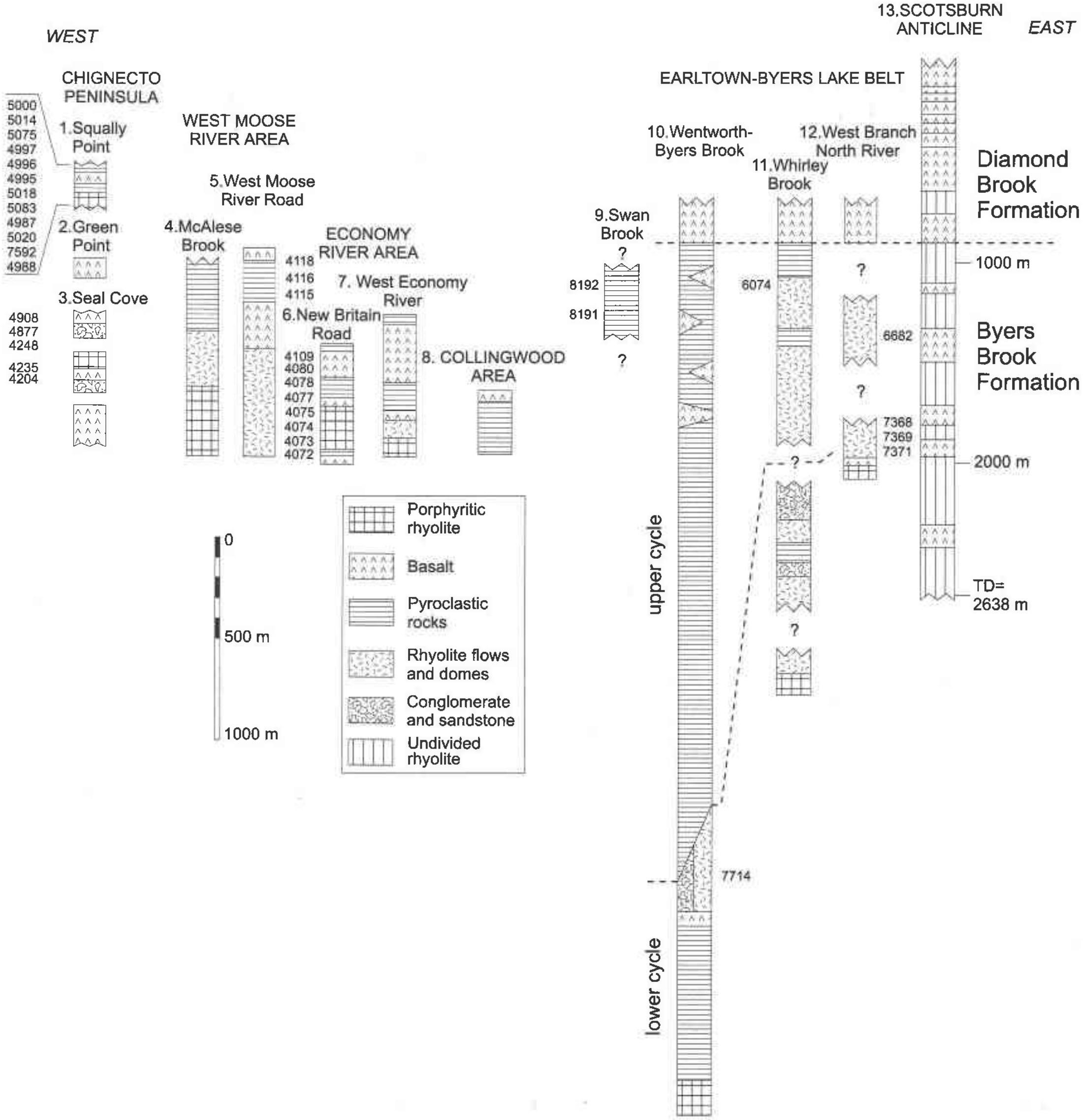

FIG. 3. Summary stratigraphic columns of the main developments of the felsic Fountain Lake Group in the Cobequid Highlands. Columns located on Figure 2; (9) from Gower (1988), and (13) from Utting *et al.* (1989).

ant Hills plutons. These outcrops dominantly contain rhyolite and pyroclastic flows interbedded with minor amounts of basalt and minor hypabyssal intrusive rhyolite. Steep south-dipping thrusts separate the Fountain Lake Group from Neoproterozoic and Silurian sedimentary rocks to the south, and gabbro and minor granite of the late Devonian Wyvern Pluton to the north (Fig. 3).

Pyroclastic flows and air-fall tuffs of rhyolitic composition are the dominant lithology of the Fountain Lake Group in the Collingwood area (8 in Figs. 2, 3). These units achieve thicknesses of several hundred meters in steeply dipping units in Bulmer and Arsenic brooks. Minor rhyolite and basalt associated with these units occur as flows and hypabyssal intrusions.

The largest occurrence of the Fountain Lake Group lies between Earltown and Byers Lake. In this area, the rocks are steeply dipping and can be divided into two mappable formations. The predominantly felsic rocks of the Byers Brook Formation are between 1 and 3.5 km thick and are conformably overlain by approximately 1.5 km of predominantly mafic rocks of the Diamond Brook Formation. Gower (1988) investigated the stratigraphy in detail between Wentworth and Byers Lake, and used information from a large number of diamond drill holes together with field mapping. In this area, he recognized two discrete volcanic cycles separated by a conglomerate–siltstone horizon. Ash flows and tuffs are dominant in the lower portion of each cycle, passing upward into rhyolite flows and domes interbedded with basalt and some tuffs (9 in Fig. 3). Prominent ignimbrites outcrop in Swan Brook (10 in Fig. 2) near the top of the Byers Brook Formation. Farther west in Whirley Brook (11 in Figs. 2 and 3), the thickness of pyroclastic rocks seems much reduced, and only a few hundred meters of the lower cycle are present. In the eastern part of the Earltown – Byers Lake belt, rhyolite domes predominate (12 in Fig. 3), and the overall thickness is as little as a kilometer. Outcrop is quite discontinuous in both sections 11 and 12, and the logs presented may overestimate thickness of resistant rhyolite flows and domes and underestimate thickness of pyroclastic units. The thinning from west to east in the Earltown – Byers Lake belt seems to be achieved in part by a reduction in thickness of pyroclastic rocks and in part by the absence of the lower part of the formation in the east. This absence cannot entirely be accounted for by intrusion of late plutonic rocks into the base of the formation, and must result either from non-deposition or removal of the base of the section by faulting.

The Fountain Lake Group is also recognized from seismic reflection profiling in the subsurface of the Scotsburn Anticline and the southeastern Cumberland basin (Durling 1996). Lithologies in the Irving Chevron Scotsburn #2 well are known only from cuttings and log interpretation.

Rhyolite sills and dykes in places cut the Fountain Lake Group. Their spatial relationship to the Fountain Lake Group and the coeval plutons suggests that they are chronologically and genetically related to the volcanism. Most appear to be relatively late in the volcanic sequence. At Seal Cove, volcanic rocks are cut by a rhyolite dyke (sample 4908; Table 1). A rhyolite dyke (7597) cuts plutonic rocks of the Cape Chignecto pluton that show a syn-intrusion deformation (Koukouvelas *et al.* 1996). North of the Pleasant Hills pluton, in the Black Brook region (Piper *et al.* 1996b), thrust faults within Silurian sedimentary rocks are occupied by porphyritic rhyolite sills (7330, 7339) that are geochemically similar to Fountain Lake Group rhyolites elsewhere.

