Field and Geochemical Evidence for Contemporaneous Mafic Magmatism and Iron Oxide-Copper-Gold (IOCG) Mineralization and Alteration along the Cobequid-Chedabucto Fault Zone

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Introduction

Carboniferous (ca. 340-315 Ma) alkalic-tholeiitic mafic magmatism associated with the development of the Maritimes Basin has been documented in several areas of Maritime Canada: central New Brunswick, on the Magdalen Islands in Quebec, and in Nova Scotia north of Windsor and on southern Cape Breton Island (Fig. 1). Undated gabbroic intrusions located along a relatively narrow, but extensive, segment of the Cobequid-Chedabucto Fault Zone (CCFZ) in Nova Scotia (Fig. 1) are suspected to be of similar age based on locally preserved intrusive contacts with Carboniferous strata that include the Windsor, Mabou and Cumberland groups (see O'Reilly, 2005; Naylor *et al.,* 2005a and b). A Carboniferous age for this magmatism might suggest an important role in the formation of the widespread iron oxide-Cu-Au±Ba±Co±Ni (IOCG)-style of mineralization and alteration that occurs along the CCFZ (O'Reilly, 2005; Kontak *et al.,* 2008; MacHattie and O'Reilly, 2009). Alternatively, a Jurassic age for magmatism in the CCFZ would also be consistent with intrusive relationships with Late Carboniferous strata and the proximity to voluminous Jurassic basalt sequences that underlie the Bay of Fundy.

In order to better understand the nature, origin and age of the gabbros and their potential relationship to IOCG-style mineralization occurring within the CCFZ, a petrological and geochemical (major, trace element, Nd isotope) study has been undertaken. Characterizing the geochemical signatures of the gabbros allows comparison to be made with known Carboniferous and Jurassic mafic magmatism in the region. This comparison supports a genetic relationship between the gabbros located within the CCFZ and regionally recognized ca. 340-310 Ma mafic magmatism within the Maritimes Basin. Thus, there is a strong possibility that the gabbros contributed heat and/or fluids involved in IOCG-style mineralization along the CCFZ, particularly as emplacement of both the magmas and the IOCG deposits appears to be fault controlled, and because at least some of the gabbros appear to have exsolved alkaline and Fe-rich magmatic/ hydrothermal fluids.

General Geology of the CCFZ in Central Nova Scotia

The CCFZ is the east-west boundary zone separating the Meguma and Avalon terranes of the northeastern Appalachians in Nova Scotia (Fig. 1). Radiometric age dates along the CCFZ record a protracted, ca. 370-310 Ma history of both high- and low-grade metamorphism, deformation and hydrothermal alteration (see Fig. 1 and 2 in MacHattie and O'Reilly, 2009, and references therein). Within the fault zone this time interval was also marked periodically by intense periods of magmatism and significant amounts of siliciclastic and chemical sedimentation. The latter includes the Horton, Windsor, Mabou and Cumberland groups which, along with their correlatives elsewhere in Atlantic Canada, collectively constitute most of the Maritimes Basin strata (Fig. 1). Magmatism coeval with deformation in the fault zone occurs predominantly in the Avalon Terrane, the most prominent and voluminous being the ca. 365-350 Ma bimodal mafic-felsic plutonism and volcanism recorded in rocks of the Cobequid

