Atlantic Geoscience
Journal of the Atlantic Geoscience Society

# Geochemistry, tectonic setting, and petrogenesis of the Coldbrook Group and associated plutons, southern New Brunswick, Canada: A unique Late Ediacaran magmatic episode in Avalonia

# Géochimie, cadre tectonique et pétrogenèse du Groupe de Coldbrook et des plutons associés, sud du Nouveau-Brunswick, Canada : un épisode magmatique unique de l'Édiacarien supérieur en Avalonie

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Volume 59, 2023

URI: https://id.erudit.org/iderudit/1108392ar
DOI: https://doi.org/10.4138/atlgeo.2023.010



Publisher(s)

Atlantic Geoscience Society

ISSN

2564-2987 (digital)



Cite this article

Escribano, A. & Barr, S. (2023). Geochemistry, tectonic setting, and petrogenesis of the Coldbrook Group and associated plutons, southern New Brunswick, Canada: A unique Late Ediacaran magmatic episode in Avalonia. *Atlantic Geoscience*, *59*, 241–257. https://doi.org/10.4138/atlgeo.2023.010

Article abstract

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# Geochemistry, tectonic setting, and petrogenesis of the Coldbrook Group and associated plutons, southern New Brunswick, Canada: a unique Late Ediacaran magmatic episode in Avalonia

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*Date received: 28 August 2023 ¶ Date accepted: 19 October 2023*

## ABSTRACT

The Coldbrook Group is a unique suite of late Ediacaran volcanic and epiclastic rocks deposited in an extensional setting in the Avalonian Caledonia terrane of southern New Brunswick. It is informally divided into a lower part composed of mainly andesitic to dacitic tuffs and epiclastic sedimentary rocks intruded by bimodal plutons, and an upper part composed mainly of mafic flows and tuffs interlayered with but mainly overlain by rhyolitic flows and tuffs and minor epiclastic sedimentary rocks. Recent U–Pb (zircon) dating of four formations in the Coldbrook Group and a subvolcanic granitic dome led to the proposal that the lower and most of the upper Coldbrook Group and associated plutons were formed within <760 kyr at about 551.5 Ma whereas the uppermost rhyolite (Fundy Trail Parkway rhyolite) and underlying basalt of the Hosford Brook Formation formed in a younger event at about 549.5 Ma. Overlapping dates and chemical data also suggest that the subvolcanic granitic domes are the plutonic counterparts of the ca. 551.5 Ma felsic volcanic rocks whereas the other granitic plutons represent extracted melts that evolved separately. Whole-rock geochemical and isotopic data combined with previous field work and map information and integrated with the geochronological data provide new insights into the genesis of these magmas and their change from intermediate to bimodal magmatism. The data indicate that the volcanic and plutonic rocks are mainly tholeiitic and were derived from varying proportions of juvenile melts and recycled older arc lithosphere. The mafic rocks have chemical similarities to flood basalts which inherited some calc-alkalic signatures from older arc-like rocks. Intermediate magmas that formed much of the lower Coldbrook Group had larger lithospheric inputs and thus have mainly calc-alkalic signatures. The Vernon Mountain, Blackall Lake and Silver Hill area rhyolites represent evolved melts derived from the lower Coldbrook Group magmas, and their chemical differences are interpreted to result from melt extraction and solid-liquid dripping magmatic processes. Enhanced extension and thinning led to formation of less lithosphere-contaminated melts that formed the ca. 549.5 Ma bimodal units of the upper Coldbrook Group.

## RÉSUMÉ

Le groupe de Coldbrook est une succession de roches volcaniques et épiclastiques de l'Édiacarien tardif qui se sont déposées à l'intérieur d'un milieu de distension dans le terrane avalonien de Caledonia dans le sud du Nouveau-Brunswick. Le groupe est officieusement divisé en une section inférieure composée de tufs principalement andésitiques à dacitiques et de roches sédimentaires épiclastiques pénétrés par des plutons bimodaux, et en une section supérieure essentiellement constituée de tufs et de coulées mafiques interstratifiées avec des tufs et des coulées rhyolitiques ainsi qu'une quantité modeste de roches sédimentaires épiclastiques qui, toutefois, les recouvre principalement. Une datation U–Pb (sur zircon) des quatre formations dans le groupe de Coldbrook et d'un pluton granitique subvolcanique a abouti à la proposition que la section inférieure et la majeure partie de la section supérieure du groupe de Coldbrook et les plutons associés se sont formés il y a moins de 760 milliers d'années, soit il y a environ 551,5 Ma, alors que la rhyolite sommitale (rhyolite de la Promenade du Sentier Fundy) et le basalte sous-jacent de la Formation de Hosford Brook se sont formés au cours d'un épisode plus récent il y a environ 549,5 Ma. Les dates qui se chevauchent et les données chimiques permettent par ailleurs de supposer que les intrusions granitiques subvolcaniques constituent les équivalents plutoniques des roches volcanofelsiques d'il y a environ 551,5 Ma tandis que les plutons granitiques représentent des magmas extraits ayant évolué séparément. Des données isotopiques et géochmiques de roche totale combinées à de l'information cartographique et de l'information émanant de travaux sur le terrain antérieurs intégrées aux données chronologiques livrent de nouveaux renseignements sur la genèse de ces magmas et leur transformation d'un magmatisme intermédiaire à bimodal. Les données révèlent que les roches volcaniques et plutoniques sont

ATLANTIC GEOSCIENCE 59, 241–257 (2023)
2564-2987|23|0241–0257$3.55|0
doi:10.4138/atlgeo.2023.010

principalement tholéiitiques et qu'elles sont provenues de proportions variables de magmas juvéniles et de la lithosphère d'un arc âgé recyclé. Les roches mafiques ont des similarités chimiques avec les basaltes de plateau et les signatures calco-alcalines héritées des roches d'arc volcanique âgées. Les magmas intermédiaires qui constituent la section inférieure du groupe de Coldbrook ont bénéficié d'afflux lithosphériques plus substantiels et affichent en conséquence des signatures essentiellement calco-alcalines. Les rhyolites des secteurs du mont Vernon, du lac Blackall et de la colline Silver représentent des magmas provenant de magmas de la section inférieure du groupe de Coldbrook et leurs différences chimiques sont interprétées comme un résultat des processus magmatiques de stillation solide-liquide et d'extraction de magma. L'extension et l'amincissement accrus ont entraîné la formation de magmas moins contaminés par la lithosphère qui ont créé les unités bimodales il y a environ 549,5 Ma dans la section supérieure du groupe de Coldbrook.

## INTRODUCTION

Volcanic and epiclastic rocks of the Coldbrook Group and associated plutons underlie about half of the Avalonian Caledonia terrane of southern New Brunswick (Fig. 1). These voluminous volcanic and plutonic rocks formed in a large intraplate magmatic event that accompanied extension and the opening of sedimentary basins throughout Avalonia in the northern Appalachian orogen during the late Ediacaran (Barr and White 1999a; van Staal *et al.* 2021; Beranek *et al.* 2023; Alvaro *et al.* 2023; Escribano *et al.* 2023). However, elsewhere, in contrast to the Caledonia terrane, only comparatively minor magmatic activity occurred during the late Ediacaran. Also, in other parts of Avalonia,

