A Late Neoproterozoic age for the Caledonia Mountain Pluton, a high Ti-V layered gabbro in the Caledonia (Avalon) terrane, southern New Brunswick

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Gabbro from the Caledonia Mountain Pluton in the northeastern Caledonian Highlands of southern New Brunswick yielded a U-Pb (zircon) crystallization age of 615 ± 1 Ma. The age shows that the Caledonia Mountain Pluton is co-genetic with its host metavolcanic rocks, significantly older than the Mechanic Settlement Pluton, and probably unrelated to the Lower Coverdale ferrogabbro complex. The chemical characteristics of the pluton are consistent with those of mafic volcanic rocks in the arc-generated Broad River Group, with which the pluton is likely to be co-magmatic. However, the chemical compositions of the gabbroic samples show strong evidence for modification by processes of crystal fractionation and accumulation, and most are unlikely to reflect magmatic compositions. The epsilon Nd value of +3.7 indicates that, like other igneous rocks in the Caledonia terrane, the magma that formed the Caledonia Mountain Pluton was not derived directly from depleted mantle, but had a component of older crust involved in its petrogenesis, either directly in the source area or by subsequent interaction with crustal materials. Elevated values of Ti, Fe, V, and P in the gabbro suggest that potential may exist for economic deposits, either in the Caledonia Mountain Pluton or other similar bodies in the Caledonian Highlands.

On a situé la cristallisation du gabbro du pluton du mont Caledonia dans le nord-est des collines calédoniennes du Sud du Nouveau-Brunswick à 615 ± 1 Ma par datation au U-Pb (à partir de zircon). Cet âge révèle que le pluton du mont Caledonia est cogénétique avec ses roches métavolcaniques hôtes, qui sont infiniment plus âgées que le pluton de Mechanic Settlement et qui ne sont probablement pas apparentées au complexe de ferrogabbro de Lower Coverdale. Les caractéristiques chimiques du pluton correspondent à celles des roches volcanomafiques du groupe formé par un arc de la rivière Broad, avec lequel le pluton est vraisemblablement comagmatique. Les compositions chimiques des échantillons gabbroïques affichent toutefois des signes marqués de modifications en vertu de processus de fractionnement et d'accumulation de cristaux, et la majorité ne devraient pas présenter de compositions magmatiques. La valeur de +3,7 epsilon Nd révèle qu'à l'instar des autres roches ignées du terrane de Caledonia, le magma qui a formé le pluton du mont Caledonia ne provenait pas directement du manteau épuisé, mais qu'une partie de l'écorce plus âgée a été mêlée à sa pétrogenèse, soit directement dans le secteur d'origine ou par interaction subséquente avec le matériel crustal. Les valeurs élevées de Ti, de Fe, de V et de P dans le gabbro permettent de supposer qu'il pourrait exister un potentiel de gîtes rentables, soit dans le pluton du mont Caledonia, soit dans des massifs analogues à l'intérieur des collines calédoniennes.

Traduit par la rédaction

INTRODUCTION

The Caledonia Mountain Pluton is a small (ca. 4 km^2) gabbroic body located in the northeastern Caledonian Highlands of southern New Brunswick (Figs. 1, 2). Ruitenberg *et al.* (1979) named the pluton and assumed an age of Mississippian or older, the same age as was assumed for other gabbroic plutons that are rare components of the Caledonian Highlands. A detailed petrological study of the Caledonia Mountain Pluton was done by Blackwood (1991), as a follow-up study to a mineral exploration programme in the area (Blackwood and Cormier 1990). He referred to the pluton as the Weldon Creek stock, described its locally layered composition, and documented its high Ti, P, and V contents. Barr and White (1999) briefly described the pluton, and assumed an age of ca. 550 Ma, based on the age of the Mechanic Settlement Pluton, a larger gabbroic pluton located in the Caledonian Highlands 40 km southwest of the Caledonian Mountain Pluton (Fig. 1). The Mechanic Settlement Pluton has a U-Pb (zircon) age of 557 ± 3 Ma and $^{40}Ar/^{39}Ar$ cooling ages on hornblende and phlogopite of ca. 550 and 539 Ma, respectively (Grammatikopoulos *et al.* 1995).

The purpose of this paper is to present a new U-Pb age for the Caledonia Mountain Pluton, and to draw attention to its unusual chemical characteristics. The work was undertaken mainly to investigate the possibility that the pluton is related to the Lower Coverdale ferrogabbro complex encountered in

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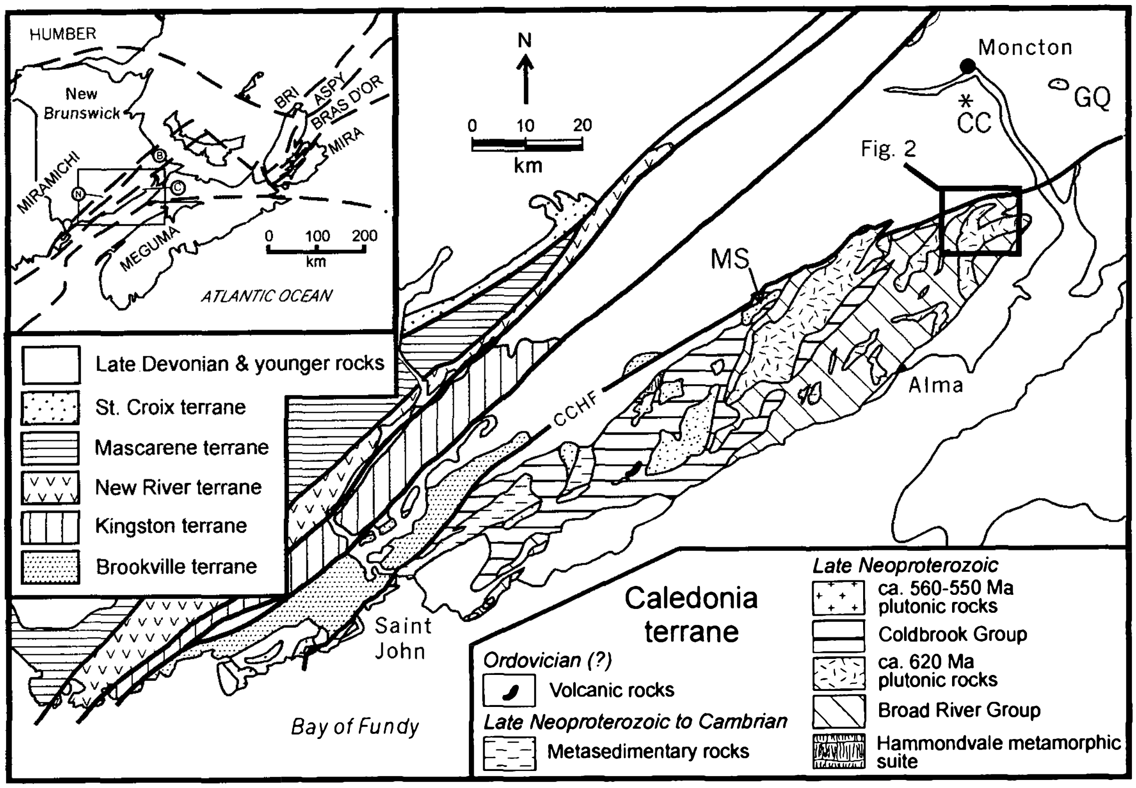