A series of rhyolite dykes with >900 ppm Zr (Gower 1988) cut the Byers Brook Formation (6083) and possi-

TABLE 1. ANALYZED SAMPLES USED IN THIS STUDY

Sample	Location	Location Number	Universal Transverse Mercator Coordinates	Rock Type	**
4204	Seal Cove	8701805	349767E–5030709N	Intrusion	1
4235	Seal Cove	8711510	349246E–5029648N	Intrusion	1
4248	Seal Cove	8711512	349267E–5029464N	Intrusion	1
4877	Seal Cove	9000304	349341E–5029390N	Intrusion	3
4908	Seal Cove	9000409	349222E–5029762N	Dyke	1
4987	Squally Point	9000515	350678E–5032474N	Flow	1
4988	Squally Point	9000516	350685E–5032507N	Flow	1
4995	Squally Point	9000519	350614E–5032517N	Tuff	1
4996	Squally Point	9000519	350614E–5032517N	Flow	1
4997	Squally Point	9000519	350614E–5032517N	Flow	1
5000	Squally Point	9000523	350399E–5032536N	Flow	1
5014*	Squally Point	9000608	350454E–5032530N	Ignimbrite	1
5018	Squally Point	9000616	350201E–5032275N	Flow	1
5020	Squally Point	9000620	350262E–5032075N	Flow	1
5075	Squally Point	9101205	350550E–5032550N	Tuff	1
5083	Squally Point	9101209	350256E–5032238N	Flow	1
7592	Squally Point	9000620	350262E–5032075N	Flow	1
7597*†	Cape Chignecto	9404607	351101E–5023291N	Dyke in pluton	3
4072	W. Moose River	8623107	406435E–5033967N	Flow	3
4073	W. Moose River	8623110	406377E–5034098N	Flow	3
4074	W. Moose River	8623111	406367E–5034102N	Flow	3
4075	W. Moose River	8623114	406343E–5034302N	Flow	3
4077	W. Moose River	8623116	406329E–5034378N	Flow	3
4078	W. Moose River	8623118	406325E–5034552N	Flow	3
4080*	W. Moose River	8623120	406360E–5034627N	Flow	3
4109	W. Moose River	8623310	406491E–5035006N	Flow	3
4115	W. Moose River	8623325	406513E–5035587N	Ignimbrite	3
4116	W. Moose River	8623327	406481E–5035718N	?Intrusion	3
4118	W. Moose River	8623328	406367E–5035875N	Flow	3
7330	Black Brook	9403210	430632E–5037369N	Sill	2
7339	Black Brook	9403244	431687E–5038006N	Sill	2
6074*	Whirley Brook	9300332	470852E–5049494N	Flow, upper BB Fm	3
6083†	Whirley Brook	9300411	470832E–5049284N	Dyke in BB Fm	3
6087†	Whirley Brook	9300426	470920E–5048859N	Dyke in BB Fm	4
6307†	Whirley Brook	9302607	470671E–5048220N	N margin W. pluton	4
6688†	W.B. North River	9402116	475178E–5045434N	N margin W. pluton	4
6682	W.B. North River	9402108	478104E–5056855N	Flow, middle BB Fm	3
6915†	Byers Brook	9415145	467804E–5050926N	Dyke, basal DB Fm	3
7589	Whirley Brook	9300404	470586E–5050458N	Flow, middle DB Fm	3
7290*†	W.B. North River	9402717	478311E–5044846N	N margin W. pluton	3
7291†	W.B. North River	9402722	478377E–5044947N	N margin W. pluton	3
7368	W.B. North River	9403539	479646E–5046639N	?Dome, lower BB Fm	3
7369	W.B. North River	9403545	479802E–5045695N	?Dome, lower BB Fm	4
7371	W.B. North River	9403549	480602E–5044581N	?Dome, basal BB Fm	4
7704†	Whirley Brook	9505020	471248E–5047455N	N margin W. pluton	3
7714	Byers Brook	9505313	469034E–5049188N	?Dome, lower BB Fm	3
8191†	Swan Brook	9502816	461185E–5051970N	Ignimbrite	3
8192†	Swan Brook	9502821	460997E–5051502N	Ignimbrite	3
8195	Swan Brook	9700319	460715E–5051153N	?Intrusion	3

Intrusion: interpreted as a hypabyssal intrusive body. ?Intrusion: could be hypabyssal intrusive body or dome. DBFm: Diamond Brook Formation; BBFm: Byers Brook Formation; W. pluton: Wentworth pluton.

* Nd isotopes (Pe-Piper & Piper 1998).

** Sources of geochemical analyses: 1: Piper *et al.* (1996a), 2: Piper *et al.* (1996b); 3: This paper, 4: Unpublished data.

† Zr > 900 ppm.

bly the basal part of the Diamond Brook Formation (6915). In places, these dykes are composite diabase and rhyolite (Gower 1988), with the diabase geochemically similar to the basalts of the Fountain Lake Group.

The basal part of the Byers Brook Formation is poorly exposed. The formation appears to be fault-bounded and, in most areas, this fault acted as a pathway for a series of steeply dipping sheets of intrusive rhyolite (6307, 6688, 7290, 7291, 7704), each typically a few tens of meters wide. Irregular enclaves and sheets of diabase occur within these rhyolites, with textures suggesting that the mafic magma was immiscible (*cf.* Pe-Piper *et al.* 1996). These intrusive rhyolites separate the Byers Brook Formation from the Wentworth pluton granites to the south [the Hart Lake – Byers Lake granite of Donohoe & Wallace (1982)]. This intrusive rhyolite unit is marked by a strong magnetic anomaly (Piper *et al.* 1993), suggesting the presence of voluminous mafic rocks at shallow depth.

PETROGRAPHY AND GEOCHEMISTRY OF FELSIC ROCKS OF THE FOUNTAIN LAKE GROUP

Petrography

The Fountain Lake Group consists of several felsic lithologies including rhyolitic flows, intrusive porphyritic rhyolite and a wide variety of rhyolitic pyroclastic flows including unwelded tuff and ignimbrite. Some of the samples of rhyolite and pyroclastic rocks have undergone silicification, resulting in rocks with up to 85% silica.

Most of the samples of intrusive porphyritic rhyolite are red, purple or grey and have a bimodal distribution of grain size in the groundmass. The coarse-grained zones are mostly quartz with some altered plagioclase, whereas the formerly glassy zones are cloudy and altered to chlorite and white mica. Phenocrysts occur in both zones and are mostly white to buff feldspar of ≤1 mm diameter, but quartz of the same size also occurs. The accessory minerals include zircon, apatite, chlorite, allanite, titanite, epidote, and minor opaque minerals, including pyrite and pyrrhotite.

The flow-banded rhyolites range in color from pink to purple to grey-green and have a hypocrystalline-microporphyritic texture. The recrystallized formerly glassy groundmass contains phenocrysts of plagioclase and quartz, both less than 1 mm and concentrated in the darker flow-bands. Most phenocrysts are euhedral, but a few are fragmental. In the Earltown – Byers Lake belt, the most common accessory minerals are titanite, present in small amounts, and magnetite or ilmenite, which are present in most samples. In the West Moose River road section of the eastern Cobequid Highlands, accessory titanite is more abundant, magnetite or ilmenite is less abundant, and most samples contain small amounts of accessory zircon. At Squally Point, zircon is an accessory mineral in most samples, and a few contain trace amounts of apatite, allanite or titanite.