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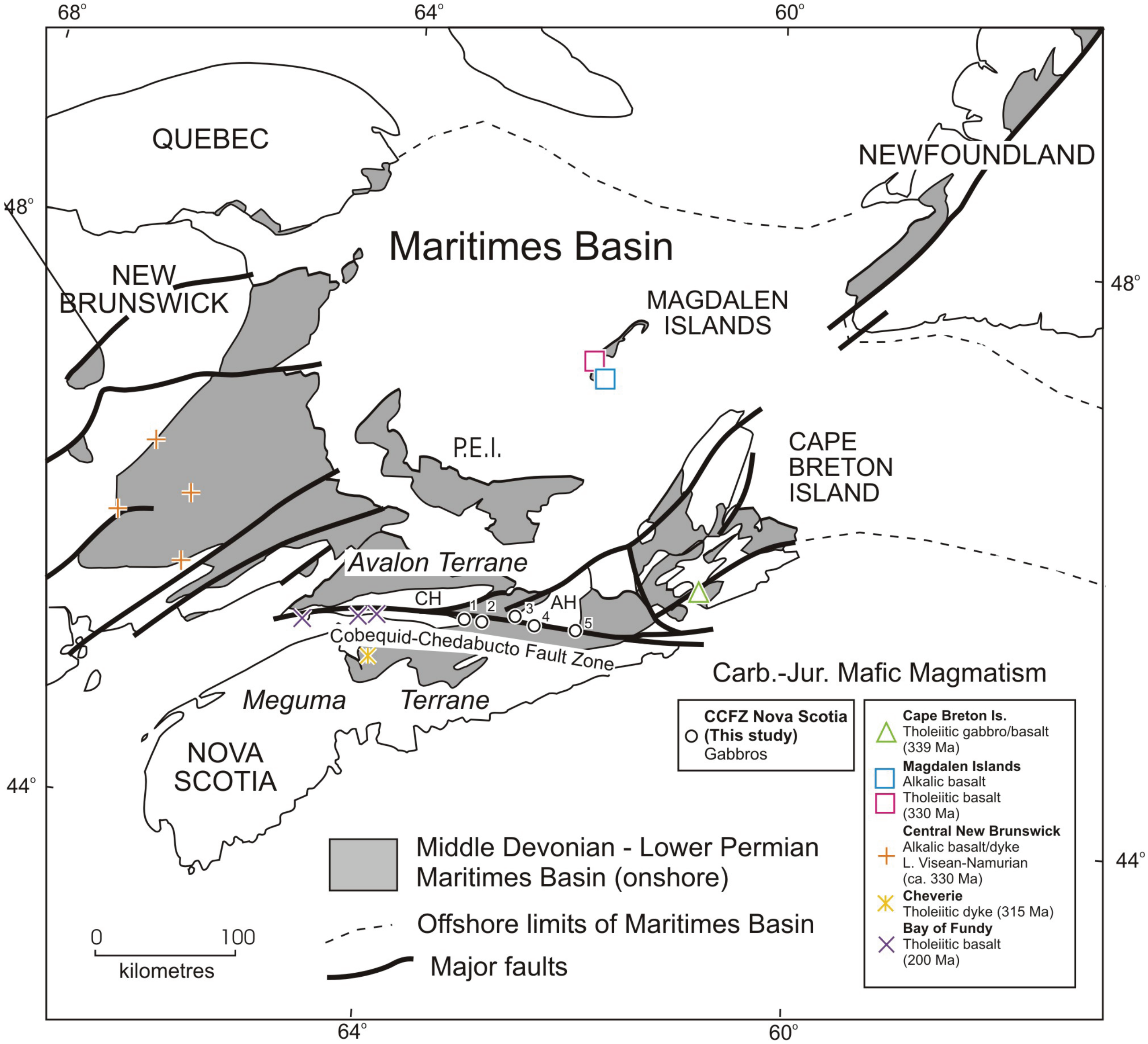

Figure 1. Regional map of Atlantic Canada depicting the distribution of the Maritimes Basin, major faults, and Carboniferous and Jurassic mafic magmatism discussed in this contribution (see caption to Fig. 4 for references). Cobequid Chedabucto Fault Zone (CCFZ), Cobequid Highlands (CH), Antigonish Highlands (AH). Gabbros located along the CCFZ and discussed in this contribution include: (1) East Mountain, (2) Salmon River, (3) Marshdale, (4) Centerdale and (5) College Grant. Map modified from Dunning *et al.* (2004).

Highlands (Doig *et al.,* 1996; Dunning *et al.,* 2004; Pe-Piper *et al.,* 2004). Carboniferous magmatism has been documented (dated) in two areas peripheral to the fault zone, including the ca. 340 Ma St. Peter's Gabbro located in southeastern Cape Breton Island, which intrudes Windsor Group rocks (Barr *et al.,* 1994), and a ca. 315 Ma tholeiitic diabase dyke located in the Cheverie area north of Windsor, which intrudes the Horton Group (Kontak *et al.,* 2000).

Geology and Petrology of Gabbroic Intrusions

The five gabbros sampled and discussed as part of this study include, from west to east: (1) the East Mountain, (2) Salmon River, (3) Marshdale, (4) Centerdale and (5) College Grant gabbros (Figs. 1 and 2). General descriptions and field relations of all the gabbros and their country rocks,