Fig. 1. Simplified geological map of the Caledonia Highlands (after Barr and White 1999), showing the location of the Caledonia Mountain Pluton and other units referred to in the text. CC, GQ, and MS indicate the locations of the Lower Coverdale ferrogabbro complex, the Gaytons quarry, and the Mechanic Settlement Pluton, respectively. CCCF is the Caledonia-Clover Hill fault. Inset map shows the location of the map area in southern New Brunswick in relation to terranes of Barr and White (1996b); BRI, Blair River inlier, C, Caledonia terrane, B, Brookville terrane, and N, New River terrane.

drill holes in a Carboniferous basin about 20 km north of Caledonia Mountain (Boyle and Stirling 1994; Woods 1995; Ascough 1997) (Fig. 1). Like the Caledonia Mountain Pluton, the Lower Coverdale ferrogabbro complex has been reported to contain high Ti, P, and V contents, and a genetic relationship between the two intrusions would have important implications for the history of the relationship between the Caledonia terrane, which hosts the Caledonia Mountain Pluton, and the adjacent Brookville terrane, which hosts the Lower Coverdale ferrogabbro complex (Fig. 1), as well as for the economic potential of the area.

GEOLOGICAL SETTING

Two suites of volcanic and sedimentary rocks underlie the Caledonian Highlands (Fig. 1). The ca. 620 Ma Broad River Group forms most of the eastern part of the highlands and consists mainly of intermediate to felsic tuffaceous rocks, together with less abundant mafic tuff, mafic to felsic flows, tuffaceous sedimentary rocks, and arkosic sandstone and conglomerate (Barr and White 1999). A varied suite of comagmatic ca. 620 Ma plutonic rocks of dominantly dioritic, granodioritic, and granitic compositions intrudes the Broad River Group. The volcanic and plutonic rocks have been deformed and metamorphosed to greenschist facies, and also show effects of widespread ductile deformation. They are unconformably overlain by, and in places in faulted contact with, younger (ca. 560–550 Ma) and generally less deformed and unmetamorphosed volcanic and sedimentary rocks of the Coldbrook Group and related plutons that form most of the western part of the highlands (Fig. 1). The Coldbrook Group includes intermediate to felsic tuff, dacitic to rhyolitic flows and plugs, tuffaceous conglomerate, laminated tuffaceous siltstone, basaltic and rhyolitic flows, and coarse clastic sedimentary rocks (Barr *et al.* 1994; Barr and White 1999). Comagmatic plutonic rocks are mainly syenogranite with less abundant diorite and gabbro. The largest gabbroic pluton is the Mechanic Settlement Pluton (Fig. 1), a layered peridotite/dunite/gabbro/diorite body that hosts platinum-group element (PGE) mineralization (Paktunc 1988; Grammatikopoulos *et al.* 1995).

Based on petrological characteristics, the Broad River Group and associated plutons are interpreted to have formed in a continental margin subduction zone, whereas the Coldbrook Group and associated plutons apparently formed during later extension within that continental margin (Barr and White 1996a, 1999). These rock units, together with latest Neoproterozoic and Cambrian sedimentary rocks and minor younger volcanic rocks that locally overlie the older rocks in the southwestern part of the highlands, constitute the Caledonia terrane (Barr and White 1989). The Caledonia terrane is a typical part of the extensive Avalon terrane of the northern Appalachian orogen (Williams 1979).