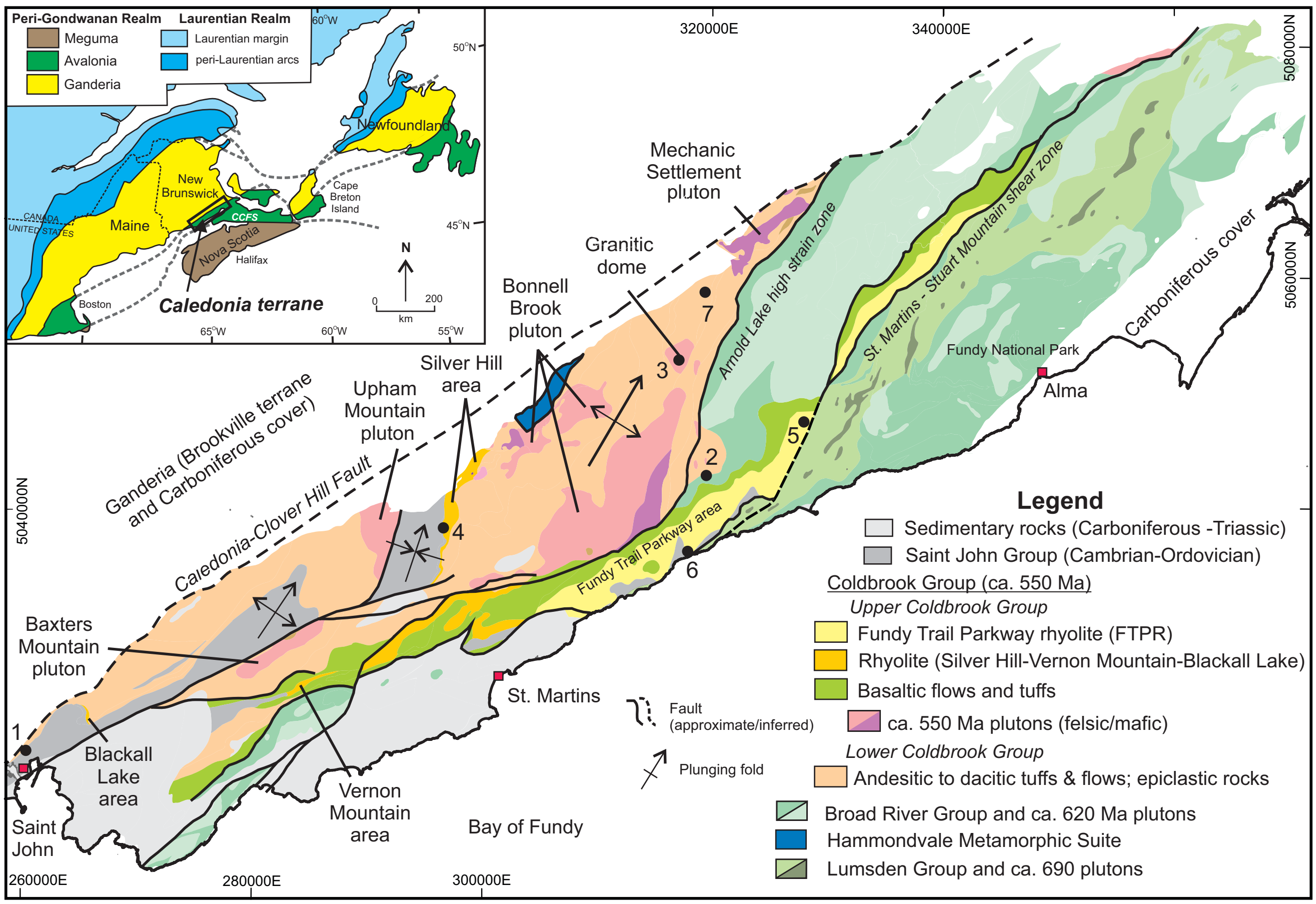


**Figure 1. Simplified geological map of the Caledonian Highlands showing the Coldbrook Group and related plutons, younger rocks, and older arc rocks of the Broad River and Lumsden groups after Barr and White (1999a, b, 2004), Barr *et al.* (2020), and Park *et al.* (2014), including some regional structural features. Locations of precisely dated samples from Escribano *et al.* (2023) are shown: 1, 551.57 ± 0.23 Ma (sample NB21-451); 2, 551.38 ± 0.24 Ma (sample NB18-381); 3, 551.71 ± 0.19 Ma (sample NB20-438); 4, 551.70 ± 0.20 Ma (sample NB20-426); 5, 549.18 ± 0.09 Ma (sample NB19-390). Samples labelled 2 and 5, as well as 6 (NB 15-350) and 7 (NB19-391) also have new Sm–Nd isotopic data reported in Table 1. Abbreviation (on inset): CCFS, Cobequid–Chedabucto Fault system.**

 

arc-related magmatism was recorded between ca. 620 Ma and 570 Ma ("main arc phase" of van Staal *et al.* 2021), whereas in the Caledonia terrane, arc magmatism appears to have ended by ~615 Ma and was followed by a magmatic gap until ~551.5 Ma (Escribano *et al.* 2023). Although previous less precise U–Pb zircon dating had indicated that the Coldbrook Group and related plutons formed over a wider late Ediacaran age range of ~560 to 550 Ma (Bevier and Barr 1990; Barr *et al.* 1994, 2019, 2020; Miller *et al.* 2000), Escribano *et al.* (2023) showed that four volcanic samples from throughout the stratigraphic succession (lower Coldbrook Group and Silver Hill Formation and from a subvolcanic intrusion (dome) crystallized in <760 kyr at ca. 551.5 Ma, and was followed by a large bimodal volcanic event represented by the Hosford Brook Formation and the uppermost rhyolite in the Silver Hill Formation, here termed the Fundy Trail Parkway rhyolite, at ca. 549.5 Ma (Fig. 2).

Previous geochemical studies of the Coldbrook Group and related plutons showed ambiguous within-plate to arc-related signatures and did not clearly identify their petrogenesis and tectonic setting (Currie and Eby 1990; Barr and White 1999a). However, the magmatic rocks were inferred to have formed in a within-plate extensional environment consistent with rift-related sedimentation and minor magmatism recorded elsewhere in Avalonia;

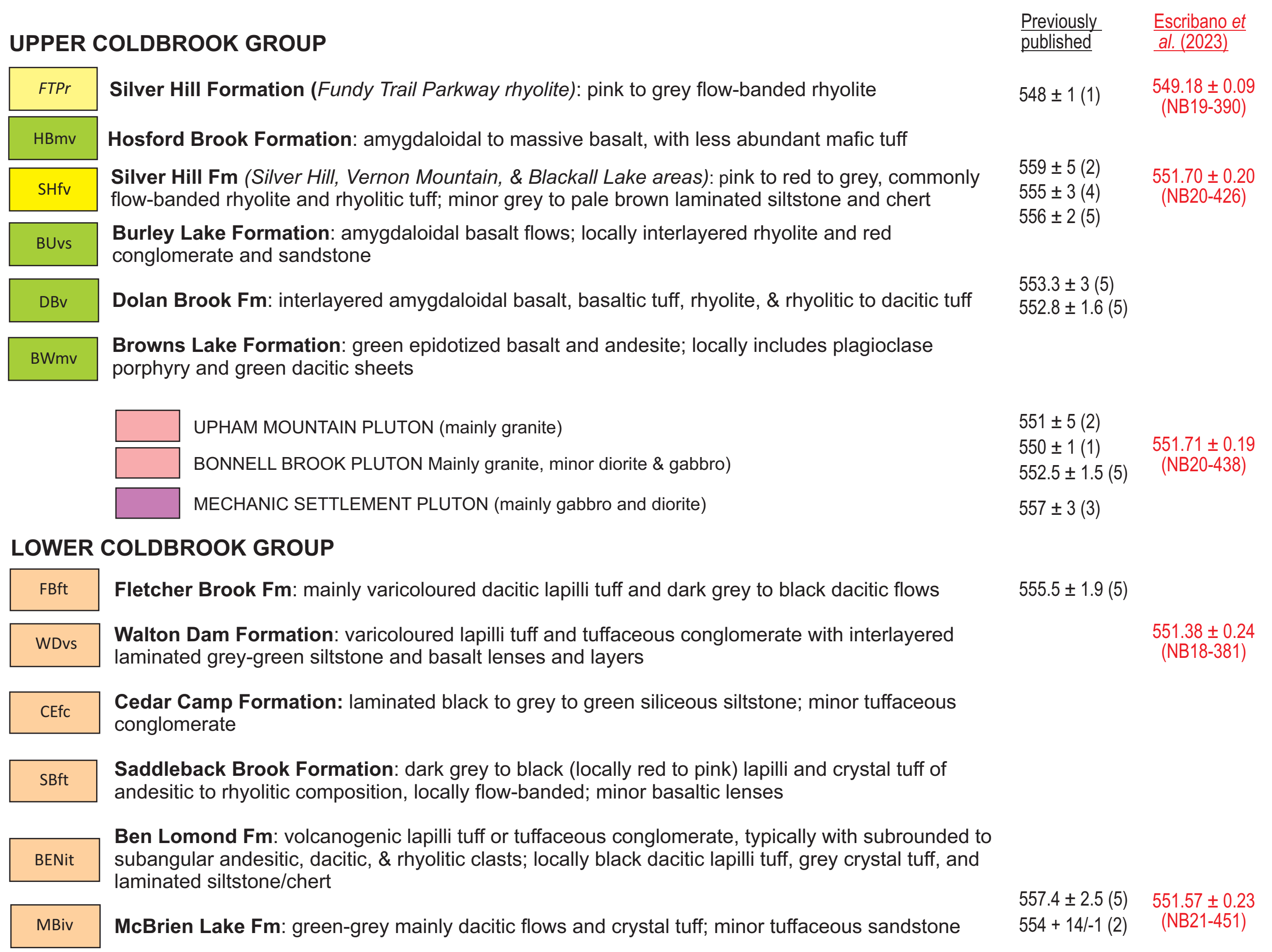


**Figure 2. Summary of main formations and rock types in the lower and upper Coldbrook Group listed in postulated stratigraphic order modified after Barr and White (2004). The Silver Hill Formation is subdivided by area as shown on Figure 1, and the Hosford Brook Formation is inferred to be similar in age to the younger Fundy Trail Parkway rhyolite. Dated plutons are shown above the formations that they intruded based on mapping by Barr and White (1999b, 2004). Previously published U–Pb dates are shown in black in the first column on the right of the figure, with source reference in brackets: (1) Bevier and Barr (1990); (2) Barr *et al.* (1994); (3) Grammatikopoulos *et al.* (1995); (4) Miller *et al.* (2000); (5) Barr *et al.* (2020). Red numbers in the second column are dates and sample numbers from Escribano *et al.* (2023), positioned in approximate stratigraphic position relative to the less precise previously published dates. Some minor formations are omitted from the diagram. Unit colours match Figure 1.**

their arc characteristics were interpreted to have been inherited from their source rocks and/or contamination by those rocks during magma evolution (Currie and Eby 1990; Barr and White 1999a). The cause of voluminous but localized magmatism in the Caledonia terrane, and the reason for the evolution from mainly intermediate-felsic to subsequent bimodal magmatism were not considered in those publications.

The present study is based in part on a compilation of previously reported petrographic, whole-rock major and trace element, and Sm–Nd isotopic data from volcanic and plutonic rocks (Guy 1998; Barr and White 1999a; Samson *et al.* 2000). Those historical data are combined with new petrographic, whole-rock geochemical, and Sm–Nd isotopic data to better interpret the characteristics of both the intermediate-felsic and bimodal magmatism and the genesis of these voluminous magmas that led to late Ediacaran super-eruption(s) in the Caledonia terrane.

## REGIONAL GEOLOGY

The Caledonia–Clover Hill Fault separates the Caledonia terrane from adjacent rocks of the Brookville terrane and other Ganderian terranes to the north (Fig. 1 and inset map; Barr and White, 1999a, b, 2004). The southern boundary is inferred to be the extension of the Cobequid–Chedabucto Fault system through the Bay of Fundy, separating Caledonia and the Avalonian terranes in Nova Scotia from the adjacent Meguma terrane to the south (Fig. 1, inset map).