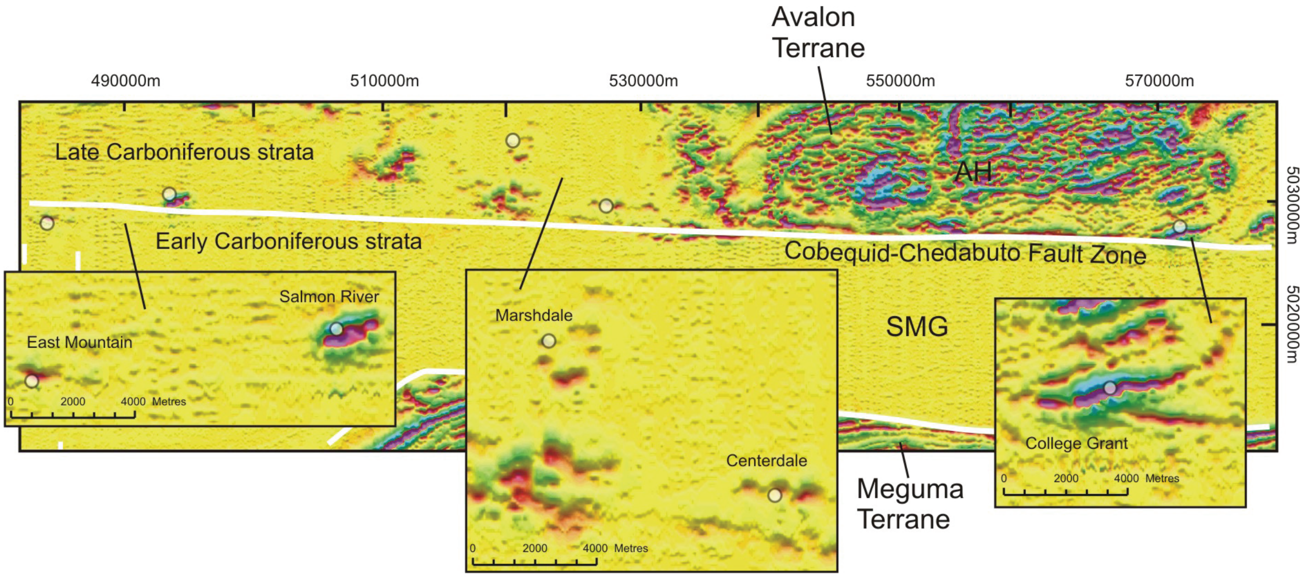

Figure 2. Regional second-derivative magnetic map of the central CCFZ displaying the locations of the gabbro samples collected in this study and the magnetic signatures that define the approximate size and shape of the intrusions. Insets show a more detailed magnetic image. Antigonish Highlands (AH), Saint Mary's grabben (SMG).

with the exception of the College Grant gabbro, can be found in O'Reilly (2005). A brief synopsis of this work and the general petrographic aspects of the samples collected during this study is presented here. The reader is also referred to maps by Naylor *et al. (*2005a and 2005b).

The East Mountain gabbro is an ovoid intrusion ~350-400 m in diameter that intrudes limestone of the Windsor Group (see Fig. 6 in O'Reilly, 2005). Along the contact with gabbro the limestone has been metamorphosed to marble. The pluton has a composite nature, consisting, in part, of fine-grained, plagioclase- and olivine-phyric gabbro (Fig. 3a) and medium-grained, subophitic gabbro consisting predominantly of plagioclase, olivine, clinopyroxene and Fe-Ti oxides (Fig. 3b). A sample of medium-grained gabbro was collected for geochemical analysis.

The Salmon River gabbro is a dyke ~30 m thick (minimum) and ~500-600 m long that intrudes sandstone of the Cumberland Group (see Fig. 7 in O'Reilly, 2005). A sample of medium-grained, intergranular gabbro consisting predominantly of plagioclase, clinopyroxene and Fe-Ti-oxides was collected a few metres from the contact for geochemical analysis. The core of the dyke is medium- to coarse-grained and possesses an ophitic texture.

The Marshdale gabbro is an ovoid, composite intrusion consisting of at least three separate outcroppings that together underlie an area of ~1 km^2 (see Fig. 2 in O'Reilly, 2005). The gabbro intrudes siltstone and sandstone of the Mabou Group, which is highly altered where in direct contact with the gabbro (Fig. 3c). The gabbro is predominantly medium grained, displays an ophitic texture (Fig. 3d), and consists predominantly of plagioclase, olivine, clinopyroxene and Fe-Ti oxides. A primary, late-stage concentration of volatiles in the gabbro is recorded by centimetre-sized metasomatic pods, rich in coarse hornblende, that display gradational contacts with the main phase of the gabbro (e.g. see Fig. 3e). A medium- to coarse-grained locally pegmatitic, sub-vertical anastomosing dyke consisting predominantly of albite (≥ 80-90 vol.%) with lesser, sub-equal amounts of interstitial rutile, chlorite, carbonate, and minor muscovite, epidote and zircon occurs along a spike-like outcrop within the main phase of the gabbro (Figs. 3f-l). This rock is hereafter informally referred to as the albitite dyke. A sample of the main phase of the gabbro and a medium-grained sample of the albitite dyke were collected for geochemical analysis.