Unwelded tuffs contain mostly felsic lithic fragments, angular devitrified shards, and quartz and feldspar crystals. The matrix is microcrystalline and has been chloritized and partly transformed to white mica. Ignimbrites contain mostly angular devitrified shards, with a lower proportion of lithic fragments and crystals. The silicified pyroclastic rocks have a fine-grained groundmass with zones of very fine-grained quartz crystals. The angular pyroclastic fragments consist mostly of quartz, although some fragments are quartz with granophyric intergrowths of feldspar. Accessory minerals include pyrite and allanite, with epidote and chlorite as alteration products in the groundmass. Clast sizes in the pyroclastic rocks vary from one sample to another, with most being lapilli tuffs.

The high-Zr rhyolite dykes and the intrusive high-Zr rhyolites at the northern margin of the Wentworth pluton are porphyritic with quartz and feldspar phenocrysts. Titanite is found in all these rocks, and allanite and magnetite are common accessory minerals in most samples. Epidote and chlorite are common secondary minerals. Allanite, epidote and titanite commonly occur as clusters of crystals in the groundmass, which is interpreted as devitrified glass, and these minerals may locally account for several percent of the modal mineralogy. In some samples, accessory pseudomorphs after amphibole, with a characteristic 124° basal section, comprise fine-grained quartz, white mica, chlorite and titanite. Zircon is not seen as an accessory mineral. Microprobe X-ray mapping shows that zirconium occurs only in 1–4 μm crystallites in the groundmass (Fig. 4). The dyke from the Cape Chignecto pluton has a spherulitic texture in the groundmass.

Geochemistry

The felsic rocks range in composition from dacite, through rhyolite, to pantellerite in classification schemes based on SiO_2, Zr, TiO_2, Nb, and Y (Fig. 5), after Winchester & Floyd (1977). The assignment of pantellerite is the result of very high Zr contents, but abundances of other trace elements are not typical of peralkaline rocks. On a normative QAP diagram (not shown), after Streckeisen (1976), the samples plot mostly as monzogranite and trend through the syenogranite and alkali-feldspar granite fields into the quartz-rich field. The quartz-rich granite samples are likely the result of secondary silicification. On an A/NK *versus* A/CNK diagram (Maniar & Piccoli 1989), almost all samples plot in the peraluminous and metaluminous fields.

Plots of selected elements against silica (Fig. 6) show that there is a striking bimodality in Zr content (Fig. 6d), with almost no samples containing between 600 and 1000 ppm Zr. High-Zr rhyolites occur as ignimbrite flows in the upper Byers Brook Formation in Swan

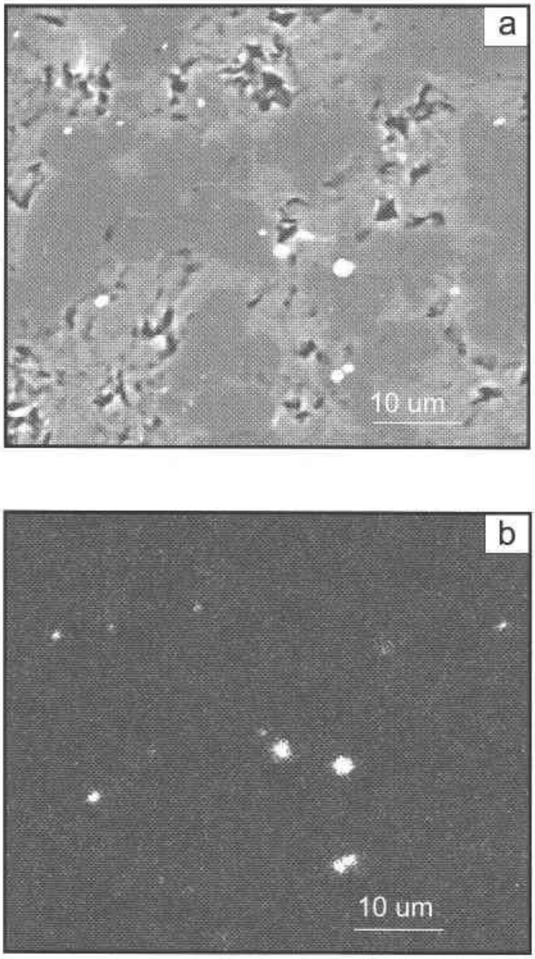

FIG. 4. (a) Back-scattered-electron scanning image and (b) X-ray map for Zr of high-Zr rhyolite sample 6083, showing occurrence of zircon as small crystallites.

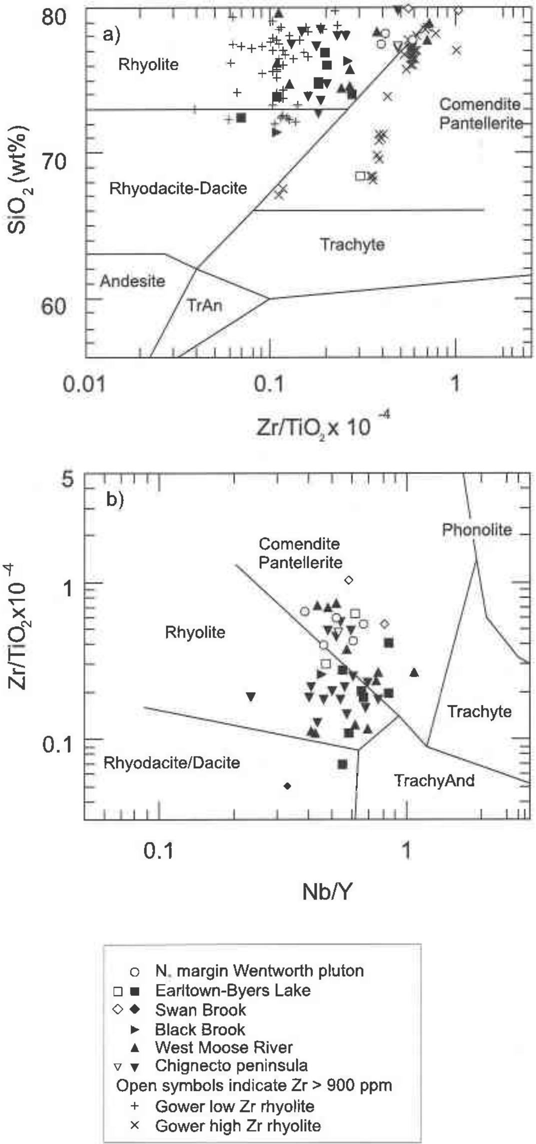

FIG. 5. Discrimination diagrams for rhyolite classification showing our bulk compositions and those of Gower (1988). a) $Zr/TiO_2 * 10^{-4}$ *versus* Nb/Y, after Winchester & Floyd (1977) (no data from Gower because levels of Nb and Y were not documented); b) $Zr/TiO_2 * 10^{-4}$ *versus* SiO_2, after Winchester & Floyd (1977). "High-Zr" refers to rocks with >900 ppm Zr.

Brook, as dykes cutting the Byers Brook Formation and possibly the basal Diamond Brook Formation in the Earltown – Byers Lake belt, as a dyke in the Cape Chignecto pluton, and as intrusive bodies between the base of the Byers Brook Formation and the main Wentworth pluton granite.