The Caledonia-Clover Hill fault separates the Caledonia

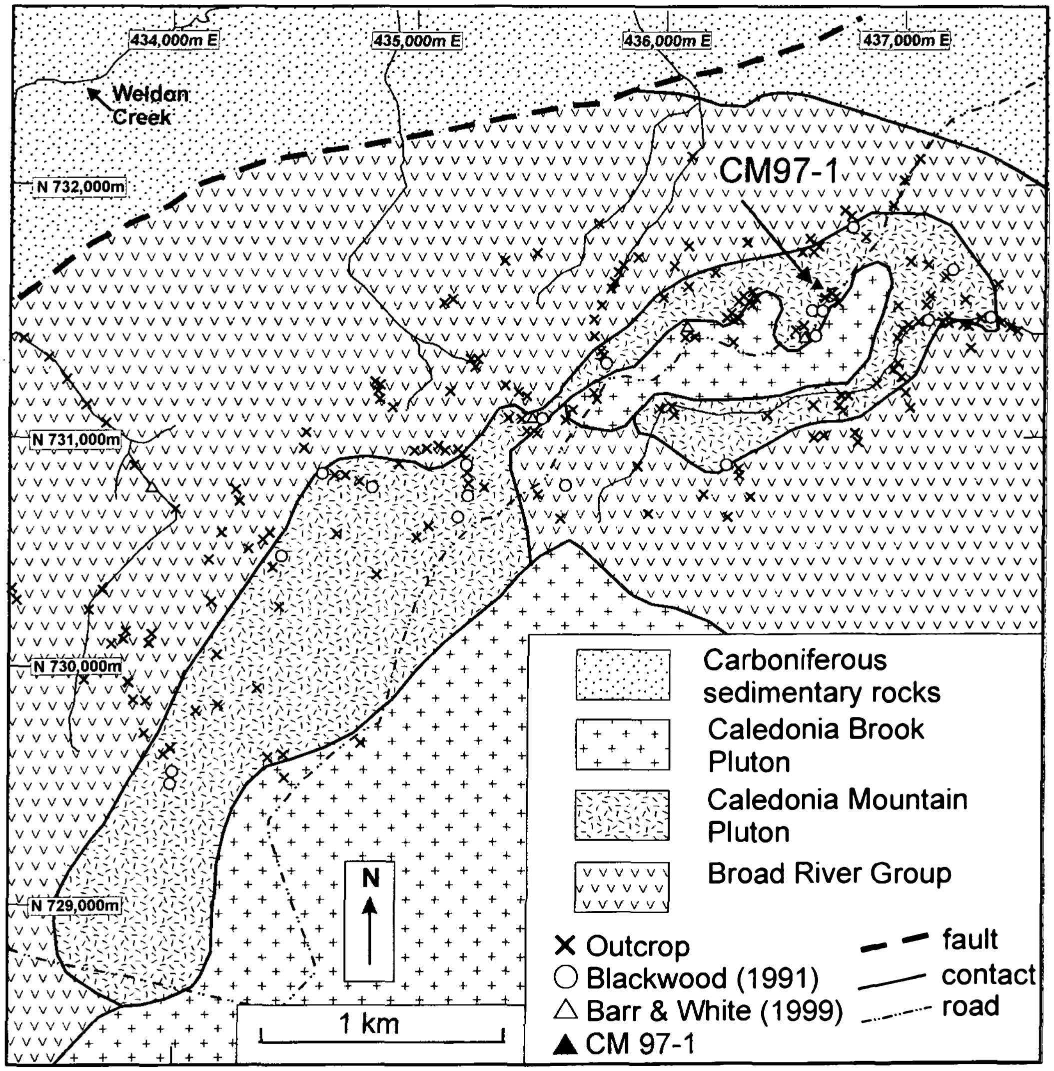

Fig. 2. Geological map of the Caledonia Mountain Pluton and surrounding area showing sample locations from Blackwood (1991) and Barr and White (1999). Outcrops (x) were compiled from Blackwood and Cormier (1990) and Barr and White (1993). Locations of analyzed samples of Blackwood (1991) were inferred from data in Blackwood and Cormier (1990) and Blackwood (1991). CM97-1 is the dated sample.

terrane from the Brookville terrane to the northwest (Fig. 1). The Brookville terrane, like the Avalon terrane, is generally considered peri-Gondwanan. However, its distinct stratigraphy and tectonothermal history, as well as isotopic characteristics, show that, in contrast to the Caledonia terrane, it is not part of the Avalon terrane *sensu stricto* (White and Barr 1996; Barr and White 1996b; van Staal *et al.* 1998; Samson *et al.* 2000).

Field Relations

The Caledonia Mountain Pluton and surrounding area were mapped in detail as part of an exploration programme to evaluate the potential of the pluton for Ni and PGE mineralization (Blackwood and Cormier 1990). It was mapped in less detail by Ruitenberg *et al.* (1978) and Barr and White (1993, 1999). Outcrop in the area is limited, and hence the extent of the pluton is speculative in some places, and based in part on the shape of an apparently associated aeromagnetic anomaly (Geological Survey of Canada 1958). The host rocks are mainly varied fine-grained crystal tuff and laminated sedimentary rocks typical of the Lumsden unit of the Broad River Group (Barr and White 1999). Examination of samples of the host rocks in thin section reveals that they contain a mineral assemblage typical of greenschist facies, including actinolite, epidote, muscovite, and minor amounts of biotite, and display faint to weak foliation. Contact metamorphic effects from the gabbro are not widely apparent, and it is likely that later regional deformation and metamorphism may have overprinted the original contact metamorphic aureole. However, dark hornfels occurs locally where the gabbro intruded pelitic rocks. Locally dykes and small bodies of gabbro probably related to the Caledonia Mountain Pluton are present in the country rocks.

On its southern margin, the Caledonia Mountain Pluton is in contact with granodioritic rocks of the Caledonia Brook Pluton. Blackwood (1991) reported that the Caledonia Brook Pluton grades from monzogranite to tonalite near its margins, possibly as a result of interaction with the adjacent gabbro. He also reported that a large lobe of granodioritic to tonalitic rocks similar to those of the Caledonia Brook Pluton occurs in the eastern part of the gabbro body and truncates layering in the gabbro, and that dykes of similar granodiorite occur locally in the gabbro. On the other hand, Barr and White (1999) interpreted gabbroic dykes that they observed in the Caledonia Brook Pluton to indicate that it is older than the Caledonia Mountain Pluton, although Blackwood (1991) reported that similar gabbroic dykes also occur in the Caledonia Mountain Pluton itself. In either case, the close spatial relationship between the Caledonia Mountain and Caledonia Brook plutons suggests that they are of similar age.

GEOCHRONOLOGY

Analytical methods

Isotope dilution U-Pb analytical work was carried out at the Geological Survey of Canada in Ottawa. Sample preparation and analytical methods used in this study broadly follow previously described procedures (Hamilton *et al.* 1998; Parrish *et al.* 1987); data reduction and propagation of analytical errors follow the methods of Roddick (1987). Concordia diagram error ellipses are shown at the 2σ (95% confidence) level of uncertainty. Linear regression of the data array made use of method modified from York (1969). Attempts were made at all times to use only the best quality hand-picked grains of zircon. All zircons were air-abraded prior to dissolution and chemistry in order to reduce surface-correlated Pb-loss and generally improve concordancy, following the methods of Krogh (1982).

Description and Results

The dated sample is an inequigranular coarse-grained gabbro with about 60% plagioclase grains and interstitial pyroxene, amphibole, and magnetite. Zircon grains recovered from the sample were separated into distinct euhedral morphological groups: equant, well-faceted stubby prisms (A), sharply terminated elongate prisms and needles (B), short faceted prisms (C), and a very small population of flat prisms. All grains were colourless, clear, and contained very few inclusions; no grains with visible cores or overgrowths were included. U-Pb data from populations A, B, and C, comprising approximately 30–45 grains each, show a small amount of dispersion below concordia, being 0.5%–1.6% discordant (Table 1; Fig. 3). With the exception of fraction A2, however, the fractions are effectively co-linear. Analysis of one multi-grain fraction of the flat zircon morphology yielded an imprecise result due to elevated common Pb and is not shown here. Linear regression of the data for A1, B, C1, and C2, assuming a lower intercept of zero, yields an upper intercept age of 614.6 ± 0.9 Ma, with an MSWD of 0.8 (Fig. 3). Data for fraction A2, which has a slightly older $^{207}Pb/^{206}Pb$ age and falls slightly to the right of the best-fit line, is interpreted to result from a combination of minor inheritance and Pb-loss. Thus, an upper intercept age of 615 ± 1 Ma is considered to represent the best estimate for the crystallization age of the gabbro.