The Centerdale gabbro is a poorly exposed, east-west dyke ~2 km long and ~200-300 m wide, based primarily on its magnetic signature (see Fig. 2 and Fig. 5 in O'Reilly, 2005). The poor exposure made it impossible to observe an intrusive contact with the surrounding siltstone and

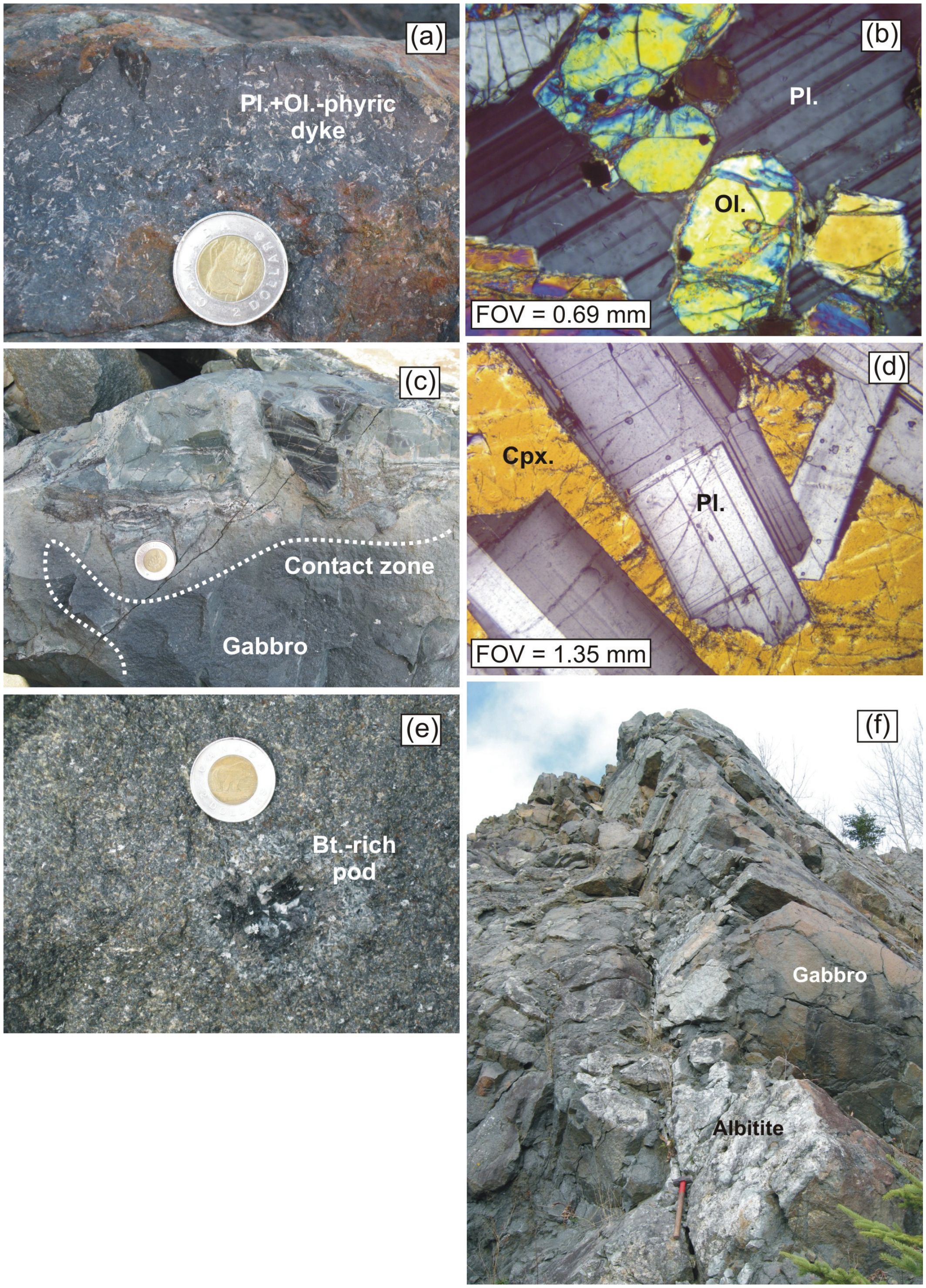

Figure 3. (a) Fine-grained plagioclase-olivine phyric dyke phase of the East Mountain gabbro. (b) Cross polarized light photomicrograph of the medium-grained, sub-ophitic phase of the East Mountain gabbro showing early olivine and Fe-Ti oxide enclosed by plagioclase. (c) Contact between fine-grained siliciclastic sediment and the Marshdale gabbro, note the significant discoloration and alteration of both. (d) Crossed polarized photomicrograph depicting the medium-grained ophitic phase of the Marshdale gabbro. (e) Centimetre-sized hornblende-rich clot in the Marshdale gabbro; note the zonation between the clot and the main plagioclase-clinopyroxene-olivine-Fe-Ti-oxide-bearing phase of the gabbro. (f) Sub-vertical medium- to coarse-grained albitite dyke within the Marshdale gabbro; hammer is ~50 cm long.