The term Coldbrook Group was originally applied to volcanic rocks throughout southern New Brunswick (e.g., Ruitenberg *et al.* 1979; Dostal and McCutcheon 1990) but based on field observations, geochemistry, and a few widely separated U–Pb zircon dates from volcanic and plutonic samples, Barr and White (1999a, b) divided volcanic rocks in the Caledonian Highlands into an older (ca. 620 Ma) Broad River Group and a younger (ca. 560–550 Ma) Coldbrook Group, and excluded volcanic rocks from Ganderian terranes north of the Caledonia-Clover Hill Fault from those groups. More recent work in the Caledonian Highlands led to the recognition of even older volcanic rocks, now termed Lumsden Group, based on ca. 690 Ma U–Pb zircon dates from cross-cutting plutons (Fig. 1; Barr *et al.* 2019, 2020; 2023). Both the Lumsden and Broad River groups and associated plutons are interpreted to have formed in continental margin arcs (Barr and White 1999a) and are exposed mainly in the eastern and southern highlands (Fig. 1). Although contacts are now mainly tectonic, the Coldbrook Group was likely deposited unconformably on the older units (Park *et al.* 2008; 2017; Barr *et al.* 2020, 2023). The Hammondvale Metamorphic Suite on the northern margin of the Caledonia terrane contains high pressure-low temperature (9 kb, 580°C) pelitic and calcareous rocks that have been interpreted to have been part of an accretionary prism related to the Broad River Group arc (Fig. 1; White *et al.* 2001).

The ca. 550 Ma non-marine clastic sedimentary rocks of the Coldbrook Group are overlain by marine fossiliferous siliciclastic platformal sediments of the Cambrian-Ordovician Saint John Group that are considered typical of Avalonia (Tanoli and Pickerill 1988; Landing 1996; Landing and Westrop 1998; Palacios *et al.* 2011; Alvaro *et al.* 2023).

In the central and western parts of the Caledonian Highlands, both the Coldbrook and Saint John groups are affected by regional folds plunging to the north-northeast (Fig. 1; Barr and White, 1999a, b, 2004). In contrast, in the southeastern part of the highlands, the Coldbrook Group has been thrust over the Lumsden and Broad River groups and related plutons along the Arnold Lake and St. Martins–Stuart Mountain high strain zones, and the younger bimodal units of the Coldbrook Group are mylonitic in the St. Martins–Stuart Mountain high-strain zone (Fig. 1; Park *et al.* 2008, 2017).

## COLDBROOK GROUP STRATIGRAPHY

Barr and White (1999a, b) divided the Coldbrook Group formations into lower and upper based on sparse evidence observed in the field for younging directions and the fact that units in the lower part are intruded by plutons including Bonnell Brook, Baxters Mountain, Upham Mountain, and Mechanic Settlement (Figs. 1, 2). That terminology is retained here, although Escribano *et al.* (2023) showed, using precise geochronology, that ages of the plutons and their host volcanic rocks of the lower Coldbrook Group are similar to the age of rhyolite in part of the Silver Hill Formation in the upper Coldbrook Group and that much of the Coldbrook Group and related plutons formed in less than 760 000 years (Fig. 2). Formations in the lower Coldbrook Group consist predominantly of andesitic to dacitic lithic and/or crystal lapilli tuff and less abundant mafic, intermediate and rhyolitic flows with an estimated thickness of about 10 km (Barr and White 1999a). The intermediate tuffs are characterized by a flow-banded matrix of cryptocrystalline to very fine-grained aggregates of quartz and feldspar. They typically contain sparse (<5%) plagioclase crystals as well as mafic and felsic lithic fragments (Escribano 2021).

Basalt flows are a minor component of the lower Coldbrook Group and mostly consist of clinopyroxene and plagioclase intergrown in intergranular texture with variable amounts of secondary saussurite, epidote, and chlorite (Barr and White 1999a). Interlayered volcanogenic sedimentary formations consist of laminated red to grey siltstone, minor conglomerate, epiclastic sandstone, and laminated grey siltstone, and were described in more detail by Satkoski (2008) and Satkoski *et al.* (2010).

The upper Coldbrook Group formations consist mainly of basalt and rhyolite. Basalt-dominated formations extend from near the city of Saint John to the northeast for about 75 km. The most extensive formation, Hosford Brook, is typically amygdaloidal, with amygdales filled by epidote, chlorite, calcite, albite, and quartz. The groundmass consists mainly of albitized plagioclase, chlorite, epidote, and opaque phases (Barr and White 1999a). The Burley Lake and Dolan Brook formations include minor interlayered rhyolite and dacite, and in the case of Burley Lake, red conglomerate and sandstone (Fig. 2).

Barr and White (1999a) assigned felsic volcanic rocks in the upper Coldbrook Group to the Silver Hill Formation, which occurs in the Silver Hill area in the northwestern highlands, the Blackall Lake area near Saint John, the Vernon Mountain area, and in a belt that extends from the St. Martins area for 75 km to the northeast parallel to the basaltic Hosford Brook Formation (Fig. 1). The latter belt is informally termed the Fundy Trail Parkway rhyolite (FTPR), and a sample from that unit yielded an age of 549.18 ± 0.09 Ma, 2.5 million years younger than the age of 551.70 ± 0.20 Ma for a rhyolite sample from the Silver Hill area (Fig. 2). Although the rhyolites in the Blackall Lake and Vernon Mountain areas are undated because samples from those areas did not yield zircon (Escribano *et al.* 2023), they are interpreted to be similar in age to rhyolite in the Silver Hill area. Furthermore, the close association between the Hosford Brook Formation and Fundy Trail Parkway rhyolite suggests that it is also younger than the other basaltic units, leading to a revised stratigraphic interpretation (Fig. 2). Rhyolite in the Silver Hill, Vernon Mountain, Blackall Lake areas is typically flow-banded with sparse plagioclase phenocrysts and lithic fragments. The Blackall Lake rhyolite contains highly vesicular pumice fragments, the rhyolite in the Silver Hill area contains lenses with spherulitic textures, and in the Vernon Mountain area, the rhyolite is characterized by perlitic textures and rare lithic clasts with large quartz and feldspar grains and fine aggregates of chlorite and pyrite, rimmed by iron oxide (Escribano 2021). The Fundy Trail Parkway rhyolite is also typically flow-banded with sparse quartz crystals and plagioclase crystals and fragments in a fine-grained groundmass of quartz and feldspar. In places it contains lenses with perlitic fractures and spherulitic texture (Escribano 2021). In the eastern Fundy Trail Parkway area and farther northeast, the rhyolite is moderately to pervasively mylonitized in the St. Martins–Stuart Mountain high-strain zone.

## PLUTONIC ROCKS

The largest pluton is Bonnell Brook (Fig. 1), composed mainly of syeno- and monzogranite that intruded units of the lower Coldbrook Group. The modal mineralogy is plagioclase (35–45%), quartz (35–40 %), perthitic orthoclase (30–35 %), chloritized biotite (<3 % wt.), and rare amphibole. Accessory phases include magnetite, titanite, and less abundant allanite, rutile, apatite, and zircon (Guy 1998; Escribano 2021). Toward the margins of the main body, the medium- to coarse-grained texture in the granite changes to fine-grained allotriomorphic inequigranular to porphyritic, as a result of more rapid cooling (Escribano 2021). The south-eastern part of the pluton consists of dioritic rocks, locally intruded by granitic dykes (Guy 1998; Barr and White 1999a). The dioritic rocks consist mainly of plagioclase and hornblende, with minor interstitial quartz, K-feldspar and relict clinopyroxene in the cores of some hornblende grains (Barr and White 1999a).

A fine-grained granitic dome with spherulitic to granophyric texture and miarolitic cavities occurs north of the main body of the Bonnell Brook pluton and has been previously interpreted to be a subvolcanic intrusion that is part of the Bonnell Brook pluton and cogenetic with the Silver Hill Formation (Guy 1998; Barr and White 1999a). The samples from this dome consist of plagioclase, quartz, and K-feldspar microphenocrysts in a fine-grained groundmass of quartz and feldspar, and highly chloritized biotite and amphibole (Escribano 2021). Granitic samples from the Upham Mountain pluton farther to the southwest (Fig. 1) also have spherulitic to granophyric textures and miarolitic cavities, and that pluton may also be a subvolcanic intrusion, although it has not yet been mapped in detail.

Other plutons interpreted to be comagmatic with the Coldbrook Group based on field relations, rock types, and previous geochronology include the bimodal Baxters Mountain pluton and the layered mafic-ultramafic Mechanic Settlement pluton (Fig. 1; Barr and White 1999a, b, 2004). The petrology of the Mechanic Settlement pluton and associated Cu-Ni and platinum-group-element mineralization were studied previously (Grammatikopoulos 1992; Grammatikopoulos *et al.* 1995, 2007; Hiebert 2005; Hiebert *et al.* 2008) and hence that pluton is not included in the present study.

## WHOLE-ROCK GEOCHEMISTRY

### Methodology

To investigate the chemical characteristics of the Coldbrook Group and associated plutons, previously acquired whole-rock geochemical data were compiled from Guy (1998) and Barr and White (1999a and unpublished data). The data are from 89 volcanic samples and 68 plutonic samples and were obtained by different methods as documented in the source references. Because the initial work was done decades ago, trace element data, especially rare-earth element (REE) data, were few and of uncertain quality. Hence, 43 of the archived powders were re-analyzed for REE and selected other trace elements by N. Eby at the University of Massachusetts (Lowell) in the early 2000s, using X-ray fluorescence (XRF)and instrumental neutron activation methods as described by Eby and Currie (1996). For the present study, an additional 68 of the archived sample powders were reanalyzed for trace elements by inductively coupled plasma-mass spectrometry (ICP-MS) at Bureau Veritas Lab in Vancouver, BC. For those samples and those analyzed by N. Eby, the existing trace element data in the data compilation were replaced by the new data. In addition, 38 silicic volcanic and plutonic samples were collected as part of the present study to facilitate a more detailed investigation of the relationships among those units. The new samples were also analysed at Bureau Veritas Lab in Vancouver using XRF and ICP-MS methods. For quality control, 5 duplicates, 12 reference materials, and 6 blanks were included in the analytical runs. The analytical data used in the diagrams presented in this paper are tabulated in the M.Sc. thesis of Escribano (2021), available digitally in the Acadia University Library, and in the Supplementary data table that accompanies this paper.