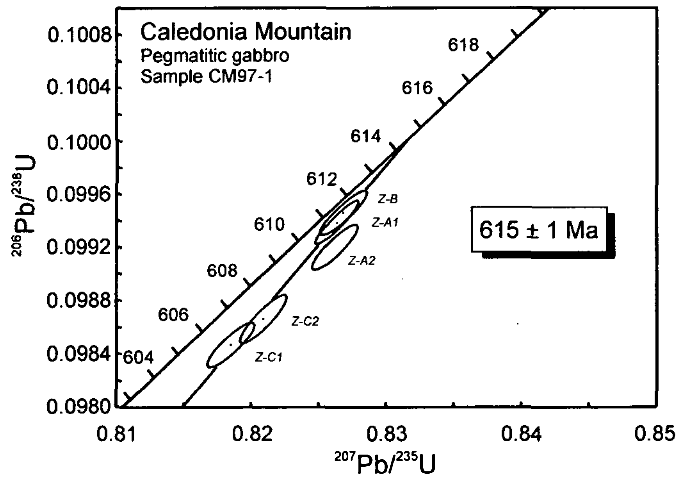

Fig. 3. U-Pb concordia diagram for zircon fractions from the Caledonia Mountain gabbro (sample CM97-1). Shaded ellipse (fraction A2) is excluded from the age regression. Data are from Table 1.

PETROLOGY

Blackwood (1991) reported the results of petrographic work, some mineral chemistry, and whole-rock chemical analyses using a suite of samples collected from the pluton (Fig. 2). Additional reconnaissance-level investigations were reported by Barr and White (1999). The pluton is composed mainly of gabbro, in places with light and dark layers resulting from varying relative abundance of felsic and mafic minerals. According to Blackwood (1991), the layering trends approximately east to east-northeast, parallel to the length of the pluton, and dips steeply (68 to 88°) to the northwest. Hence both the pluton and its internal layering are approximately concordant with layering in the host rocks (Blackwood 1991; Barr and White 1993).

The gabbro consists mainly of medium- to coarse-grained plagioclase (andesine to labradorite), clinopyroxene (ferroaugite), and opaque minerals in intergranular to subophitic and rarely ophitic texture. Plagioclase is partly altered to saussurite and sericite, and pyroxene is variably altered to pale brown and pale green actinolitic amphibole, chlorite, and epidote. Minor interstitial quartz is present, mainly in the most altered samples. Previously, both gabbro and diorite have been reported in the pluton, and it has been suggested that gabbro grades to diorite toward the margins (Ruitenberg *et al.* 1979; Blackwood 1991). However, based on observations during the present study, the dioritic-looking rocks are those in which pyroxene has been mainly or completely altered to amphibole, and all the rocks were originally gabbro with no evidence for primary igneous amphibole. Opaque minerals are anhedral and interstitial to plagioclase and pyroxene. According to Blackwood (1991), the opaque minerals are mainly ilmenite and magnetite, with minor sulphide minerals (dominantly pyrite).

Chemical data from the pluton include 20 analyses from Blackwood (1991), four analyses from Barr and White (1999), and a new analysis of the dated sample CM97-1 (Table 2). Some of the chemical features are illustrated on silica

Table 1. U-Pb analytical data

Fraction			Concentrations			Atomic Ratios (± 1σ, %)[6]					Ages (± 2σ, Ma)		
Description[1]	# grains	Wt.[2] cg	U[2] ppm	Pb*[2] ppm	Pb[3] pg	$^{206}Pb/^{204}Pb$[4]	$^{208}Pb/^{206}Pb$[5]	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
CM97-1 (z5550) Pegmatitic gabbro, Caledonia Mountain													
A1 NM5°,eu, clr, co,eq-sp, 1-2:1	45	37	175	19	4	10225	0.2141	0.09939 ± 0.08%	0.8264 ± 0.10%	0.06030 ± 0.04%	610.8 ± 1.0	611.6 ± 1.5	614.4 ± 1.5
A2 NM5°,eu, clr, co,eq-sp, 1-2:1	45	35	148	16	5	6048	0.2144	0.09920 ± 0.09%	0.8262 ± 0.10%	0.06040 ± 0.05%	609.7 ± 1.0	611.5 ± 0.9	618.1 ± 2.0
B NM5°,eu, clr, co, needles	32	47	283	32	19	4333	0.2432	0.09946 ± 0.08%	0.8269 ± 0.11%	0.06029 ± 0.05%	611.2 ± 1.0	611.9 ± 1.0	614.1 ± 2.0
C1 NM5°,eu, clr, co,sp, 2:1	45	51	169	19	15	3541	0.2287	0.09847 ± 0.08%	0.8185 ± 0.11%	0.06028 ± 0.05%	605.4 ± 1.0	607.2 ± 1.0	613.8 ± 2.3
C2 NM5°,eu, clr, co,sp, 2:1	45	55	208	23	7	10218	0.2219	0.09866 ± 0.09%	0.8209 ± 0.11%	0.06034 ± 0.05%	606.6 ± 1.1	608.5 ± 1.0	615.9 ± 2.1

Notes:

Errors in ratios are 1 std. error of mean in %; Age errors are 2 std. errors in Ma; Pb* = radiogenic Pb.

[1]Colour: co = colourless; clr = clear. Shape: eu = euhedral; eq = equant; sp = short prism; 1-2:1 = aspect ratio between 1:1 and 2:1. Magnetic properties: NM5° = nonmagnetic at 5 degrees side slope on Frantz™ magnetic separator at maximum current.

[2]Uncertainties in concentrations are estimated to be <10% for sample weights >10µg, >10% for sample weights <10µg. Uncertainties in sample weights estimated at ±1mg.