The high-Zr samples have silica values from ~85% to as low as 67%. The low-silica, high-zirconium rhyolites generally have high TiO_2, FeO_t, P_2O_5, and Zn. Compared with low-Zr samples, they also have rather lower Al_2O_3 (Fig. 6a) and total alkalis (Fig. 6c) for the same SiO_2 content and show slightly higher Y and Nb (Figs. 6e, f). In general, Zr shows a positive correlation with the high-field-strength elements Nb and Y (Fig. 7a), although samples from the Earltown – Byers Lake belt show a slight decrease in Zr with increasing Nb and Y. The high-Zr samples show a strong positive correlation of TiO_2 with Zr (Fig. 7b), whereas the low-Zr samples show no systematic trend.

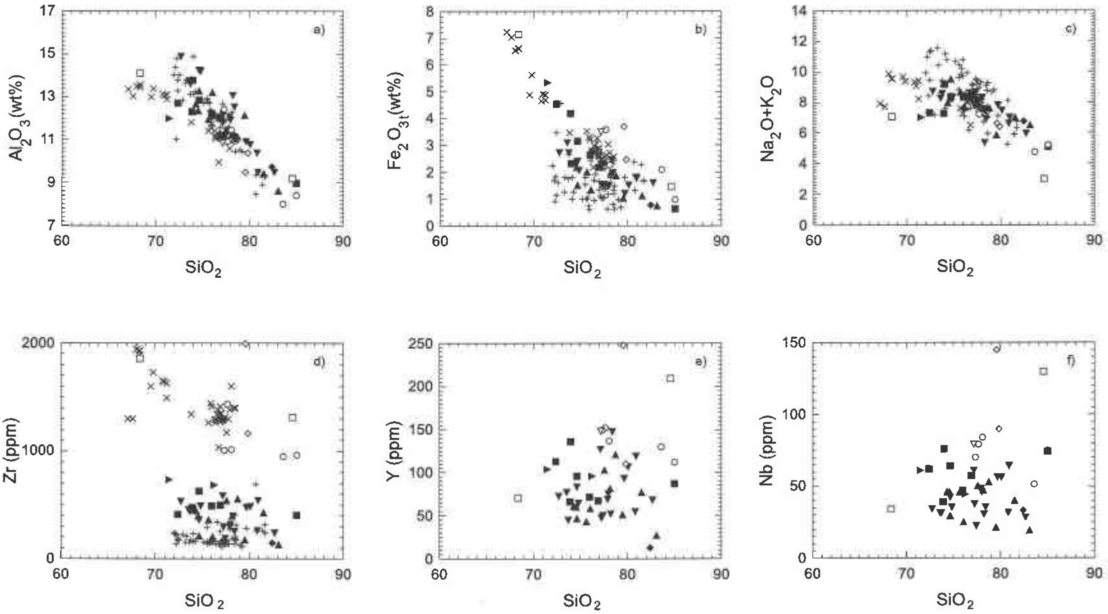

FIG. 6. Selected Harker diagrams showing element variation with SiO_2: a) Al_2O_3, (b) Fe_2O_{3t}, c) $Na_2O + K_2O$, d) Zr, e) Y, and f) Nb. Symbols as in Figure 5.

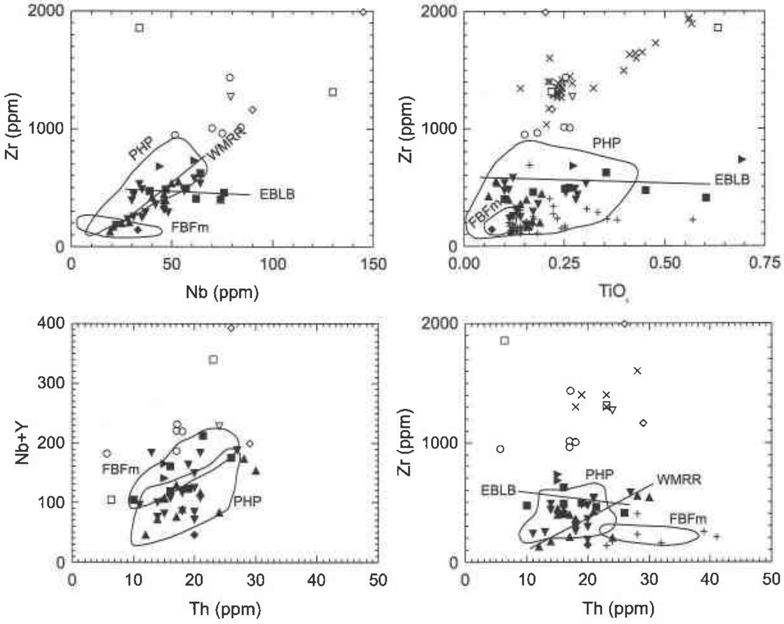

FIG. 7. Selected element plots: (a) Zr *versus* Nb, (b) Zr *versus* TiO_2, (c) Nb + Y *versus* Th, (d) Zr *versus* Th. Symbols as in Figure 5. Comparisons with the Fisset Brook Formation (FBFm) based on Barr *et al.* (1996), Barr & Peterson (1998) and our unpublished data. Data for the Pleasant Hills pluton (PHP) based on Pe-Piper & Piper (1996). EBLB: Earltown – Byers Lake belt; WMRR: West Moose River road section.

Thorium is commonly used as an index of fractionation in felsic rocks, although it may be mobile in some rhyolites of the Fountain Lake Group (Dostal *et al.* 1983b). Elements such as Rb, Nb and Y show a general increase in abundance with increasing Th (*e.g.*, Fig. 7c), the correlation being stronger when individual geographic areas are considered. A plot of Zr against Th (Fig. 7d), however, shows a positive correlation for some groups (*e.g.*, the lower part of the West Moose River road section and most high-Zr rocks), but a slight negative correlation in low-Zr rhyolites of the Earltown – Byers Lake belt (as was noted in Fig. 7a). Rhyolites from Squally Point show no clear pattern.

The high-Zr rhyolites have higher contents of the rare-earth-elements (*REE*) and a smaller Eu anomaly than the low-Zr rhyolites (Fig. 9). Low-Zr rhyolites from Squally Point show decreasing abundances of the light *REE* with increasing fractionation (measured by SiO_2, Th or Nb) but increasing abundance of the heavy *REE*. In the low-Zr rhyolites of the eastern Cobequid Highlands, both light and heavy *REE* increase with increasing fractionation, whereas Eu decreases.

Stratigraphic trends in geochemistry can be most readily assessed in the West Moose River road section, where a thick succession of rhyolite flows outcrops (Fig. 3). Flows between 100 and 400 m from the base of the succession show an upward decrease in most large-ion lithophile and high-field-strength elements and a concomitant increase in Na and Sr, with an almost constant Zr/Th value (Fig. 10). At Squally Point, in contrast, where eight samples are available through an 80-m-thick stratigraphic section (Piper *et al.* 1996a, their Fig. 7), no systematic vertical changes in element abundance are recognized.

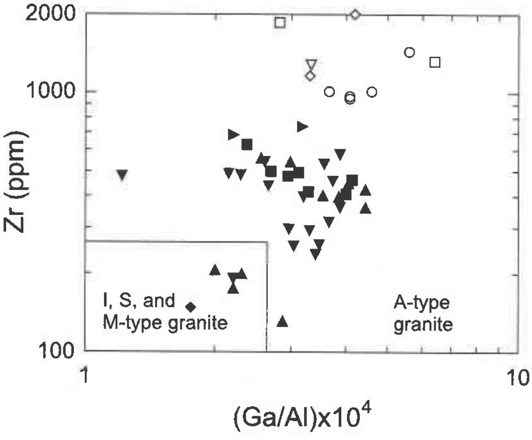

FIG. 8. Plots of Zr *versus* Ga/Al for rhyolites of the Fountain Lake Group. Rectangular box separates A-type granites (upper right) from I-, S-, and M-type granites (after Whalen *et al.* 1987). Symbols as in Figure 5.