As part of the present study, Sm–Nd isotopic data were obtained from lithic tuff samples NB19-381 and NB19-391 from the lower Coldbrook Group and rhyolite samples NB15-350 and NB19-390 from the upper Coldbrook Group (Table 1). Analyses were done at the Department of Earth Sciences, Memorial University, St. John's, NL, using mass spectrometry (Table 1 footnotes). These new data are compared to previously published Sm–Nd isotopic data from 11 igneous samples from the Broad River Group and related plutons and 12 samples of the Coldbrook Group and related plutons from Whalen *et al.* (1994), Samson (1995), Samson *et al.* (2000), and Barr *et al.* (2000). The software package REFLEX™ from ioGAS™ was used to display the compiled chemical data on diagrams to illustrate their compositional characteristics and tectonic setting.

## Overview

The lower Coldbrook Group samples span a wide range of compositions from mafic to felsic, whereas samples from the upper Coldbrook Group are generally bimodal (Fig. 3a, b, c). The associated plutons are also bimodal, and previous interpretations suggested that the plutons are intrusive equivalents of the basalt and rhyolite in the upper Coldbrook Group (e.g., Barr and White 1999a). The results of more precise U–Pb dating suggest that this interpretation may be appropriate for some rhyolite such as that in the Silver Hills area, but it is not the case for the younger Fundy Trail Parkway (FTP) rhyolite and associated Hosford Brook Formation basalt of the uppermost Coldbrook Group (Fig. 2).

All analyzed samples are subalkalic (Fig. 3b) and the alkalis-$FeO^T$-MgO (AFM) diagram shows iron enrichment suggesting that they are tholeiitic (Fig. 3c). Most of the silicic samples from both the lower and upper Coldbrook Group plot in the igneous spectrum for unaltered rocks (Fig. 3d). A few samples, mostly from the lower Coldbrook Group, show potassium enrichment and about one-third of the andesitic and dacitic samples from the lower Coldbrook Group and most of the mafic samples from both the lower and upper Coldbrook Group show a gain in sodium, probably related to albitization (Fig. 3d). Thus, the Coldbrook Group and related plutons are not highly altered and with caution, some mobile elements may be useful to characterize them.

### Silicic samples

The silicic samples (those with >70% $SiO_2$) are from the lower Coldbrook Group, felsic domes and plutons, and the Blackall Lake, Silver Hill, Vernon Mountain, and FTP rhyolites (Fig. 3a). Two trends are visible on the Zr/Y–Y diagram, with the lower Coldbrook Group rhyolite, Blackall Lake and Vernon Mountain rhyolite and felsic dome samples showing higher Zr/Y ratios compared to samples from the felsic plutons and Silver Hill and FTP rhyolites (Fig. 4a). The silicic volcanic and plutonic samples plot mostly in the transitional field, with fewer samples in the tholeiitic field and even fewer in the calc-alkalic field (Fig. 4a).

On the Nb-Y diagram (Fig. 4b), most samples plot in the field for within-plate granite, with a few samples, mostly from plutons, plotting in the field for volcanic-arc granite (Fig. 4b). On the Rb-Hf-Ta ternary diagram of Harris et al. (1986), approximately half of the volcanic and felsic dome samples plot in the volcanic-arc field whereas the other samples plot in the field for within-plate granite (Fig. 4c). In contrast, the felsic pluton samples plot mostly in the field for late- and post-collisional granite with fewer samples in the within-plate granite field (Fig. 4c). Most samples from the lower Coldbrook Group, Vernon Mountain and Blackall Lake rhyolites, and felsic domes have relatively high Zr contents and plot in the field for within-plate granite (Fig. 4d). In contrast, most samples from the FTP rhyolite, felsic plutons, and Silver Hill rhyolite have lower Zr and plot in the field for I-, S-, and M-type granite (Fig. 4d). Most of those samples also have Ga/Al ratios within the range typical of I-, S-, and M-type granite, although the FTP rhyolite samples have higher Ga/Al ratios than most other low Zr samples (Fig. 4d), indicating that these rocks are more evolved (Collins et al. 1982; Whalen et al. 1987).

Chondrite-normalized rare-earth element (REE) plots for the silicic samples of the Coldbrook Group and related plutons show similar patterns, with moderate slopes from light REE to middle REE and flat patterns from middle REE to heavy REE (Fig. 5a–c). The REE concentrations vary between 10- and 300-times chondrite. Average negative Eu anomalies are well developed in every sample, and are probably related to plagioclase fractionation (e.g., Holder *et al.* 2015). The least pronounced Eu anomalies are in the felsic dome samples with average [Eu/Eu*] of 0.54, and the most pronounced Eu anomalies are in the felsic pluton samples with an average [Eu/Eu*] of 0.45 (Fig. 5c). Average $[La/Sm]_N$ ranges from 2.80 to 3.36, with the lowest and highest values in the FTP rhyolite and felsic pluton samples, respectively. Average $[Gd/Yb]_N$ values range from 1.00 to 1.06. However, the middle REE to heavy REE contents in the felsic pluton samples show a wide range, with contents that vary from 10- to 60-times chondrite, compared to 30- to 60-times chondrite in the felsic dome samples, and 30- to 100-times chondrite in the FTP rhyolite samples. The FTP rhyolite samples show a wide range in light REE and some middle REE, and a narrow range in heavy REE, which

Table 1. New Sm–Nd isotopic data for felsic samples* from the Coldbrook Group.

| SAMPLE | UNIT | Easting | Northing | Lithology | Age (Ma) | $^{143}Nd$ | $^{147}Sm$ | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | $^{143}Nd/^{144}Nd$ (t) | εNd(t) | TDM (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NB18-381(2) | Walton Dam Fm | 319403 | 5042156 | dacitic tuff | 551.38 | 35.48 | 8.1 | 0.13790 | 0.512478 | 0.511980 | 1.1 | 1152 |
| NB19-390(5) | Silver Hill Fm (FTPR) | 326435 | 5045221 | rhyolite | 549.18 | 46.92 | 10.51 | 0.13540 | 0.512475 | 0.511988 | 1.2 | 1124 |
| NB15-350(6) | Silver Hill Fm (FTPR) | 318792 | 5036263 | rhyolite | 549 | 36.83 | 8.14 | 0.13360 | 0.512482 | 0.511999 | 1.5 | 1089 |
| NB19-391(7) | Saddleback Brook Fm | 318792 | 5036263 | felsic tuff | 551 | 30.73 | 6.85 | 0.13480 | 0.512450 | 0.511963 | 0.8 | 1160 |

Notes:

*Numbers in brackets after sample numbers refer to numbered locations shown on Figure 1.

Analyses were done at Memorial University by thermal ionization mass spectrometry using a Finnigan MAT 262V mass spectrometer (https://www.mun.ca/creait/the-earth-resources-research-and-analysis-facility/thermal-ionization-mass-spectrometer-facility-tim/)

Depleted mantle age (TDM) was calculated using a linear evolution for a mantle separated from the CHUR at 4.55 Ga and having a present day epsilon value of +10.

Ratio of $^{143}Nd/^{144}Nd$ is corrected from the deviation from JNdi-1 (mean value of MUN TIMS Lab is 0.512096, σ = 7, n = 16).

Easting and northing coordinates are in NAD83 and grid zone 20.

Ages in blue were obtained by TIMS (thermal ionization mass spectrometery; Escribano *et al* . 2023). The other two ages are estimated based on TIMS ages in similar units.