[3]Total common Pb in analysis, corrected for spike and fractionation.

[4]Measured ratio, corrected for spike and Pb fractionation of 0.09%/AMU.

[5]Radiogenic Pb.

[6]Corrected for blank and spike Pb and U, and for common Pb (Stacey-Kramers model Pb composition equivalent to the $^{207}Pb/^{206}Pb$ age).

Table 2. Chemical data from sample CM97-1.

SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni	V	Cr
42.59	1.71	18.53	15.02	0.17	4.93	11.55	1.93	0.82	0.06	2.71	100.01	201	17	469	24	45	25	<2	8	23	88	48	20	573	16

Notes: Analyses by X-ray Fluorescence at the Regional Geochemical Centre, Saint Mary's University, Halifax, Nova Scotia.

Major elements and some trace elements were determined on fused glass disks and other trace elements were measured in pressed powder pellets (methodology as described by Slauenwhite 1999). Analytical error is generally less than 5% for major elements and 2-10% for trace elements. $Fe_2O_3^t$ is total Fe as Fe_2O_3. LOI is loss on ignition at 1000°C.

variation diagrams (Fig. 4). The analyzed samples range in SiO_2 content from about 40 to 53%, but most contain about 45% or less. They are characterized by high contents of TiO_2 (up to 3%), $Fe_2O_3^t$ (up to about 20%), and V (up to 900 ppm), reflected in abundant modal ilmenite and magnetite. Al_2O_3 content shows wide variation from less than 10% to more than 20% (Fig. 4b), correlated with variation in plagioclase content as a result of fractionation and accumulation (Blackwood 1991). P_2O_5 contents are less than 0.4% except in 3 samples in which they approach 1% (Fig. 4d). Two of the three high P_2O_5 samples are from the present study, and contain relatively abundant modal apatite. Ni, Cr, and Cu contents show variation but values are generally low (Fig. 4f, g, h).

Sm-Nd Isotopic Data

Sm and Nd isotopic data from igneous rocks can provide information about the source area, and hence are a valuable tool for comparing rock units. Hence the dated sample, CM97-1, from the Caledonia Mountain Pluton was analyzed for Sm and Nd isotopes (Table 3) at Syracuse University using the methods described by Samson *et al.* (2000) and Samson *et al.* (1995). Additional information about the analyses is given with the results in Table 3.

The epsilon Nd value calculated at 615 Ma is +3.7, significantly lower than the approximate depleted mantle value at that time (ca. +6; DePaolo 1981). The lower value indicates that the magma that formed the Caledonia Mountain Pluton was not derived directly from depleted mantle, but had a significant component of older crust involved in its petrogenesis, either directly in the source area or by subsequent interaction with crustal materials. Because of the relatively high $^{147}Sm/^{144}Nd$ ratio (>0.15), it is not possible to calculate a meaningful model age for the sample.

Comparison with Other Igneous Rocks of the Caledonian Highlands

The age obtained for the Caledonia Mountain Pluton is similar to ages of 600 – 625 Ma obtained from the Broad River Group and associated plutons (Bevier and Barr 1990; Barr *et al.* 1994). Compared to analyzed samples from those units, shown as fields on Fig. 4, most samples from the Caledonia Mountain Pluton have lower SiO_2 but higher TiO_2, $Fe_2O_3^t$, and V contents. Al_2O_3 contents are more varied (Fig. 4b), and Ni, Cr, and Cu contents tend to be lower (Fig. 4f, g, h). The enhanced V, and to a lesser extent TiO_2, contents compared to those in volcanic rocks of the Broad River Group and associated plutons are illustrated on Fig. 5a. Increased TiO_2 content relative to Zr and Y contents results in most samples plotting outside fields for normal mafic igneous rocks on the Ti-Zr-Y ternary diagram (Fig. 5b), consistent with the fact that the CaO + MgO contents in many samples exceeds the value of 20% characteristic of the normal basaltic rocks on the basis of which this discrimination diagram was constructed (Pearce and Cann 1973). FeO^t/MgO ratios are similar to those in many volcanic samples from the Broad River Group, but TiO_2 content extends to higher values and the rocks appear more tholeiitic, whereas the Broad River Group is more calc-alkalic based on its limited increase in TiO_2 with increasing FeO^t/MgO ratio (Fig. 4c).

The chemical variability combined with textural features such as the occurrence of melanocratic and leucocratic layering (Blackwood 1991) suggests that many of the analyzed samples represent crystal cumulates, rather than magma compositions. However, trends on the diagrams suggest that they may have been derived from magmas similar to those that formed volcanic rocks of the Broad River Group and associated plutons in a volcanic arc setting. This interpretation is supported by the Sm-Nd isotopic data; the epsilon Nd value of +3.7 is within the range of values (-0.4 to +4.6) previously reported for these rocks (Whalen *et al.* 1994; Samson *et al.* 2000).

Because of their gabbroic compositions, Barr and White (1999) assumed that the Caledonia Mountain Pluton was part of the ca. 560–550 Ma plutonic suite of the Caledonia Highlands, such as the Mechanic Settlement Pluton. The difference in age revealed by the present study provides an explanation for the apparent petrological differences between the two gabbroic bodies, in particular the more tholeiitic composition of the Mechanic Settlement Pluton and the presence of Ni and PGE mineralization (Paktunc 1988; Grammatikopoulos *et al.* 1995). In contrast, the Caledonia Mountain Pluton appears to lack potential for PGE, based on the assessment of Blackwood (1991), but may have greater potential for Ti-V-P mineralization.

Comparison with the Lower Coverdale Ferrogabbro Complex

The Lower Coverdale ferrogabbro complex is not exposed at the surface, and has been sampled only from drill core (Boyle and Stirling 1994; Woods 1995, Ascough 1997). Although reported to intrude Precambrian metavolcanic and metasedimentary rocks of the Caledonia Highlands (Boyle and Stirling 1994), the complex is located 20 km north of the exposed area of the highlands (Fig. 1) and is underlain by rocks of the Brookville terrane (Nickerson 1994; White and Barr 1996). Detailed descriptions have not been published but the complex has been reported to have an aerial extent of 30 km^2 based on an aeromagnetic anomaly (Boyle and Stirling 1994).