DISCUSSION

Geochemical variation in eruptive products in time and space

In the eastern Cobequid Highlands, there is a clear stratigraphic distinction between the felsic Byers Brook Formation and the mafic Diamond Brook Formation; the total thickness of volcanic products is everywhere greater than 2 km. In contrast, in the central and western Cobequid Highlands, the overall stratigraphic thickness is less than 1 km, and basalt units several hundred meters thick are interbedded with predominantly rhyolitic successions (*cf.* rare basalts <100 m thick in the Byers Brook Formation). This abrupt diminution in thickness and stratigraphic interfingering cannot readily be explained by tectonic dismemberment or erosion of a succession originally similar to that in the eastern Cobequid Highlands. We suggest that the formational

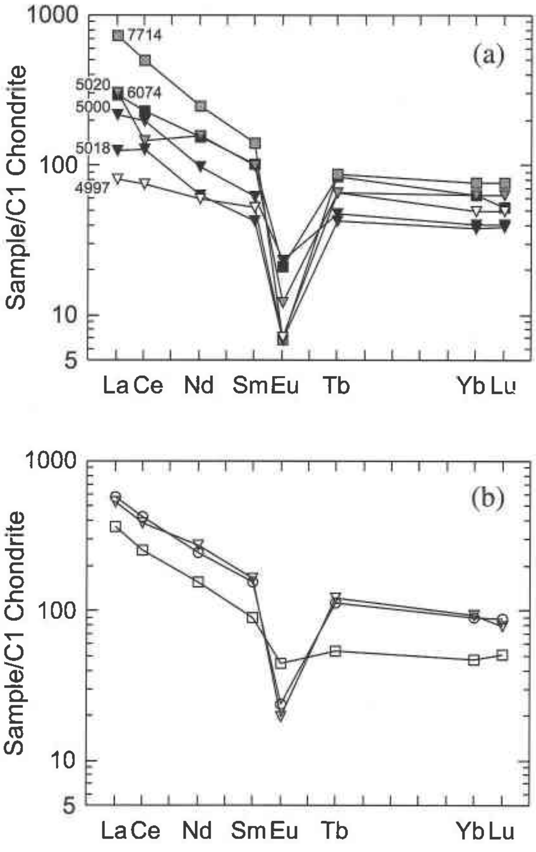

FIG. 9. Rare-earth-element plots for the Fountain Lake Group rhyolites normalized to C1 chondrite; (a) low-Zr rhyolites, (b) high-Zr rhyolites. Symbols as in Figure 5.

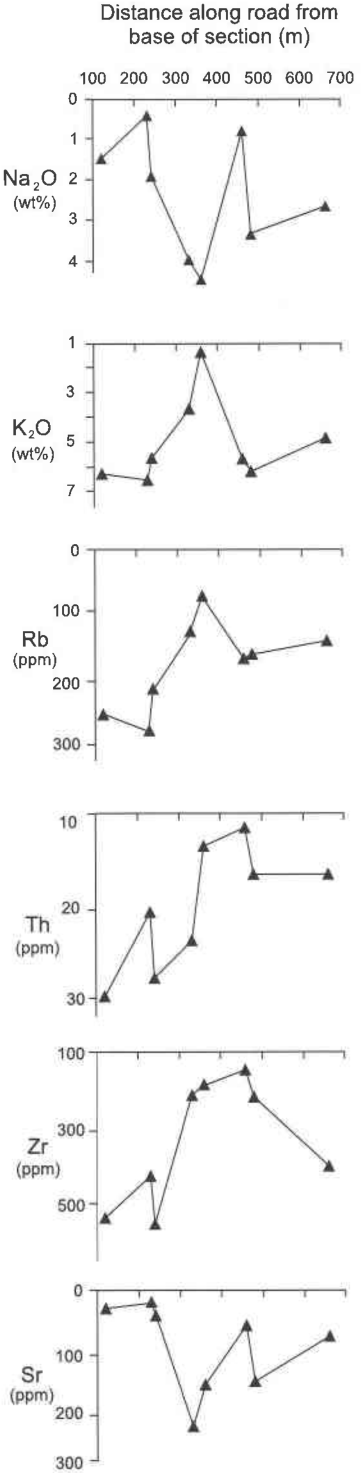

FIG. 10. Vertical variation in abundance of selected elements in rhyolite flows exposed on the West Moose River road.

nomenclature of the eastern Cobequid Highlands should not be applied to the central and western highlands. The change in volcanic style correlates spatially with a change from the large Wentworth pluton in the east to a series of small, more granitic plutons in the west. The thickest succession of rhyolites [between Wentworth and Byers Lake, (9) in Fig. 3] is closest to the voluminous heat-source of the gabbroic part of the Wentworth pluton (Fig. 2).

The distinctive high-Zr rhyolite ignimbritic flows occur near the top of the Byers Brook Formation in Swan Brook. The geochemically correlative dykes cut only the Byers Brook Formation and possibly the extreme base of the Diamond Brook Formation, but do not cut younger rocks. This suggests that high-Zr dykes and pyroclastic flows are synchronous. The geochemically similar intrusions at the northern margin of the Wentworth pluton are probably also synchronous. This high-Zr magma immediately preceded the voluminous flood basalts of the Diamond Brook Formation. The only other geographic region in which high-Zr rhyolite has been found is a single dyke in the Cape Chignecto pluton. In this area, large tholeiitic mafic dykes, probably correlative with the Diamond Brook Formation, are widespread in both the pluton and the adjacent Fountain Lake Group.

Comparative geochemistry of the low-Zr rhyolites

The low-Zr rhyolites of the Fountain Lake Group are geochemically similar to coeval granites from the Cobequid Highlands (Pe-Piper *et al.* 1991, Pe-Piper & Piper 1998) and to rhyolites from the Fisset Brook Formation of western Cape Breton Island (Barr *et al.* 1996, Pe-Piper & Piper 1998, Barr & Peterson 1998). In general, all these felsic rocks resemble A-type granites. Most samples have high Zr, Nb and Ga/Al ratios typical of A-type granites (Figs. 6d, f, 8), although some samples trend into the I-, S-, or M-type granite field (*cf.* Whalen *et al.* 1987). The ratio Nb/Y shows no correlation with Zr content, and all samples have Nb/Y values below 1.2, thus corresponding to the A2 type rhyolite and granite in the classification of Eby (1990, 1992), which are interpreted as resulting from crustal anatexis. Most samples plot as within-plate granites on the basis of trace elements such as Nb, Y, Rb on Pearce *et al.* (1984) diagrams. These similarities imply that the petrogenesis of the low-Zr rhyolites is similar to that previously inferred for Cobequid Highlands granites (Pe-Piper *et al.* 1991, 1998, Pe-Piper & Piper 1998). Felsic magmas appear to be derived by melting of material in the lower crust as a result of the thermal effect of voluminous mafic magma. High Ga/Al and the common presence of fluorite suggest that the source area was relatively anhydrous and rich in halogens.