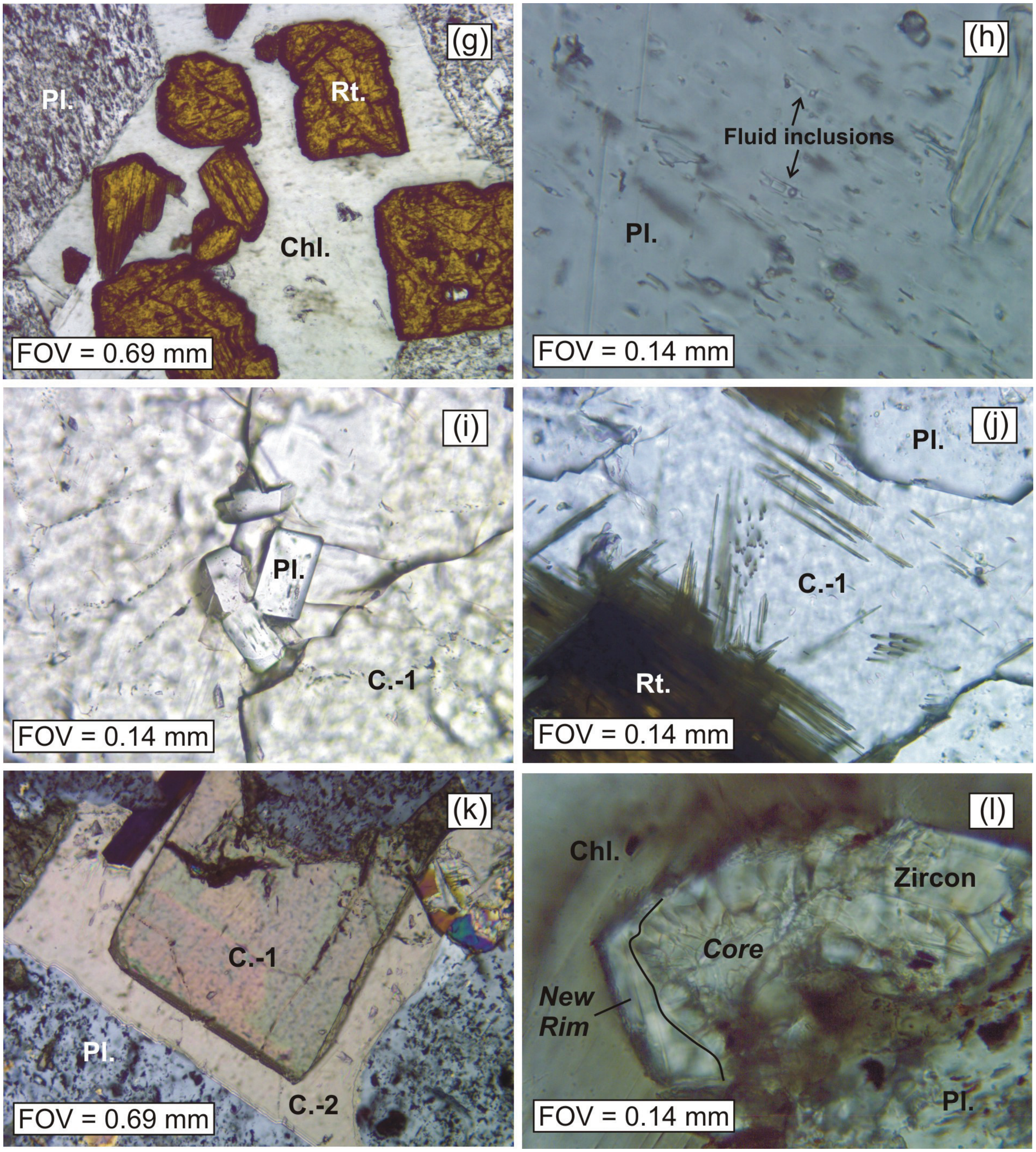

Figure 3. (cont'd): (g) Plane polarized light photomicrograph of albitite dyke displaying fluid-inclusion-rich albite and matrix chlorite and rutile. (h) Plane polarized light photomicrograph of the albitite dyke depicting fluid inclusions in albite. (i) Plane polarized light photomicrograph of small euhedral hydrothermal albite crystals incased in a carbonate phase from the albitite dyke. (j) Plane polarized light photomicrograph of the albitite dyke depicting the co-precipitation of rutile needles and a carbonate phase. (k) Crossed polarized photomicrograph of the albatite dyke depicting the early growth of a high-relief carbonate (C.-1, dolomite-ankerite/siderite(?)) and later infiltration of a lower relief matrix filling calcite (C.-2). (l) Plane polarized photomicrograph of a zircon crystal within the albitite dyke; note the new overgrowth and earlier core. See Table 1 for abbreviations used in Figure 3.

sandstone of the Mabou Group. The sample collected for geochemical analysis is medium grained, displays ophitic texture and consists predominantly of plagioclase, clinopyroxene, hornblende and Fe-Ti-oxides.