Abbreviations: Fm, formation; FTPR, Fundy Trail Parkway rhyolite

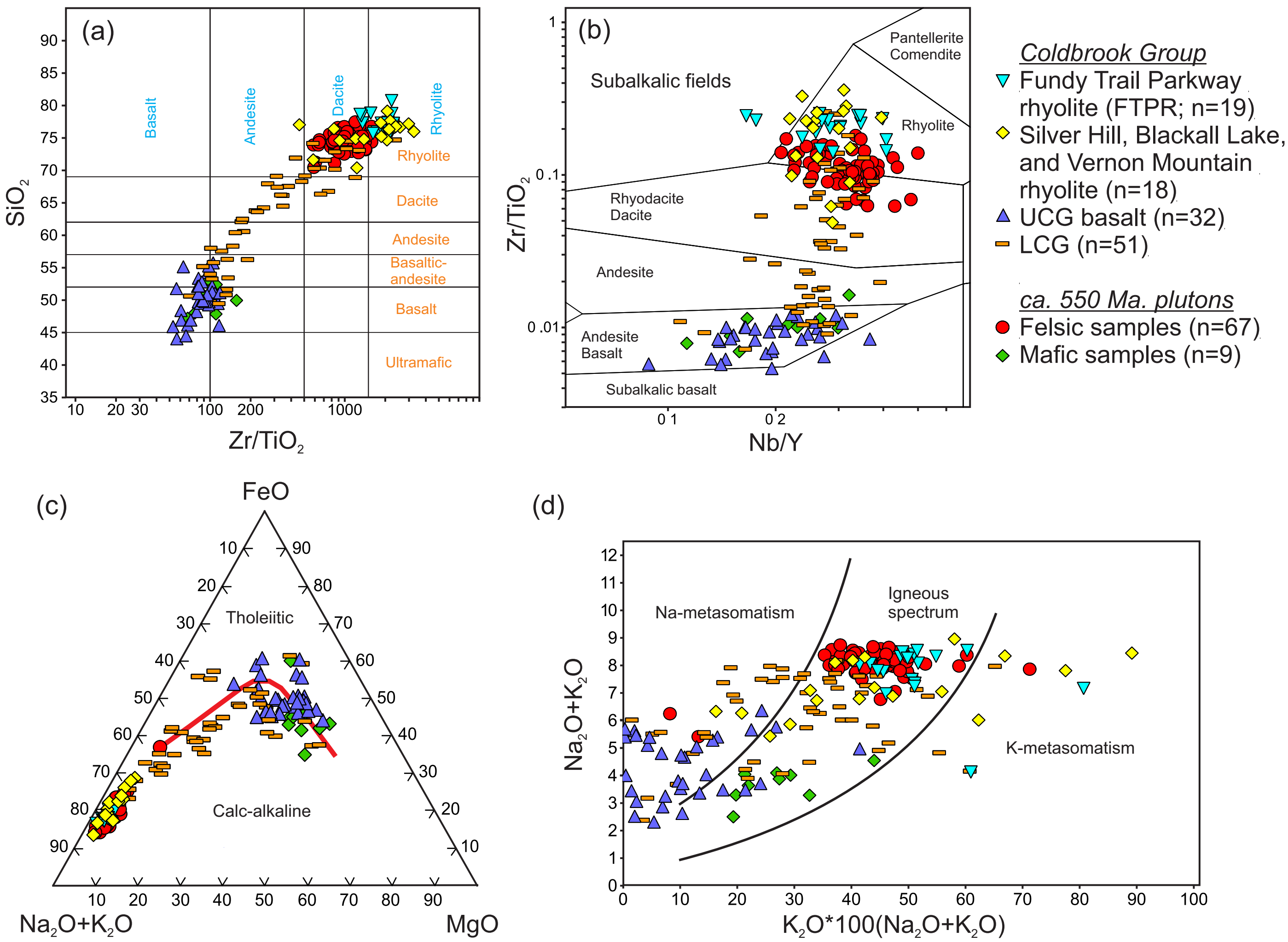


**Figure 3. Diagrams illustrating chemical variation in samples from the Coldbrook Group and related plutons. (a) $SiO_2$ against $Zr/TiO_2$ with fields after Le Maitre *et al.* (1989) and Hallberg (1984). Diagram is after Stanley (2017). (b) $Zr/TiO_2$ against Nb/Y with fields after Winchester and Floyd (1977). (c) $Na_2O+K_2O$-FeO-MgO ternary diagram. Tholeiitic-calc-alkalic dividing line (red) is after Irvine and Baragar (1971). (d) $Na_2O+K_2O$ against $K_2O*100/(Na_2O+K_2O)$ with fields after Hughes (1972). Abbreviations: UCG, upper Coldbrook Group; LCG, lower Coldbrook Group.**

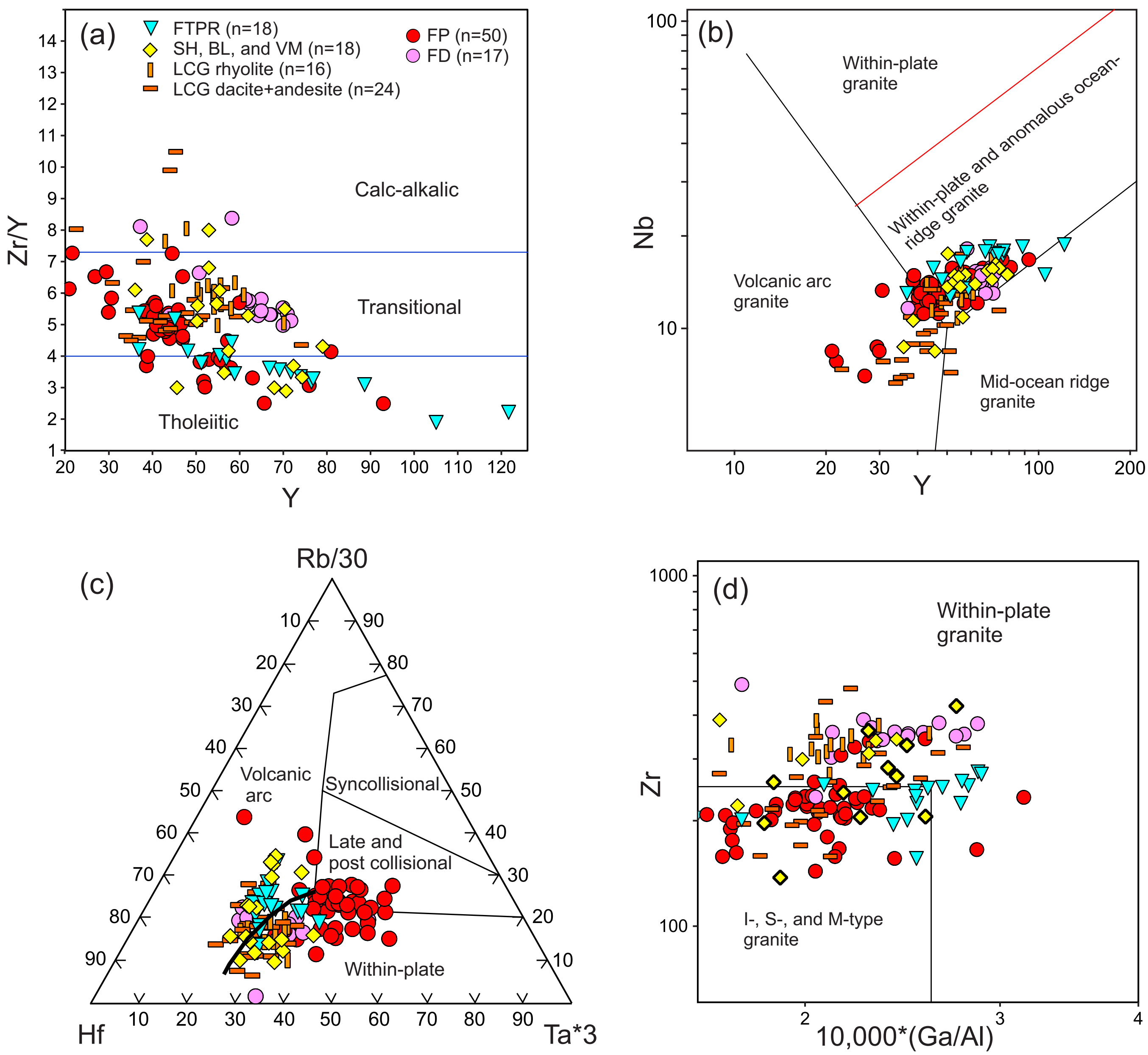


**Figure 4. Chemical discrimination diagrams for intermediate and felsic samples from the Coldbrook Group and related granitic plutons and domes. (a) Zr/Y against Y with fields after Lesher *et al.* (1986). (b) Nb against Y with fields after Pearce *et al.* (1984). (c) Hf-Rb/30-Ta*3 ternary plot with fields after Harris *et al.* (1986). (d) Zr against 10000*(Ga/Al) with fields after Whalen *et al.* (1987). Abbreviations: BL, Blackall Lake area rhyolite; FD, felsic dome: FP, felsic pluton: FTPR, Fundy Trail Parkway rhyolite; LCG, lower Coldbrook Group intermediate and felsic units; SH, Silver Hill area rhyolite; VM, Vernon Mountain area rhyolite. Symbols for rhyolite samples from the Silver Hill area are displayed with thicker outline in (d).**