In detail, there are regional variations, most noticeable in the relatively stable HFS elements. Most granite samples taken from plutons from the western Cobequid

Highlands consisting of <10% gabbro have Zr < 300 ppm. There is a much greater range of Zr contents in the Cape Chignecto (<800 ppm), Pleasant Hills (<850 ppm) and Wentworth (<1000 ppm) plutons, all of which have sizeable gabbro bodies. This range is a little greater than that in the low-Zr rhyolites of the Fountain Lake Group. Most rhyolites of the Fisset Brook Formation have <200 ppm Zr, but higher Nb/Zr, Th/Zr and TiO_2/Zr values than both the Fountain Lake Group and the Pleasant Hills pluton, although Y/Zr values are similar (Fig. 7).

The systematic behavior of element abundances as a function of Th, Nb and SiO_2 contents suggests that general differentiation trends can be inferred from Harker diagrams (Fig. 6). These trends imply that feldspar fractionation has predominated, with some removal of Fe, Mg and HFS elements by biotite and iron–titanium oxides. Abundance of Zr and the *REE* is influenced by fractionation of accessory phases. In the West Moose River road section, Zr and other HFS elements increase with increasing Th. At Squally Point, Nb and Y increase, but Zr shows scatter. In contrast, in the low-Zr rhyolites of the Earltown – Byers Lake belt (and also in the Fisset Brook Formation), Zr content decreases slightly with increasing Th, whereas the level of both Nb and Y increases, which suggests two different patterns of fractionation of Zr in the low-Zr rhyolites. In the Earltown – Byers Lake belt and at Squally Point, zircon is an accessory phase, so that Zr is removed from the magma as it differentiates. In the West Moose River road section, zircon is much less common as an accessory phase, and Zr appears to increase with differentiation. The light *REE* depletion with increasing differentiation at Squally Point is probably the result of removal of accessory allanite (*cf.* Evans & Hanson 1993).

Such trends can be used to interpret stratigraphic variation in extrusive rhyolites. In the basal 400 m of the West Moose River road section, most fractionated magmas (low levels of Na, Ca, Sr; enriched in large-ion lithophile elements concentrated in hydrous melts; high Ga/Al) were erupted first, followed by progressively less fractionated magmas. Such a sequence is analogous to that produced by progressive eruption of magmas from a zoned chamber (Hildreth 1981). Our sample density is insufficient to determine patterns in the two major eruptive cycles of the Wentworth area recognized by Gower (1988), but it is noteworthy that both terminate with the eruption of basalts.

Origin of Zr variations in the low-Zr rhyolites

We examine possible explanations for the observed variation in Zr content of the low-Zr rhyolites. Some of this variation may be due to differences in Zr content of the parental magma. Felsic magmas in the southern Maritimes Basin show geographic variation in Pb isotopic composition (Pe-Piper & Piper 1998) as a result of variation in the composition of lower crust, which could also show variation in Zr content. Both mafic and felsic rocks of the Fisset Brook Formation have unusually low Nb/Zr values compared with other volcanic rocks of the Maritimes Basin (Pe-Piper & Piper 1998, their Fig. 12), which again may reflect differences in parental magmas.

Most differences in the abundance of trace elements in felsic rocks, however, develop during magma differentiation (*e.g.*, Evans & Hanson 1993). The ratio of alkalies to Si and Al has an important influence on zircon saturation. Watson & Harrison (1983) expressed this as the cation ratio (Na+K+2Ca)/(Al.Si) and showed that zircon solubility depends on this cation ratio and temperature. Plots of this cation ratio against Zr for the Fountain Lake Group (Fig. 11) show a weak positive correlation for the low-Zr rhyolites. A similar weak positive correlation is shown by the Pleasant Hills pluton. The rhyolites of the eastern Cobequid Highlands, together with those of the Fisset Brook Formation and the Pleasant Hills granites, have a higher cation ratio for the same Zr content than do rhyolites of the western Cobequid Highlands, demonstrating that alkalinity variations are not sufficient to explain observed variation in Zr content.

In metaluminous melts, fluorine increases the solubility of zircon (Collins *et al.* 1982, Keppler 1993). Recent experimental work by Marr *et al.* (1998) on peralkaline melts showed that Cl substantially reduces zircon solubility. In the eastern Cobequid Highlands, Gower (1988) found no correlation between F and Zr contents in rocks of the Fountain Lake Group. Our data on basalt and rhyolite from throughout the Fountain Lake Group and of associated diabase and rhyolite dykes (results of 40 analyses) and from the Fisset Brook

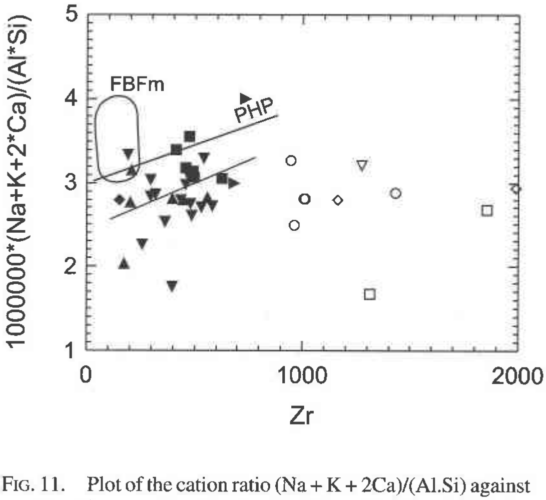

FIG. 11. Plot of the cation ratio (Na + K + 2Ca)/(Al.Si) against Zr with regression line for rhyolites of the Fountain Lake Group. Also shown are regression line for the Pleasant Hills Pluton and field for Fisset Brook Formation.

TABLE 2. WHOLE-ROCK CHEMICAL COMPOSITION OF REPRESENTATIVE RHYOLITIC ROCKS OF THE COBEQUID HIGHLANDS, NOVA SCOTIA

Sample	4072	4073	4074	4075	4077	4078	4080	4109	4115	4116	4118	4877	6074
Major elements by X-ray fluorescence (XRF)													
SiO_2 wt.%	77.06	81.26	78.32	76.42	78.83	84.98	75.22	78.07	73.71	72.88	75.64	76.44	70.70
TiO_2	0.08	0.06	0.08	0.19	0.16	0.12	0.17	0.11	0.19	0.15	0.14	0.17	0.59
Al_2O_3	11.36	9.39	11.06	13.25	12.00	8.80	13.38	11.21	12.57	12.05	11.94	12.06	12.40
Fe_2O_{3t}	2.37	1.13	1.86	1.36	1.02	0.77	1.52	1.98	2.36	2.13	2.01	1.54	4.42
MnO	0.03	0.02	0.02	0.03	0.02	0.01	0.02	0.03	0.04	0.05	0.03	0.04	0.08
MgO	0.64	0.85	0.53	0.85	0.97	0.87	0.75	0.83	2.41	2.40	1.60	b.d.	0.84
CaO	b.d.	b.d.	0.01	0.61	0.30	b.d.	0.10	0.07	0.02	b.d.	b.d.	0.16	1.34
Na_2O	1.48	0.44	1.91	3.99	4.41	0.84	3.35	2.66	0.90	0.62	1.19	3.57	2.79
K_2O	6.23	6.51	5.61	3.71	1.35	5.80	6.22	4.83	6.94	7.40	7.44	4.99	4.30
P_2O_5	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.23
L.O.I.	0.80	1.0	0.40	0.40	0.90	0.30	0.40	0.30	1.70	1.60	0.90	0.20	1.80
Total	100.07	100.68	99.82	100.83	99.99	102.51	101.15	100.11	100.86	99.3	100.91	99.19	99.49
Trace elements by XRF													
Ba ppm	174	98	143	244	44	538	347	107	411	473	517	167	609
Rb	246	268	216	125	83	167	162	142	155	171	159	174	175
Sr	23	14	33	219	150	51	144	69	38	38	43	24	80
Y	103	77	121	58	51	27	47	82	61	60	43	48	113
Zr	539	424	556	200	175	131	206	398	445	394	358	296	413
Nb	50	40	53	25	21	19	29	47	46	46	46	37	62
Th	30	21	28	24	14	12	17	17	15	15	18	20	26
Pb	72	50	43	32	39	14	11	25	9	8	7	<5	23
Ga	18	22	15	16	14	13	14	21	27	25	28	19	22
Zn	19	36	29	41	36	27	22	45	86	61	54	14	145
Cu	6	21	4	42	32	5	1	2	4	4	5	<5	5
Ni	4	5	5	6	<5	7	1	4	2	3	4	<5	5
V	<5	19	5	6	1	1	3	3	<5	<5	3	13	43
Cr	16	4	7	7	6	3	2	<5	5	4	<5	<5	<5
The rare-earth elements and selected trace elements by instrumental neutron-activation analysis													
La ppm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	71
Ce	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	141
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	73
Sm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	15.8
Eu	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.23
Tb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.2
Yb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	10.8
Lu	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.34
Co	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	37
Hf	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	13.0
Sc	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.5
Ta	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.6
Th	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	24
U	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	7.0
Li by atomic absorption and F by specific-ion electrode													
Li ppm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	324