The College Grant gabbro is very poorly exposed, consisting of a single outcrop only a few square metres in size. The contact with the enclosing country rock is not exposed but the gabbro is interpreted to intrude the Late Silurian-Early Devonian Knoydart Formation of the Arisaig Group (Keppie, 2000). The magnetic signature of the gabbro suggests it is an east-northeasterly-trending dyke similar in size to the Centerdale gabbro dyke, ~200-300 m wide and ~2-3 km long (Fig. 2 and O'Reilly, 1995). The sample collected for geochemical analysis is medium-grained, displays subophitic texture and consists predominantly of plagioclase, clinopyroxene, hornblende and Fe-Ti oxides.

Analytical Methods

Major and trace elements were determined by ICP-MS by Activation Laboratories located in Ancaster, Ontario. Details of the analytical procedures (code 4Litho) can be found on their website (actlabs.com). The Sm-Nd isotopic compositions were determined at the University of Alberta radiogenic isotope facility employing well-established cation-exchange chromatographic methods for the separation and purification of Sm and Nd, and analyses were conducted using a MC-ICP-MS.

Results

The major, trace element and Nd isotopic compositions of the five gabbro samples discussed in this study are listed in Table 1. All gabbros possess similar SiO_2 (48-50 wt.%), Fe_2O_3(T) (11-13 wt.%) and CaO (7-9 wt.%). The East Mountain gabbro sample possesses greater MgO (15 wt.%) and lower Al_2O_3 (14 wt.%) than other gabbro samples (6-9 and 17-18 wt.%, respectively), features consistent with its greater olivine content.

Employing mantle-normalized extended trace element plots (Fig. 4a and b), two geochemical groups can be defined. Group 1a consists of the East Mountain, Salmon River, Centerdale and College Grant gabbros (Fig. 4a), and Group 1b of the Marshdale gabbro (Fig. 4b). The Group 1a samples possess relatively uniform trace element abundances and extended element patterns characterized by low to moderate $(Th/Nb)_N$ (~0.5-0.8), unfractionated to elevated $(Nb/La)_N$ (≥ 0.9-1.4), moderate light rare earth element (LREE) enrichment ($(La/Yb)_N$ ~2.3-6.3), and a lack of significant high field-strength element (HFSE) anomalies with respect to the bounding REE (Fig. 4a and Table 1). The Marshdale gabbro (Group 1b) possesses $(Th\text{-}Sm)_N$ and $(La/Sm)_N$ systematics and highly incompatible element abundances that are similar to the Group 1a gabbros, but its significant positive Ti anomaly (Ti/Ti* ~2.0; Table 1) and more pronounced middle and heavy REE depletion (e.g.$(Gd/Yb)_N$ of 2.8 vs. 1.4-1.9; Table 1) are distinct from the Group 1a samples. The albitite dyke sample collected from the Marshdale Pluton is plotted along with the main gabbro in Fig. 4b. The dyke possesses variably lower REE contents than the gabbro, is notably highly enriched in Nb, possesses a significant positive Eu anomaly (Eu/Eu* of 3.7; Table 1), pronounced positive HFSE anomalies at Nb, Zr, Hf and Ti, and a negative anomaly at P relative to the bounding REE (Fig. 4b).

The Sm-Nd isotopic compositions of the East Mountain (Group 1a) and Marshdale (Group 1b) gabbros are listed in Table 1. The East Mountain sample has a marginally more depleted initial epsilon Nd signature (+4.8) compared to that of the Marshdale sample (+2.2), as calculated for a crystallization age of ca. 330 Ma.

Discussion

Evidence for Carboniferous to Permian(?) Magmatism in the CCFZ

The intrusive relationships between the East Mountain, Salmon River and Marshdale gabbros with strata of the Windsor and Cumberland groups indicates that these gabbros are Carboniferous or younger. The maximum age bracket for these gabbros is thus ca. 340-310 Ma, the lower age constraint provided by the Salmon River dyke, which intrudes the Boss Point Formation of the Cumberland Group, a formation containing Westphalian A spores (ca. 310 Ma; Okulitch, 2004; Keppie, 2000). The strong similarity of these gabbros with the Centerdale and College Grant gabbros (for which intrusive relationships are not exposed), in terms of their dimensions, petrology, chemistry and spatial association to the CCFZ, suggests they were all generated during the same magmatic event. As well, their proximity to the CCFZ suggests their migration from mantle depths was fault controlled. Notably, the four Group 1a gabbros occur directly upon a prominent east-west splay of the CCFZ where, for over a distance of ca. 100 km, variation in their north-south position is ≤ 2.5 km (Fig. 2 and UTM locations in Table 1).