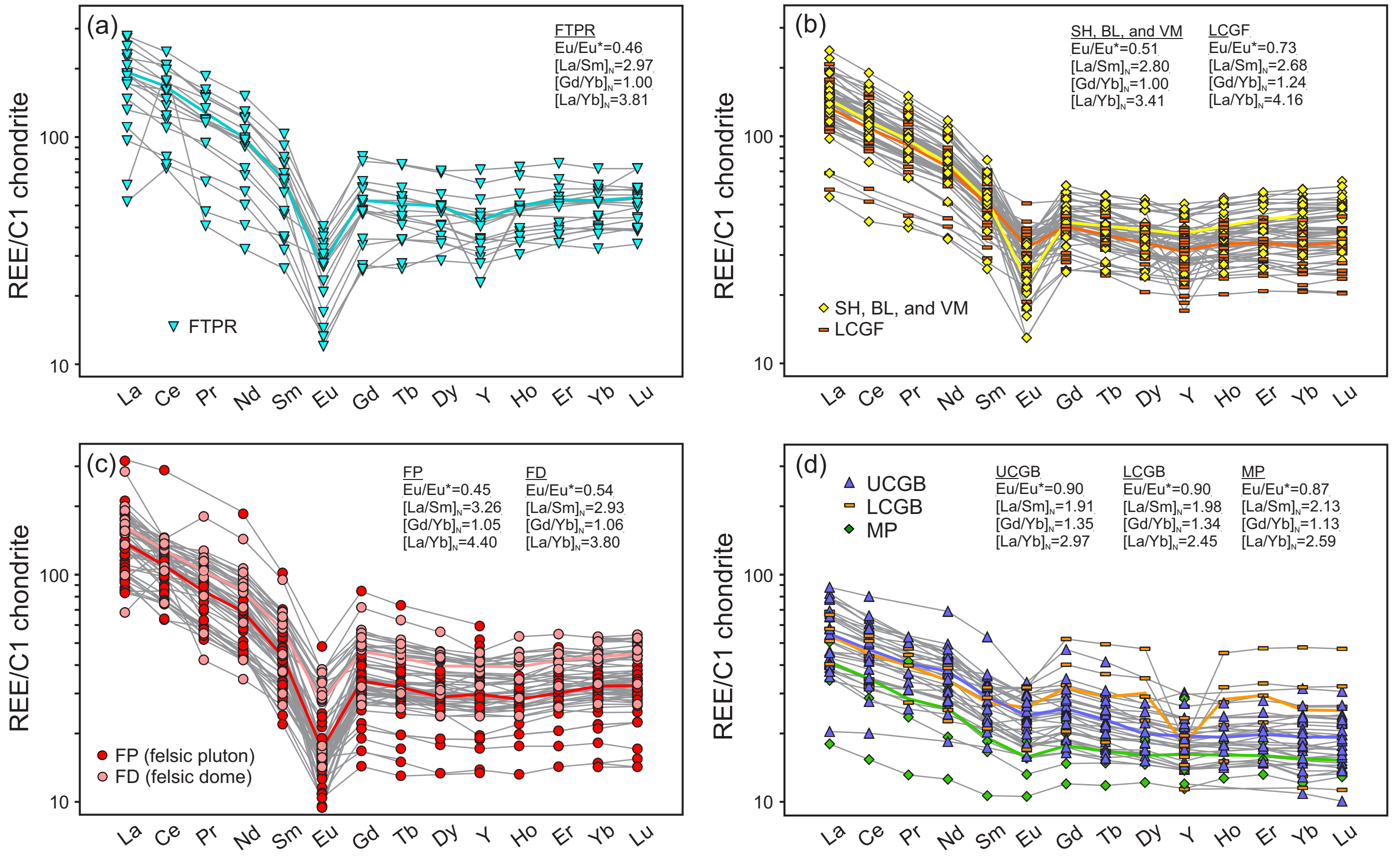


**Figure 5. Rare earth element (REE) + Y diagrams normalized to C1 chondrite (normalizing values from McDonough and Sun 1995). (a) Fundy Trail Parkway rhyolite, (b) lower Coldbrook Group and Silver Hill, Blackall Lake, and Vernon Mountain area rhyolites, (c) felsic plutons and domes, and (d) upper and lower Coldbrook Group basalt and mafic plutons. Average values per group of samples are shown coloured lines. Average values for Eu/Eu*, $[La/Sm]_N$, $[Gd/Yb]_N$, and $[La/Yb]_N$ for each group of samples are shown (normalization values after Taylor and McLennan 1985). Abbreviations: BL, Blackall Lake area rhyolite; FD, felsic domes; FP, felsic plutons; FTPR, Fundy Trail Parkway rhyolite; LCG, lower Coldbrook Group; LCGB, lower Coldbrook Group basalt; MP, mafic plutons; SH, Silver Hill area rhyolite; UCGB, upper Coldbrook Group basalt; VM, Vernon Mountain area rhyolite. In REE diagrams generated by ioGAS™, Y is used instead of Tm.**

suggests apatite fractionation as apatite has preference for the light REE (e.g., Bruand *et al.* 2020).

Primitive mantle-normalized multi-element plots for the silicic samples show generally flat patterns with trace element contents mainly ranging between 10- and 100-times primitive mantle (Fig. 6a–c). All samples show moderate Nb depletion, and Al contents similar to those of primitive mantle. Scandium contents are variable and generally range between 0.1- and 1-times primitive mantle in the lower Coldbrook Group rhyolite, Silver Hill, Blackall Lake and Vernon Mountain rhyolites, and felsic plutons and domes, whereas in the FTP rhyolite, scandium shows a narrow range between 0.1- and 0.3-times chondrite (Fig. 6), suggesting that neither pyroxene nor hornblende fractionation was involved in the genesis of the younger rhyolite (Wang *et al.* 2021). Vanadium contents show a wide range in the lower Coldbrook Group and Silver Hill, Blackall Lake and Vernon Mountain rhyolites, and are probably related to magnetite fractionation (Kelley *et al.* 2017), with contents ranging between 0.01- to 0.1-times primitive mantle. Vanadium contents vary between 0.02- to 0.3-times primitive mantle in the felsic plutons and domes.

### Intermediate samples

Samples of andesitic to dacitic composition (56–69% $SiO_2$) are from the lower Coldbrook Group (Fig 3a). With the exception of two samples with high Zr/Y ratios, they generally have lower Zr/Y ratios compared to the lower Coldbrook Group rhyolite but similar to the Zr/Y ratios of the felsic plutons, FTP rhyolite, and Silver Hill rhyolite (Fig. 4a). They also show lower Nb contents compared to the silicic samples and plot mostly in the volcanic-arc field transitioning to the field for ocean-ridge granite (Fig. 4b). Like the silicic samples, half of the intermediate samples plot in the volcanic-arc field and the other half in the within-plate granite field on the Harris *et al.* (1986) diagram (Fig.

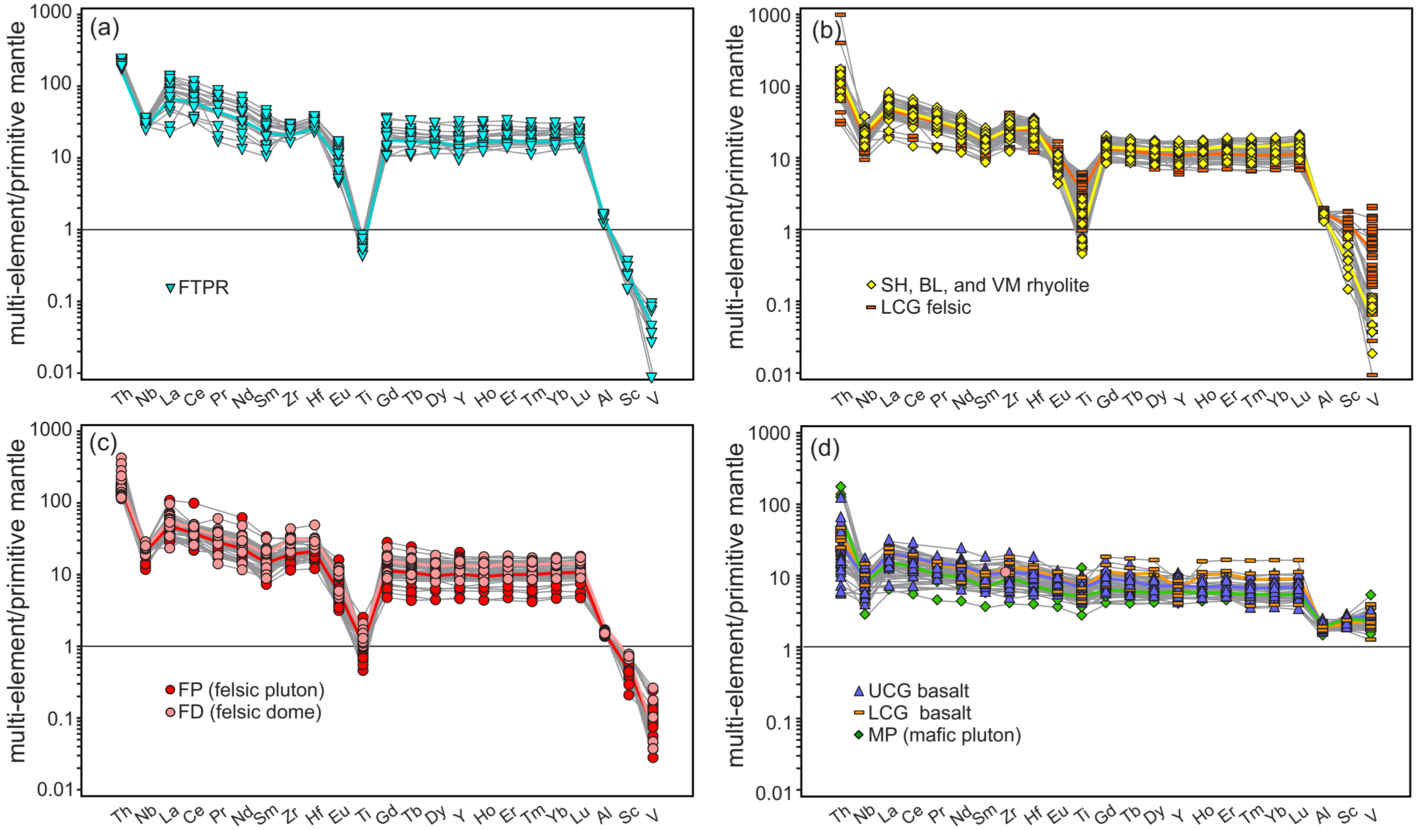


**Figure 6. Multi-element diagrams with data normalized against primitive mantle (normalizing values from Sun and McDonough 1989). (a) Samples from the Fundy Trail Parkway rhyolite. (b) Samples from the lower Coldbrook Group and Silver Hill, Blackall Lake, and Vernon Mountain area rhyolites. (c) Samples from the felsic plutons and domes. (d) Samples from the upper and lower Coldbrook Group basalt and mafic plutons. Average values per group of samples are represented by coloured lines. Abbreviations: BL, Blackall Lake area rhyolite; FD, felsic domes; FP, felsic plutons; FTPR, Fundy Trail Parkway rhyolite; LC, lower Coldbrook Group; LCB, lower Coldbrook Group basalt; MP, mafic plutons; SH, Silver Hill area rhyolite; UCGB, upper Coldbrook Group basalt; VM, Vernon Mountain area rhyolite.**

4c). About two thirds of the samples plot in the field for I-, S-, and M-type granite whereas the remaining samples have higher Zr contents and plot in the field for within-plate granite (Fig. 4d).

Chondrite-normalized REE plots for the andesitic to dacitic samples of the lower Coldbrook Group, like the silicic samples, show moderate slopes from light REE to middle REE and generally flat patterns from middle REE to heavy REE (Fig. 5b). The REE concentrations vary between 20- and 200-times chondrite. Average negative Eu anomalies are 0.73 and $[La/Sm]_N$ is 2.68. However, the samples show a higher slope in their middle REE to heavy REE contents compared to the silicic samples, as expressed by their higher $[Gd/Yb]_N$ and $[La/Yb]_N$ of 1.24 and 4.16, respectively (Fig. 5b).

The andesite and dacite samples of the lower Coldbrook Group show moderate Ti depletion with Ti contents ranging between 3- to 10-times primitive mantle, and a wide range in Sc contents that vary between 0.6- and 2-time primitive mantle (Fig. 6b), suggesting hornblende or pyroxene fractionation. Vanadium contents range between 0.1- to about 2-times primitive mantle in the intermediate samples.

### Basaltic and gabbroic samples

Both the basaltic and gabbroic samples plot in the field for island arc tholeiites on the $TiO_2$-MnO-$P_2O_5$ diagram (Fig. 7a). A plot of Th/Yb against Nb/Yb shows that the mafic plutons and lower Coldbrook Group basalt plot above the oceanic array and in the overlapping fields for oceanic and continental arcs, whereas the upper Coldbrook Group basalt samples show a wide range in Th/Yb ratios consistent with a depleted mid-ocean ridge basalt (N-MORB) source contaminated with arc crust (Fig. 7b; Pearce 2014).