Formation (results of six analyses) show F contents typically in the range 100–700 ppm, without systematic geographic variation or relationship to rock type. We have no Cl data for rocks of the Fountain Lake Group. Sodic amphiboles from the Wentworth pluton typically have a F:Cl ratio of 10–30, suggesting that F was the dominant halogen in the eastern Cobequid Highlands. Secondary (hydrothermal) biotite from the West Moose River pluton has F:Cl ratio of 0.3–10 (Pe-Piper *et al.* 1991), and scapolite veins occur near Parrsboro (J.V. Owen & J.D. Greenough, pers. commun. 1998), which may indicate that Cl is more abundant in this part of the western Cobequid Highlands. If so, it could account for the rather lower average abundances of Zr in the West Moose River road section.

Petrographic observations show that the timing of zircon precipitation influences the abundance of Zr in the low-Zr rhyolites. We suggest that variations in Zr abundance in the parental magma, the effect of alkalinity, and variable abundance of chlorine all play a role in

TABLE 2 (cont'd). WHOLE-ROCK CHEMICAL COMPOSITION OF REPRESENTATIVE RHYOLITIC ROCKS OF THE COBEQUID HIGHLANDS, NOVA SCOTIA

Sample	6083	6682	6915	7290	7291	7368	7589	7597	7704	7714	8191	8192	8195
Major elements by X-ray fluorescence (XRF)													
SiO_2 wt.%	82.00	76.28	66.98	76.26	84.81	74.03	84.41	76.83	83.35	73.33	79.98	78.75	83.08
TiO_2	0.21	0.26	0.62	0.26	0.18	0.35	0.10	0.27	0.15	0.17	0.22	0.20	0.07
Al_2O_3	8.89	11.9	13.82	12.23	8.37	12.72	8.91	10.79	7.97	13.67	10.39	9.39	9.79
Fe_2O_{3t}	1.42	2.16	6.99	1.48	0.97	3.14	0.63	3.48	2.08	2.31	2.46	3.65	0.80
MnO	0.04	0.06	0.18	0.03	0.02	0.08	0.02	0.07	0.07	0.05	0.05	0.07	0.01
MgO	0.83	0.02	1.81	0.04	0.08	0.09	0.07	0.02	0.12	0.03	0.28	0.19	0.03
CaO	0.52	0.12	0.54	0.25	0.11	0.43	b.d	0.32	1.17	0.52	0.38	0.11	0.17
Na_2O	0.19	2.05	2.50	4.66	0.38	3.11	0.07	2.62	2.48	3.14	0.96	1.48	3.35
K_2O	2.69	6.32	4.40	3.34	4.76	5.14	4.97	5.09	2.25	5.89	5.41	5.03	3.43
P_2O_5	0.05	0.03	0.08	0.03	0.03	0.04	0.01	0.01	0.02	0.01	0.01	0.02	0.01
L.O.I	2.35	0.70	2.34	0.20	0.90	0.75	1.09	0.50	0.47	1.17	0.57	0.97	0.61
Total	99.19	99.9	100.26	98.78	100.61	99.88	100.28	100	100.13	100.29	100.71	99.86	101.35
Trace elements by XRF													
Ba ppm	103	591	250	18	96	598	11	27	187	68	395	<5	174
Rb	164	257	125	102	228	201	245	215	73	295	193	243	178
Sr	10	34	98	20	26	41	21	15	62	57	95	23	28
Y	210	67	71	149	112	96	87	149	130	136	110	248	13
Zr	1314	497	1856	1036	959	627	406	1271	943	458	1160	1990	148
Nb	130	57	34	73	75	64	74	79	51	76	90	145	33
Th	23	19	6	15	17	16	16	24	6	21	29	26	20
Pb	26	15	11	<10	10	17	46	26	48	6	83	36	127
Ga	31	17	21	34	18	16	19	19	17	30	18	21	9
Zn	131	43	142	22	23	45	14	135	88	112	129	274	<5
Cu	5	<5	15	15	7	<5	<5	<5	37	12	12	51	14
Ni	5	<5	<5	<5	<5	<5	<5	<5	<5	<5	18	<5	<5
V	38	<5	15	6	8	<5	<5	<5	20	<5	10	20	<5
Cr	7	5	<5	5	5	<5	7	18	<5	<5	29	<5	6
The rare-earth elements and selected trace elements by instrumental neutron-activation analysis													
La ppm	n.d.	n.d.	86	136	n.d.	72	n.d.	126	n.d.	174	76	n.d.	n.d.
Ce	n.d.	n.d.	156	258	n.d.	143	n.d.	236	n.d.	307	155	n.d.	n.d.
Nd	n.d.	n.d.	72	115	n.d.	66	n.d.	129	n.d.	116	68	n.d.	n.d.
Sm	n.d.	n.d.	13.7	24	n.d.	12.6	n.d.	25	n.d.	22	n.d.	n.d.	n.d.
Eu	n.d.	n.d.	2.6	1.39	n.d.	1.53	n.d.	1.14	n.d.	0.40	n.d.	n.d.	n.d.
Tb	n.d.	n.d.	2.0	4.2	n.d.	2.2	n.d.	4.5	n.d.	3.3	n.d.	n.d.	n.d.
Yb	n.d.	n.d.	8.0	15.2	n.d.	9.6	n.d.	16.0	n.d.	13.1	n.d.	n.d.	n.d.
Lu	n.d.	n.d.	1.30	2.2	n.d.	1.49	n.d.	2.0	n.d.	1.97	n.d.	n.d.	n.d.
Co	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	51	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	29	n.d.	n.d.	n.d.	n.d.	n.d.
Sc	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.61	n.d.	n.d.	n.d.	n.d.	n.d.
Ta	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	6.3	n.d.	n.d.	n.d.	n.d.	n.d.
Th	n.d.	n.d.	8.8	19.0	n.d.	18.0	n.d.	23	n.d.	30	n.d.	n.d.	n.d.
U	n.d.	n.d.	2.6	9.0	n.d.	6.3	n.d.	2.0	1.8	7.3	n.d.	n.d.	n.d.
Li by atomic absorption and F by specific-ion electrode													
Li ppm	n.d.	n.d.	n.d.	n.d.	6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	524	n.d.	n.d.	510	360	192	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Samples were analyzed for 10 major- and minor-element oxides and 14 trace elements on a Philips PW1400 sequential X-ray fluorescence spectrometer using an Rh-anode X-ray tube. Major-oxide determinations were carried out on fused glass disks, whereas concentrations of the trace elements were determined from pressed-powder pellets. International standards 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 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 hours at 1050°C in an electric furnace. The rare-earth-element concentrations were determined by neutron-activation analysis. n.d.: not determined.

determining the solubility of zircon and hence the observed variations in Zr content of the rhyolites.