A petrological study of the Lower Coverdale ferrogabbro complex has not been published, but it appears to contain a large component of anorthositic rocks (Boyle and Stirling 1994; Woods 1995; Ascough 1997) that are not present in the Caledonia Mountain Pluton, at least not at the present level of exposure. Also, granitic rocks which appear to be part of the complex and previously described as charnockitic (Boyle and Stirling 1994) have yielded a U-Pb (zircon) age of ca. 390 Ma (M. Hamilton, unpublished data). Similar granitic rocks of the same age (ca. 390 Ma; M. Hamilton, unpublished data) are exposed in the Gaytons quarry, east of Lower Coverdale (Fig. 1). Hence, the Lower Coverdale ferrogabbro complex appears to be a Devonian intrusive complex and unrelated to the Caledonia Mountain gabbro.

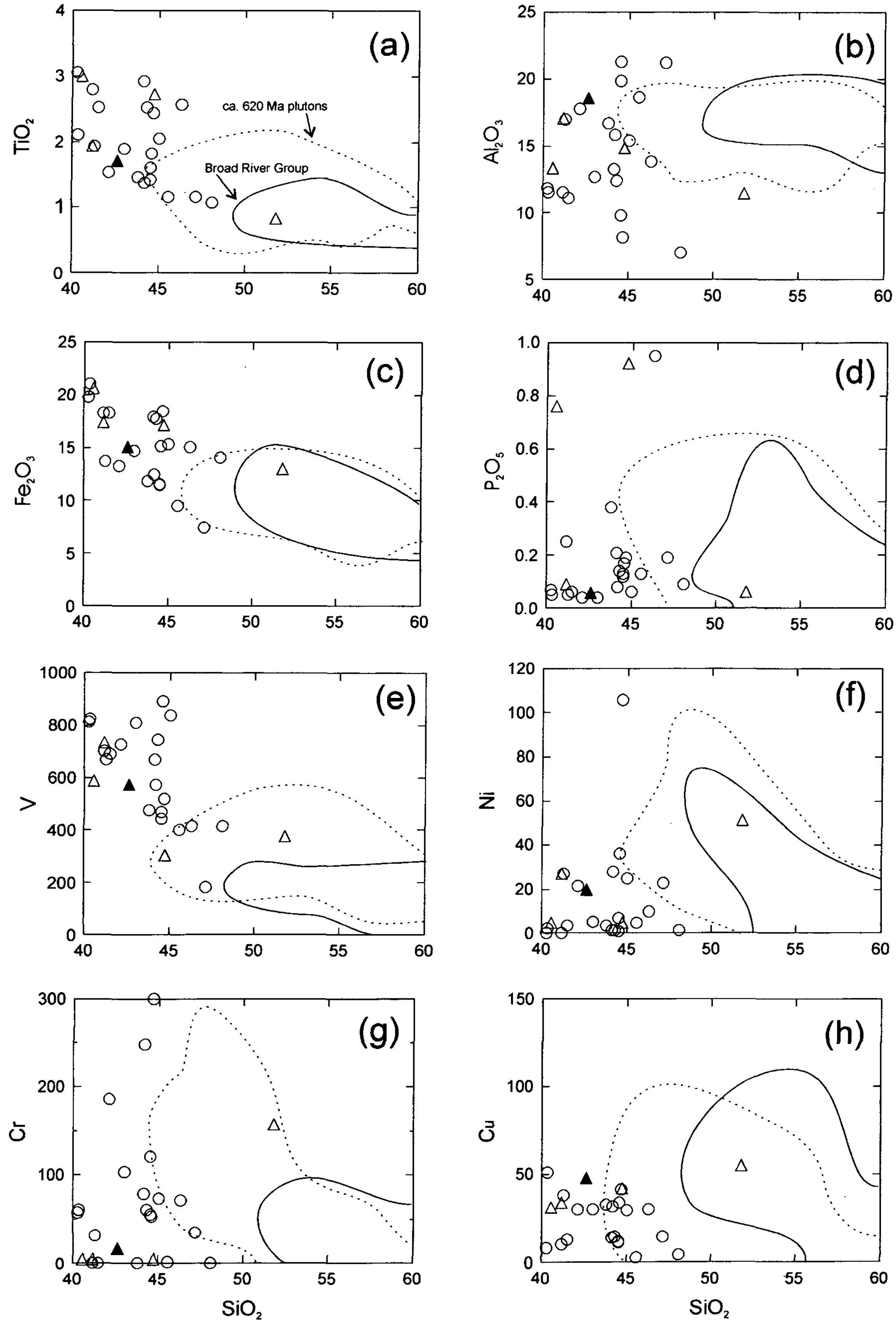

Fig. 4. Selected silica variation diagrams to illustrate chemical characteristics of the Caledonia Mountain Pluton. Circles are data from Blackwood (1991), open triangles are data from Barr and White (1999), and black triangle is dated sample CM97-1 (data in Table 2). Solid line field encloses data from volcanic rocks with less than 60% SiO_2 in the ca. 600-625 Ma Broad River Group (n = 59), and dashed line field encloses data from associated ca. 615-620 Ma plutons with less than 60% SiO_2 (n = 21) derived from data in Barr and White (1999).

Table 3. Sm-Nd isotopic data

Age	615 Ma
Sm	1.42 ppm
Nd	5.56 ppm
$^{143}Nd/^{144}Nd^1$	0.512657(5)^2
$^{147}Sm/^{144}Nd$	0.154681
$\varepsilon Nd_{(T)}{}^3$	3.17

Notes:
[1] $^{143}Nd/^{144}Nd$ is measured ratio.
[2] Uncertainty is given as the "in run" error (two standard deviations of the mean) and refers to the least significant digit.
[3] $\varepsilon Nd_{(T)}$ is the initial value, calculated with respect to Bulk Earth using present-day Bulk Earth parameters of $^{143}Nd/^{144}Nd$ = 0.512638 and $^{147}Sm/^{144}Nd$ = 0.1966 (following Samson *et al.* 2000).

However, like the Lower Coverdale ferrogabbro complex, the Caledonia Mountain Pluton may have potential for economic Ti-P-V deposits. Although the highest values of TiO_2, P_2O_5, and V in samples from the Caledonia Mountain gabbro do not reach those reported from the Lower Coverdale ferrogabbro complex, from which analyses of up to 33% TiO_2, 12 % P_2O_5, and 1500 ppm V have been reported from assays of drill core (Woods 1995; Ascough 1997), no equivalent drilling has been done on the Caledonia Mountain Pluton to investigate its composition at depth.