Carboniferous alkalic-tholeiitic mafic magmatism coincident with the ca. 340-310 Ma maximum age bracket suggested for the gabbros is well recognized within the Maritimes Basin (Fig. 1 and Fig. 5a). Importantly, the geochemical signatures of these magmas, in particular the tholeiitic end-members, are remarkably similar to the gabbros found in the CCFZ (Fig. 5a and b). With respect to their incompatible trace element profiles, the majority of the gabbros (Group 1a; n=4/5) are virtually identical to the ca. 330 Ma tholeiitic basalts found on the Magdalen Islands (La Flèche, 1998; Giles, 2008; see Fig. 1 and Fig. 5b). The alkalic end-members possess similar incompatible trace element characteristics to the tholeiites, although they are significantly more enriched in the most highly incompatible trace elements (Fig. 5b). The latter are similar to Late Viséan-Early Namurian (ca. 330 Ma) alkalic mafic magmas found in central New Brunswick (Fyfe and Barr, 1986; see Fig. 1 and 5b). The incompatible trace element profile of the Marshdale gabbro (Group 1a) is remarkably similar to the ca. 340 Ma gabbros found in the St. Peter's area on southwestern Cape Breton Island (Barr *et al.,* 1994; Fig. 1 and 5b). In particular, the degree of middle and heavy REE depletion and magnitude of their positive Ti anomalies are indistinguishable. Although lacking a Ti anomaly, the ca. 315 Ma tholeiitic diabase dyke found in the Cheverie area also possesses an incompatible trace element profile remarkably similar to the Marshdale gabbro (Kontak *et al.,* 2000; Fig. 1 and Fig. 5b).

The geochemical similarities between the CCFZ gabbros and known, ca. 340-315 Ma (Carboniferous) mafic magmatism in the Maritimes, and a ca. 340-310 Ma maximum age constraint for at least some of this magmatism, strongly suggest that the gabbros in the CCFZ are indeed a newly recognized component of this magmatic event. Absolute age dating, in particular of the ≤ ca. 310 Ma Salmon River dyke, is necessary to confirm if this magmatism extends into the Permian. Importantly though, a Jurassic age for the gabbros is unlikely based on the high $(Th/Nb)_N$ and negative HFSE anomalies that universally characterize these basalts beside and beneath the Bay of Fundy (Fig. 5b; Greenough *et al.,* 1989).

Trace Element and Isotopic Constraints for the Origin of the Gabbros

The similar incompatible trace element profiles and initial Nd isotopic compositions of the Group 1a and 1b gabbros suggest they were derived from similar mantle sources. The more significant heavy REE depletion of the Marshdale gabbro suggests that garnet was present in the source during melt extraction. Barr *et al.* (1994) proposed a similar scenario for the ca. 340 Ma gabbros in the St. Peter's area, which have virtually identical trace element signatures to the Marshdale gabbro (Fig. 5b). However, the strikingly similar highly incompatible trace element abundances and patterns of the Group 1a gabbros and the Marshdale gabbro imply broadly similar degrees of melting and source compositions. This suggests that the depth of melt generation for gabbros found in the CCFZ straddled the garnet stability field which, on the solidus of fertile peridotite, occurs at ~90 km (Herzberg *et al.,* 2000).

The initial Nd isotopic compositions of the East Mountain and Marshdale gabbros are notably lower than the modern depleted mantle mid-ocean ridge basalt (MORB) source, which possess an average maximum initial epsilon Nd value of +10 (Hofmann, 2004). This indicates a mantle source component possessing a long-term enrichment in Nd/Sm relative to the bulk silicate earth. Although

Table 1. Whole-rock geochemical analyses of gabbric rocks.

Sample No.	**TM07-015**	**TM07-023**	**TM07-016-A**	**TM07-016-B**	**TM07-021**	**TM07-024**
Int. Name	East Mountain	Salmon River	Marshdale	Marshdale	Centerdale	College Grant
Rock Type	Gabbro	Gabbro	Gabbro	Albitite dyke	Gabbro	Gabbro
Grain size	M. grained	M. grained	M. grained	M. grained	M. grained	M. grained
Texture	Subophitic	Intergranular	Ophitic		Ophitic	Subophitic
Minerals	Pl.Ol.Cpx.Fe-Ti	Pl.Cpx.Fe-Ti	Pl.Ol.Cpx.Fe-Ti	Pl.Chl.Rt.C.Ep.	Pl.Cpx.Hb.Fe-Ti	Pl.Cpx.Hb.Fe-Ti
UTMx	5028473	5030005	5034350	5034350	5029584	5027541
UTMy	484231	493422	519945	519945	527530	571792
SiO_2	47.87	49.89	48.77	53.81	49.96	47.87
Al_2O_3	13.64	18.05	16.87	20.83	18.30	17.32
Fe_2O_3(T)	11.90	11.02	13.00	8.67	10.86	11.57
MnO	0.17	0.17	0.16	0.05	0.18	0.25
MgO	15.09	6.20	6.60	3.89	6.89	8.55
CaO	6.76	7.05	8.55	2.21	7.65	9.18
Na_2O	2.97	5.35	3.44	6.81	3.43	3.07
K_2O	0.25	0.31	0.25	0.75	0.89	0.71
TiO_2	1.21	1.77	2.24	2.97	1.61	1.33
P_2O_5	0.14	0.20	0.13	0.02	0.23	0.14
LOI	2.06	3.66	1.09	3.27	1.55	3.30
Total	100.40	99.15	100.60	99.74	99.96	100.60
Sc	18	26	19	7	14	34
Be	1	2	1	2	1	1
V	144	192	218	60	199	236
Ba	59	119	79	256	235	174
Sr	255	263	532	262	1038	546
Y	16	23	10	5	14	19
Zr	75	105	48	79	73	53
Cr	610	220	170	160	70	150
Co	71	41	57	23	46	50
Ni	530	120	160	50	110	130
Cu	80	50	90	10	140	100
Zn	120	170	170	70	590	140
Ga	17	23	24	24	22	19
Ge	< 1	1	< 1	< 1	< 1	1
As	< 5	< 5	< 5	< 5	< 5	< 5
Rb	5	7	5	19	15	21
Nb	6	10	5	22	14	9
Mo	< 2	< 2	< 2	< 2	< 2	< 2
Ag	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
In	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2