Petrogenesis of the high-Zr rhyolites

The high-Zr rhyolites are not simply the result of continued fractionation of rhyolitic magma with 400–700 ppm Zr. Several lines of evidence suggest that they are quite distinct from the low-Zr rhyolites discussed above. They show quite different trends on several elemental plots, such as Zr *versus* TiO_2 and cation ratio *versus* Zr. They also have high ε_{Nd} (> +3) (Fig. 12).

The occurrence of the high-Zr rhyolites in composite rhyolite–diabase dykes and the presence of irregular patches of gabbro in the intrusive sheets at the northern edge of the Wentworth pluton suggest that in-mixed mafic magma may have played a role in the evolution of the high-Zr rhyolites, particularly those with lower SiO_2 content. In the Pleasant Hills pluton, the granite unit that shows most evidence of mingling with gabbro (unit 7) has the highest ε_{Nd}, +3.5, of all felsic units in the pluton. However, felsic rocks with Nb, Y and Zr contents as high as those in the high-Zr rhyolites are not found either in the Pleasant Hills pluton, nor in the southwestern part of the Wentworth pluton, where evidence of mixing of mafic and felsic magmas also is widespread (Pe-Piper *et al.* 1996).

The high ε_{Nd} values, together with high contents of Nb, Y and Zr, may also be interpreted as derivation of a felsic magma by fractional crystallization of a mafic magma in a chamber at depth. However, unlike extensional flood-basalt settings, where such felsic fractionates are recognized (*e.g.*, Vervoort & Green 1997), there is no bimodal distribution of ε_{Nd} values in the rhyolites, and intermediate differentiates with 60–67% SiO_2 are extremely rare in the study area.

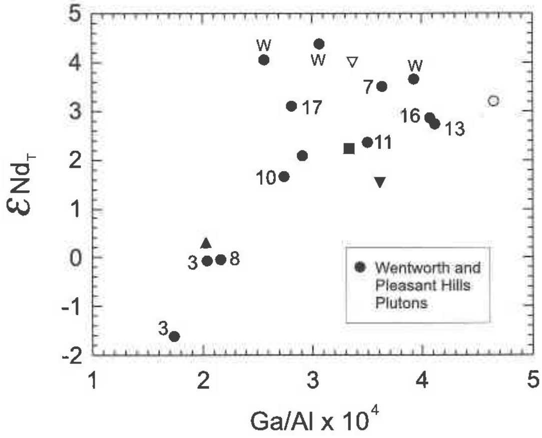

FIG. 12. Plot of ε_{Nd} *versus* Ga/Al for Fountain Lake rhyolites and plutonic rocks of the Wentworth and Pleasant Hills plutons. Numbers indicate sequence of intrusion at Pleasant Hills (3 = oldest, 17 = youngest). Data from Pe-Piper & Piper (1998, Fig. 13).

We suggest that the observed abundances of high-field-strength elements and the high ε_{Nd} could result from the interaction of an intermediate or felsic differentiated magma with lower crust, through assimilation with fractional crystallization (AFC) processes. This would also account for the range of SiO_2 values and the general geochemical similarity with the older low-Zr rhyolites in the more strongly lithophile elements and halogens.

None of the above petrogenetic models can directly account for the unusually high Zr content of the rhyolites. The hypotheses considered for the low-Zr rhyolites, namely variations in halogen content of the magma and variations in alkalinity (cation ratio), do not appear sufficient to produce very high Zr contents. For several reasons, we reject the possibility that the rhyolites were originally more strongly peralkaline than is suggested by their present geochemistry and became metaluminous as a result of devitrification. There is little scatter in Na + K, and the total alkali content is consistently lower in high-Zr dykes than in the host low-Zr rhyolites. Furthermore, neither Y nor the *REE* are particularly enriched in the Cobequid high-Zr rhyolites. Thus mechanisms of the type proposed by Wilkinson *et al.* (1996) and Mungall & Martin (1996) for peralkaline melts seem not to be applicable.

The remaining explanation, which we consider most probable, is that zircon precipitation was inhibited by high temperatures in a metaluminous melt, as demonstrated by Watson & Harrison (1983, 1984). Such inhibition of precipitation is supported by the petrographic observation of zircon crystallites in the fine-grained groundmass. It is also consistent with the geographic and temporal distribution of the high-Zr rhyolites in relation to possible sources of heat in voluminous high-level mafic magmas. The intrusion and eruption of the high-Zr rhyolites immediately preceded eruption of the 1.5-km-thick sequence of basalts of the Diamond Brook Formation. In the western Cobequid Highlands, there is no evidence for a comparable heat-source except in the Chignecto Peninsula, where mafic dykes are unusually large and abundant (Piper *et al.* 1993). The Chignecto Peninsula is the only area in the western Cobequid Highlands where high-Zr rhyolite is found.

CONCLUSIONS

1. Felsic rocks of the Fountain Lake Group are thickest (*ca.* 4 km) in the Wentworth to Byers Lake area and thin eastward toward Earltown (*ca.* 1 km) by rapid thinning of pyroclastic phases and the disappearance of the lower eruptive cycle. They are overlain by 1.5 km of continental tholeiitic basalts (Diamond Brook Formation). In the central and western Cobequid Highlands, the Fountain Lake Group is less than 1 km thick, and

the formations of the Byers Lake – Earltown belt cannot be recognized.

2. Distinctive high-Zr rhyolites (>900 ppm Zr), a few with accessory amphibole, occur as a suite of dykes (in places composite with diabase) cutting the entire Byers Brook Formation, as ignimbritic flows near the top of the Byers Brook Formation, as intrusive sheets together with gabbros along the northern margin of the Wentworth pluton, and as a late-phase dyke in the Cape Chignecto pluton of the western Cobequid Highlands.

3. The main rhyolites of the Fountain Lake Group are of similar compositions to the coeval granite plutons of the Cobequid Highlands: they are mostly metaluminous, with trace-element patterns typical of A2-type granite. They show ε_{Nd} values similar to those of the plutonic rocks, ranging from 0 to +2. Zr contents are generally low (100–500 ppm), consistent with low total alkalies and possibly a high Cl:F ratio. In the West Moose River road section, Zr content increases with fractionation, suggesting that zircon saturation in the magma had not been achieved. *REE* patterns in samples from Squally Point were influenced by the precipitation of accessory allanite.

4. Rhyolites of the eastern Cobequid Highlands typically contain 300–500 ppm Zr. As a result of precipitation of accessory zircon, Zr content decreases slightly in the more fractionated rocks.

5. In the high-Zr rhyolites, precipitation of zircon was inhibited, and zircon is restricted to small crystallites in the groundmass. Zircon precipitation was suppressed by the high ambient temperatures of a coeval mafic magma, the eruptive products of which formed the 1.5-km-thick sequence of basalts of the Diamond Brook Formation.

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