On the most recent classification diagram of Shervais (2022), the lower Coldbrook Group basalt and gabbroic pluton samples generally plot between the field for juvenile and mature arcs and continental flood basalts whereas the upper Coldbrook Group basalt samples plot mainly in the field for continental flood basalts (Fig. 7c). Continental flood basalts are characterized by Th/Nb ratios that plot above the oceanic array, and a wide range in Ti/V ratios (20–70 in the Columbia River basalt and 20–43 in the Paraná tholeiites; Shervais 2022).

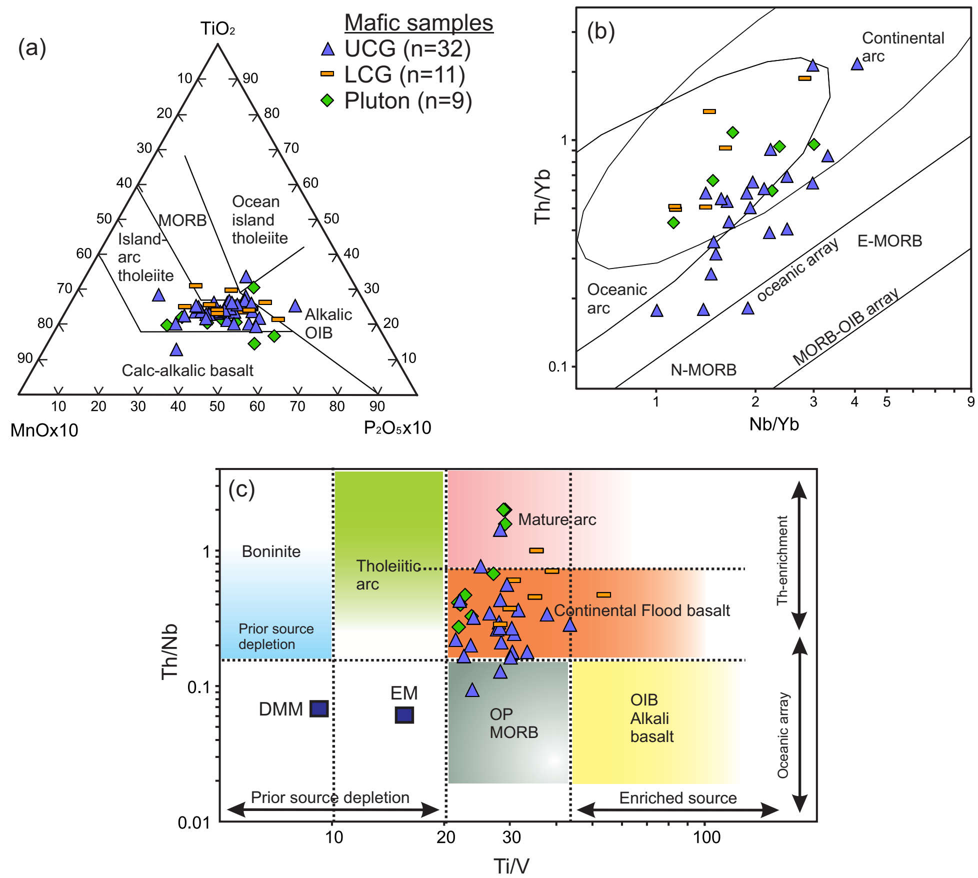


**Figure 7. Chemical discrimination diagrams for mafic samples from the Coldbrook Group and related mafic plutons. (a) MnO*10-$TiO_2$-$P_2O_5$ with fields after Mullen (1983). (b) Th/Yb against Nb/Yb with fields after Pearce (2014). (c) Th/Nb against Ti/V with fields after (Shervais 2022). Abbreviations: DMM, depleted MORB mantle source; EM, enriched MORB mantle source; LCG, lower Coldbrook Group basalt; MORB, mid-ocean ridge basalt; OIB, ocean island basalt: OP, oceanic plateaus; UCGB, upper Coldbrook Group basalt. Note: not all mafic samples have trace element data, and hence are not shown on (b) and (c).**

Chondrite-normalized REE plots for the mafic samples show smooth patterns with REE concentrations between 10- and 100-times chondrite (Fig. 5d). The REE patterns have gentle slopes from light REE to middle REE, with average Eu/Eu* ratios of 0.90, 0.90, and 0.87 for the upper and lower Coldbrook Group basalt and gabbroic plutons, respectively (Fig. 5d). Both the upper and lower Coldbrook Group basalt samples have similar light REE contents. The average $[La/Sm]_N$ ratios are 1.91, 1.98, and 2.13 for the upper Coldbrook Group basalt, lower Coldbrook Group basalt, and mafic pluton samples, respectively. The middle REE to heavy REE patterns for the mafic samples are relatively flat with average $[Gd/Yb]_N$ ratios of 1.35, 1.34 and 1.13, respectively (Fig. 5d). However, the lower Coldbrook Group basalt samples have higher average middle and heavy REE contents compared to the upper Coldbrook Group basalt and mafic pluton samples, suggesting a shallower depth of formation for these magmas (e.g., Tegner *et al.* 1998; Melluso *et al.* 2006; Shellnutt *et al.* 2014), and amphibole fractionation expressed by their strong depletion in Y contents (e.g., Dessimoz *et al.* 2012; Fig. 5).

The average $[La/Yb]_N$ ratios for the upper Coldbrook Group basalt, lower Coldbrook Group basalt, and mafic pluton samples are 2.97, 2.45, and 2.59, respectively (Fig. 5d).

Primitive mantle-normalized multi-element plots for the mafic samples show generally flat patterns with trace element contents ranging between 1 and almost 200 times primitive mantle for both basaltic and plutonic samples (Fig. 6d). The mafic samples show moderate Nb and Al depletion, consistent with arc settings and/or contamination by arc lithosphere (e.g., Pearce and Peate 1995), and plagioclase fractionation (McBirney 1984), respectively. They have higher contents of incompatible elements (e.g., Th) than typical MORB (Pearce and Peate 1995), which may be explained by the addition of a lithospheric component. This point is also illustrated in Figures 7b and 7c that show Th/Yb and Th/Nb ratios typical for arc-related rocks.

### Sm–Nd isotopes

The Coldbrook Group and related plutons have εNd values between -1.5 and +3.5 and model ages between 906 Ma and 1308 Ma (Fig. 8) which are considered typical of Avalonian rocks (e.g., Willner *et al.* 2013; Pollock *et al.* 2015). Also, like older rocks of the Broad River Group and related plutons, which have εNd values between -0.3 and +4.8 and model ages between 808 Ma and 1422 Ma, most plot in the

 

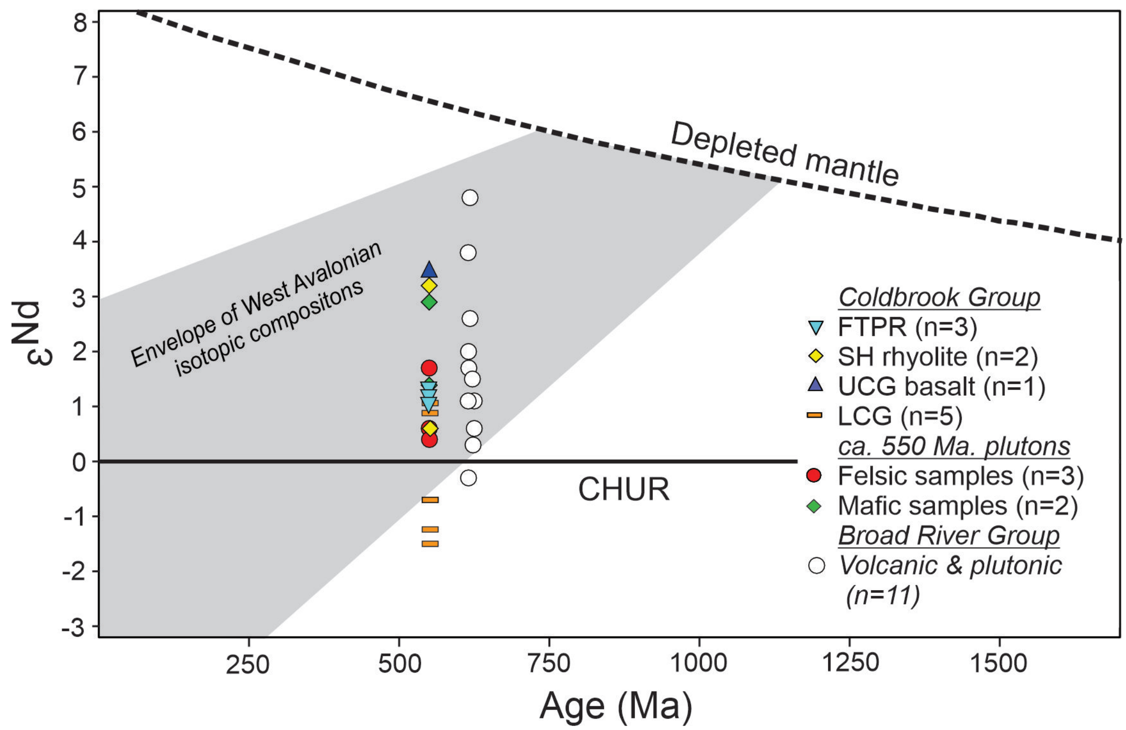


**Figure 8. Plot of εNd values against age for samples from the Coldbrook Group and related plutons (coloured symbols) and the ca. 620 Ma Broad River Group and related plutons (black unfilled circles). CHUR: Chondritic uniform reservoir. Data are from this study (Table 1) and Whalen *et al.* (1994), Samson (1995), Samson *et al.* (2000), and Barr *et al.* (2000). Field for West Avalonian isotopic compositions (in grey) is from Murphy and Nance (2002).**

Avalonian window of Murphy and Nance (2002; Fig. 8).