CONCLUSIONS

The U-Pb age and petrographic and chemical characteristics reported here indicate that the Caledonia Mountain Pluton is not related to either the Mechanic Settlement Pluton or to the Lower Coverdale ferrogabbro complex. Instead, they indicate that the pluton is related to the major arc-related magmatic event that generated the widespread Broad River Group and related plutons in the Caledonia terrane. Hence, although direct parallels cannot be made to gabbroic plutons with known PGE and Ti-P-V occurrences, the elevated values of the latter elements in the Caledonia Mountain gabbro suggests that potential may exist for such mineralization in either the Caledonian Mountain Pluton or other similar bodies in the Caledonian Highlands.

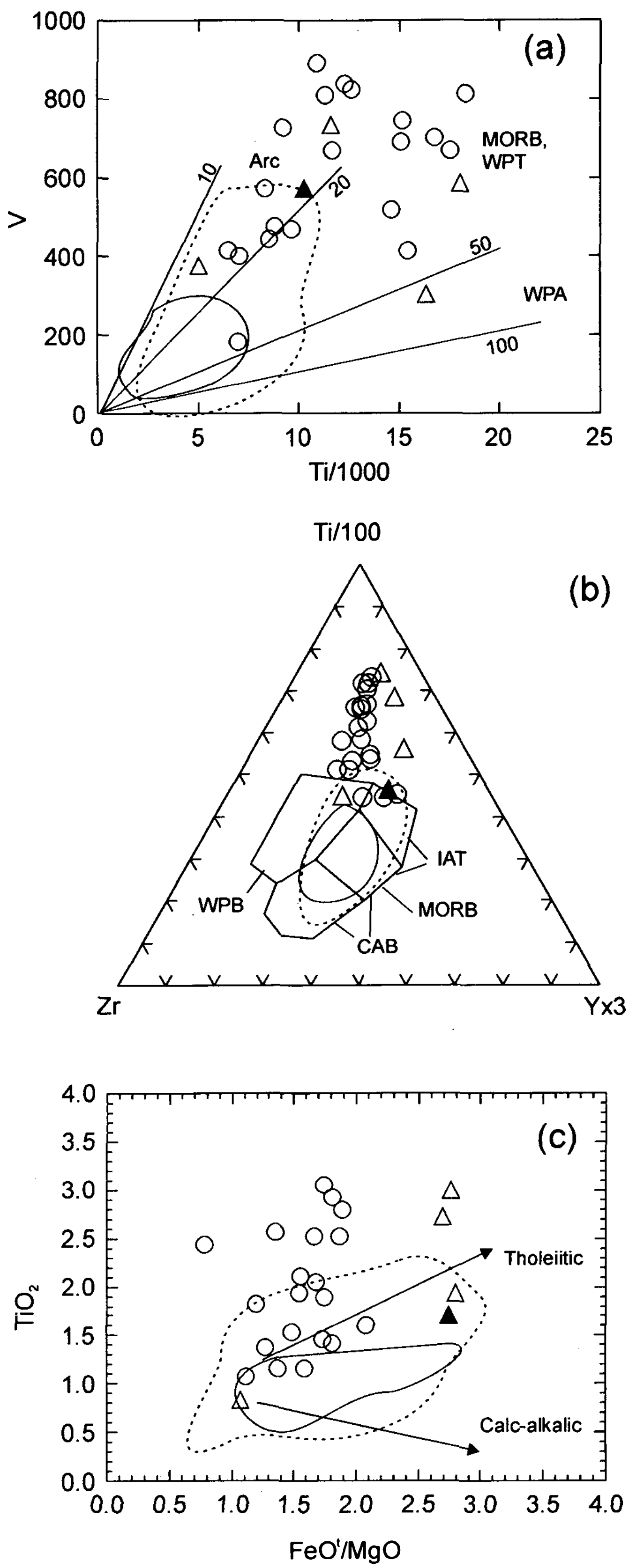

Fig. 5. Plots of (a) V-Ti, (b) Ti-Zr-Y, and (c) TiO_2 - FeO^t/MgO for data from the Caledonia Mountain gabbro with symbols and solid and dashed line fields as in Fig. 4. Labeled fields in (a) and (b) and trends in (c) are from Shervais (1982), Pearce and Cann (1973), and Miyashiro (1974), respectively. Abbreviations: MORB, mid-ocean ridge basalt; WPT, within-plate tholeiitic basalt; WPA, within-plate alkalic basalt; IAT, island-arc tholeiite; CAB, calc-alkalic basalt; WPB, within-plate basalt.

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REFERENCES

ASCOUGH, G. 1997. Assessment report on the Lower Coverdale property consisting of airborne magnetometer survey and diamond drilling. Noranda Mining and Exploration Company Incorporated. New Brunswick Department of Natural Resources and Energy Assessment Report 474861.

BARR, S.M., & WHITE, C.E. 1989. Re-interpretation of Precambrian stratigraphy in southern New Brunswick. *In* Project Summaries for 1989 and Fourteenth Annual Review of Activities, Information Circular 89-2. *Edited by* S. A. Abbot. New Brunswick Department of Natural Resources and Energy, Mineral Resources Division, pp. 182–189.

BARR, S.M., & WHITE, C.E. 1993. Geological mapping of the eastern Caledonia Highlands, southern New Brunswick. Geological Survey of Canada Open File 2600, scale 1:50,000.

BARR, S.M., & WHITE, C.E. 1996a. Tectonic setting of Avalonian volcanic and plutonic rocks in the Caledonian Highlands, southern New Brunswick, Canada. Canadian Journal of Earth Sciences, 33, pp. 156–168.

BARR, S.M., & WHITE, C.E. 1996b. Contrasts in late Precambrian - early Paleozoic tectonothermal history between Avalon Composite Terrane *sensu stricto* and other peri-Gondwanan terranes in southern New Brunswick and Cape Breton Island, Canada. *In* Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson. Geological Society of America Special Paper 304, pp. 95–108.

BARR, S.M., & WHITE, C.E. 1999. Field relations, petrology, and structure of Neoproterozoic rocks in the Caledonian Highlands, southern New Brunswick, Canada. Geological Survey of Canada Bulletin 530, 101 p.

BARR, S.M., BEVIER, M.L., WHITE, C.E., & DOIG, R. 1994. Magmatic history of the Avalon terrane of southern New Brunswick, Canada, based on U-Pb (zircon) geochronology. Journal of Geology, 102, pp. 399–409.

BEVIER, M.L., & BARR, S.M. 1990. U-Pb age constraints on the stratigraphy and tectonic history of the Avalon terrane, New Brunswick, Canada. Journal of Geology, 98, pp. 53–63.

BLACKWOOD, G.M. 1991. Geochemistry, petrology, and economic potential of the Weldon Creek Stock, New Brunswick. Unpublished B.Sc. Honours thesis, Memorial University, 118 p.

BLACKWOOD, G., & CORMIER, C. 1990. Report of geology, prospecting and geochemistry, Claim Index #08-500, Weldon Creek Property, Falconbridge Exploration Limited, Albert County, New Brunswick, NTS 21H/15. New Brunswick Department of Natural Resources Assessment file 473988.

BOYLE, D.R., & STIRLING, J.A.R. 1994. Geochemistry, mineralogy, and possible origin of the Coverdale T-P-ferrogabbro complex, New Brunswick. *In* Abstracts - Nineteenth Annual Review of Activities. *Edited by* S. A. Abbot. Miscellaneous Report 14, New Brunswick Department of Natural Resources and Energy, Mineral Resources Division, p. 4.

DEPAOLO, D.J. 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature, 291, pp. 193–196.

GEOLOGICAL SURVEY OF CANADA, 1958. Magnetic survey, NTS 21H/15. Geophysics Paper 803, Geophysics Division, Geological Survey of Canada, Department of Mines and Technical Surveys.

GRAMMATIKOPOULOS, A.L., BARR, S.M., REYNOLDS, P.H., & DOIG, R. 1995. Petrology and age of the Mechanic Settlement Pluton, Avalon terrane, southern New Brunswick. Canadian Journal of Earth Sciences, 32, pp. 2147–2158.

HAMILTON, M.A., RYAN, A.B., EMSLIE, R.F., & ERMANOVICS, I.F. 1998. Identification of Paleoproterozoic anorthositic and monzonitic rocks in the vicinity of the Mesoproterozoic Nain Plutonic Suite, Labrador; U-Pb evidence. *In* Radiogenic age and isotopic studies: Report 11 1998-F, pp. 23–40.

KROGH, T.E. 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochimica et Cosmochimica Acta, 46, pp. 637–649.

MIYASHIRO, A. 1974. Volcanic rock series in island arcs and active continental margins. American Journal of Science, 274, pp. 321–355.

NICKERSON, W.A. 1994. Geophysical constraints on the stratigraphy, structure, and tectonic evolution of the Late Devonian/Carboniferous Moncton Subbasin, New Brunswick, Canada. Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 340 p.

PAKTUNC, A.D. 1988. Mafic - ultramafic rocks in New Brunswick and their Platinum-Group-Element Potentials. *In* Thirteenth Annual Review of Activities. *Edited by* S.A. Abbot. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Information Circular 88-2, pp. 152–155.

PARRISH, R.R., RODDICK, J.C., LOVERIDGE, W.D., & SULLIVAN, R.W. 1987. Uranium-lead analytical techniques at the geochronology laboratory, Geological Survey of Canada. *In* Radiogenic age and isotopic studies: Report 1, Geological Survey of Canada, Paper 87-2, pp. 3–7.

PEARCE, J.A., & CANN, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth and Planetary Science Letters, 28, pp. 459–469.

RODDICK, J.C. 1987. Generalized numerical error analysis with applications to geochronology and thermodynamics. Geochimica et Cosmochimica Acta, 51, pp. 2129–2135.

RUITENBERG, A.A., GILES, P.S., VENUGOPAL, D.V., BUTTIMER, S.M., MCCUTCHEON, S.R., & CHANDRA, J. 1979. Geology and mineral deposits, Caledonia area. New Brunswick Department of Natural Resources, Mineral Resources Branch, Memoir 1, 213 p.

SAMSON, S.D., HIBBARD, J.P., & WORTMAN, G.L. 1995. Nd isotopic evidence for juvenile crust in the Carolina terrane, southern Appalachians. Contributions to Mineralogy and Petrology, 121, pp.171–184.

SAMSON, S.D., BARR, S.M., & WHITE, C.E. 2000. Nd isotopic characteristics of terranes within the "Avalon Zone", southern New Brunswick. Canadian Journal of Earth Sciences, 37, pp. 1039–1052.

SHERVAIS, J.W. 1982. Ti-Zr plots and the petrogenesis of modern and ophiolite lavas. Earth and Planetary Science Letters, 59, pp. 101–118.

SLAUENWHITE, D. 1999. Regional Geochemical Centre. Website http:// www.stmarys.ca / academic / science / geology / geochemctr / brochure.html.

VAN STAAL, C.R., DEWEY, J.F., MACNIOCAILL, C., & MCKERROW, W.S. 1998. The Cambrian-Silurian tectonic evolution of the Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of lapetus. *In* Lyell: The Past is the Key to the Present. *Edited by* D.J. Blundell, and A.C. Scott. Geological Society of London Special Publication 5, pp. 199–242.

WHALEN, J.B., JENNER, G.A., CURRIE, K.L., BARR, S.M., LONGSTAFFE, F.J., & HEGNER, E. 1994. Geochemical and isotopic characteristics of granitoids of the Avalon Zone, southern New Brunswick: Possible evidence for repeated delamination events. Journal of Geology, 102, pp. 269–282.

WHITE, C.E., & BARR, S.M. 1996. Geology of the Brookville terrane, southern New Brunswick, Canada. *In* Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson, Geological Society of America, Special Paper 304, pp. 133–148.

WILLIAMS, H. 1979. The Appalachian orogen in Canada. Canadian Journal of Earth Sciences, 16, pp. 792–807.

WOODS, G. 1995. Report of work, Lower Coverdale property, Albert County, New Brunswick. Noranda Mining and Exploration Company Incorporated. New Brunswick Department of Natural Resources and Energy Assessment Report 474544.

YORK, D. 1969. Least squares fitting of a straight line with correlated errors. Earth and Planetary Science Letters, 5, pp. 320–324.

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