The only negative εNd values are from andesitic and dacitic samples of the lower Coldbrook Group and suggest crustal contamination, whereas all other samples show positive values consistent with mantle-derived melts. The highest εNd values are displayed by basalt, Vernon Mountain rhyolite, and mafic pluton samples with positive values of 3.5, 3.2, and 2.9, respectively. The FTP rhyolite samples show a narrow range in εNd values between 1.2 and 1.5, whereas the εNd values are higher for the felsic pluton samples (0.6 and 1.7) compared to the felsic dome samples (0.4; Fig. 8).

## DISCUSSION

### Magma types

Major and trace element chemistry indicates that the entire late Ediacaran suite, both volcanic and plutonic, is tholeiitic or transitional to tholeiitic. The lower Coldbrook Group andesitic to rhyolitic samples, Silver Hill, Blackall Lake, and Vernon Mountain rhyolites, and felsic dome samples are transitional to tholeiitic, whereas the upper Coldbrook Group, including the FTP rhyolite, and and the lower Coldbrook Group basalt and mafic plutons are tholeiitic. However, the multi-element patterns and $[La/Yb]_N$ ratios of 2.6 to 4.4 for the Coldbrook Group and related plutons are considerably higher than those of typical tholeiitic magmas ($[La/Yb]_N$ = 1–2), and more within the range for calc-alkalic suites (e.g., Jakes and Gill 1970; Pearce and Peate 1995), although their middle to heavy REE patterns are flatter than those for calc-alkalic magmas, suggesting that they formed in shallower levels in the crust (e.g., Lesher *et al.* 1986), and are consistent with hornblende and zircon fractionation (e.g., Bea 1996).

The Th/Nb and Ti/V ratios for the lower and upper Coldbrook Group basalt and mafic pluton samples are typical for tholeiitic magmas with juvenile arc chemical characteristics (Shervais 2022). Although the upper Coldbrook Group basalts show similar Ti/V ratios as the lower Coldbrook Group basalt and mafic pluton samples, they generally have lower Th/Nb, which suggests that these younger mafic magmas are typical flood basalts with similar trace element contents as those of the Columbia River Group (Shervais 2022).

### Source for magmas

Continental flood basalts (CFB) such as the Columbia River basalt are generally interpreted to have been derived from mixing between upwelling asthenospheric mantle and a large-ion-lithophile-element (LILE)-enriched source (e.g., Wolff *et al.* 2008). The LILE-enriched source is thought to derive from the crust or subcontinental mantle and inherits the chemical characteristics of earlier subduction-related components (Hergt *et al.* 1991). Hence, the most crust-contaminated basalt magmas correspond to those that formed the earlier lower Coldbrook Group basalt, whereas the upper Coldbrook Group basalt and mafic plutons are the least contaminated with crustal melts, an interpretation supported by their higher εNd values.

The mafic samples from the Coldbrook Group and related mafic plutons have low Ti contents which characterizes them as low-Ti CFB generated at relatively shallow depths in the stability field of spinel lherzolite, either in sub-continental lithospheric mantle (SCLM) or in asthenosphere beneath thinned lithosphere (e.g., Tegner *et al.* 1998; Melluso *et al.* 2006; Shellnutt *et al.* 2014). Both models imply the presence of a mantle plume as is commonly linked to the origin of CFB like the Columbia River basalt (e.g., Camp 2013). Hence, we propose that the more crust-contaminated basalt of the lower Coldbrook Group was probably formed from partial melting of sub-continental lithosphere and arc crust, aided by the heat of mantle upwelling, whereas the upper Coldbrook Group basalt (and FTP rhyolite) and mafic plutons was derived from an N-MORB-like source, less contaminated by arc crust, beneath a thinned lithosphere. In the part of Avalonia represented by the Caledonian Highlands, deformation and strike-slip faulting during the Late Ediacaran may have resulted in the opening of a pull-apart caldera (e.g., Acocella *et al.* 2004; Holohan *et al.* 2008), focusing magmatism on thinned lithosphere, however, that process was possibly aided by the presence of a mantle plume, as proposed by Escribano *et al.* (2023) based on zircon chemistry. Other examples of pull-apart calderas occur in Sumatra with the well-known Toba volcano and in the Sierra Madre Occidental in western Mexico (e.g., Aribowo 2018; Aguirre-Díaz *et al.* 2021).

### Lithospheric contamination and calc-alkalic signatures

The generally low Ga/Al ratios of the felsic samples of the Coldbrook Group and related plutons, compared to typical within-plate granite, suggest that they formed from lower temperature liquids (<900°C) derived via partial melting within the subcontinental lithospheric mantle or crust (Pankhurst *et al.* 2011). This interpretation implies that the higher Ga/Al ratios of the FTP rhyolite are a result of less contaminated-higher temperature melts. Zircon chemical data also suggest that the contrasting chemical differences between zircon in samples from the Silver Hill rhyolite, lower Coldbrook Group rhyolite, and felsic domes compared to zircon from the FTP rhyolite reflect higher degrees of crustal assimilation involved in the genesis of the older ca. 551.5 Ma melts, compared to the younger 549.2 Ma rhyolite melt (Escribano *et al.* 2023).

In addition, Nd (this study) and Hf (Pollock *et al.* 2022) isotopic data indicate that samples from the Coldbrook and Broad River groups represent mixing of juvenile magma and isotopically evolved crust at ca. 550 Ma. Pollock *et al.* (2022) further suggested that the vertical trend of εHf data from ca. 550 Ma sampls is best explained by crustal thickening and recycling of a greater proportion (25%–30%) of an evolved Tonian crustal component. This interpretation supports the suggestion that the lower εNd values exhibited by samples from the lower Coldbrook Group reflect a larger crustal component compared to samples from the upper Coldbrook Group and related plutons.

### Chemical differences among felsic products of the 551.5 Ma magmas

Overlapping TIMS U–Pb dates indicate that the lower Coldbrook Group, felsic plutons and domes, Silver Hill area rhyolite, and probably the Vernon Mountain and Blackall Lake rhyolites were contemporaneous and probably derived from a common source. However, they have subtle chemical differences in their high field strength element (HFSE) and REE contents. The high HFSE and other trace element contents of the Blackall Lake and Vernon Mountain rhyolites suggest that those units are closely related to the andesitic to dacitic tuffs of the lower Coldbrook Group and felsic domes. In contrast, the Silver Hill rhyolite has lower HFSE contents than the Vernon Mountain and Blackall Lake rhyolites, lower Coldbrook Group, and felsic dome samples. This difference may be explained by the dripping of solid-liquid mixtures containing hornblende and zircon from the roof of the chamber to the mush below which would gradually lower the HFSE and middle and high REE contents of the overlying melts, represented by the Silver Hill rhyolite.

This mechanism of melt extraction and solid-liquid dripping can also explain the lower HFSE and middle and high REE contents of the felsic plutons compared to the felsic domes, lower Coldbrook Group, and Vernon Mountain and Blackall Lake rhyolite samples, which probably represent the lower mush (e.g., Bachmann and Bergantz 2004) from which the evolved melt was extracted.

## CONCLUSIONS

The Coldbrook Group and related plutons formed from tholeiitic magmas that originated in an extensional within-plate setting in a region of older continental arc rocks. The basaltic magmas have chemical characteristics of low-Ti continental flood basalts. The more lithosphere-contaminated lower Coldbrook Group magmas were probably derived from older arc lithosphere partially melted by the heat of upwelling mantle. In this model, the melts derived from recycled continental arc lithosphere were of intermediate compositions with arc signatures.

The more evolved Vernon Mountain, Blackall Lake, and Silver Hill area rhyolites represent fractionated melts derived from the lower Coldbrook Group and felsic domes and plutons. The lower HFSE and middle to heavy REE contents of the Silver Hill rhyolite and felsic pluton samples may reflect melt extraction and solid-liquid dripping from the upper part of the magma chamber. Enhanced extension and thinning of the crust, were marked by a change from intermediate to bimodal compositions derived from an N-MORB source, less contaminated with arc lithosphere, that form the youngest basalt and FTP rhyolite of the uppermost Coldbrook Group.

The new data in this study, combined with precise dates reported by Escribano *et al.* (2023), have significantly changed previous ideas of the late Ediacaran magmatic event(s) in the Caledonia terrane and contribute new insights about magmatism during extension in Avalonia.

## ACKNOWLEDGEMENTS

This paper is based in the M.Sc. project of A.P. Escribano. We are grateful to Susan Johnson and Rob Richard of the Geological Surveys Branch (Sussex office) for their help with sample collection when we were unable to travel to New Brunswick due to COVID-19 restrictions in the summer of 2020. Rob Richard also helped in database and map assembly. We thank Chris White for his contributions to mapping of the Caledonia terrane and Adrian Park for his structural insights in the study area. We thank Nelson Eby for giving permission for us to use his trace element analyses of some samples from the Coldbrook Group and Bonnell Brook pluton. We also acknowledge Sherri Strong of Memorial University's CREAIT Network for providing Sm–Nd isotopic data. We are grateful to journal reviewers Susan Johnson and Andrea Mills for their helpful comments which led to significant improvements in the manuscript. This work was funded by a research agreement between the Geological Surveys Branch of the New Brunswick Department of Energy and Resource Development and Acadia University, Discovery Grant 2016-04860 from the Natural Sciences and Engineering Research Council of Canada to S.M. Barr, and Acadia University graduate awards to A.P. Escribano.

## URL LINK TO SUPPLEMENTARY DATA

Supplementary Data Table S1: Whole-rock chemical data from the Coldbrook Group and related plutons.
https://journals.lib.unb.ca/index.php/ag/article/view/ 33598/1882529556

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*Editorial responsibility: David P. West, Jr.*

**APPENDIX**

Supplementary data Table S1 is also in open access here:
https://doi.org/10.25545/XUGV9X