Table 1. Cont'd:

Sample No.	TM07-015	TM07-023	TM07-016-A	TM07-016-B	TM07-021	TM07-024
Sn	< 1	< 1	< 1	1	1	< 1
Sb	< 0.5	< 0.5	< 0.5	2.3	4	2.2
Cs	0.6	3.8	0.7	< 0.5	< 0.5	7.7
La	6.3	7.5	5	3.9	12.1	6.2
Ce	13.3	18	11.4	6.3	26	13.5
Pr	1.59	2.17	1.57	0.62	2.99	1.66
Nd	7.6	10.7	8.4	2.7	12.5	8.1
Sm	2.4	3.3	2.5	0.8	2.9	2.4
Eu	0.97	1.41	1.36	1.08	1.32	1.16
Gd	2.8	4	2.8	1	3.1	3
Tb	0.5	0.7	0.4	0.2	0.5	0.5
Dy	2.9	4.2	2.2	0.9	2.9	3.4
Ho	0.6	0.8	0.4	0.2	0.5	0.7
Er	1.6	2.4	1.1	0.5	1.5	2
Tm	0.24	0.34	0.14	0.07	0.21	0.29
Yb	1.5	2.1	0.8	0.5	1.3	1.8
Lu	0.21	0.32	0.12	0.07	0.2	0.27
Hf	1.9	2.7	1.5	2.4	1.8	1.5
Ta	0.5	0.6	0.5	0.7	0.8	0.5
W	55	42	71	47	43	37
Ti	0.3	<0.1	<0.1	<0.1	0.1	<0.1
Pb	<5	10	<5	<5	505	22
Bi	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Th	0.6	1	0.4	0.4	0.9	0.5
U	0.2	0.3	0.1	0.9	0.3	0.2
$(Th/Nb)_N$	0.8	0.8	0.7	0.2	0.5	0.5
$(Nb/La)_N$	0.9	1.3	1.0	5.6	1.1	1.4
$(La/Sm)_N$	1.6	1.4	1.3	3.1	2.6	1.6
$(La/Yb)_N$	2.9	2.4	4.3	5.3	6.3	2.3
$(Gd/Yb)_N$	1.5	1.5	2.8	1.6	1.9	1.4
Nb/Nb*	1.1	1.3	1.2	6.1	1.5	1.8
P/P*	1.1	1.1	1.0	0.4	1.0	1.1
Zr/Zr*	1.2	1.2	0.7	3.6	0.8	0.8
Hf/Hf*	1.1	1.1	0.8	4.1	0.8	0.9
Ti/Ti*	1.1	1.1	2.0	7.8	1.3	1.2
Eu/Eu*	1.1	1.2	1.6	3.7	1.3	1.3
SUM REE	43	58	38	19	68	45
$^{147}Sm/^{144}Nd$	0.1819		0.1831			
$^{143}Nd/^{144}Nd$	0.512850		0.512722			
ЄNd (330 Ma)	4.8		2.2			

SiO_2 to LOI in wt.% other elements in ppm. Subscript (N) denotes normalization to primitive mantle (Sun and McDonough, 1995). Ratios denoted with a superscript (*) are a measure of the magnitude of a positive (>1) or negative (<1) anomaly for a given element as depicted in Fig. 3. These ratios are calculated by dividing an elements primitive mantle normalized value by the geometric mean of the bounding elements as ordered in Fig. 3, e.g. $Nb/Nb^* = (Nb)_N/((Th)_N x(La)_N)^{0.5.}$ Initial epsilon Nd values are calculated using an age of 330 Ma and the CHUR parameters $^{147}Sm/^{144}Nd$=0.1967 and present day $^{143}Nd/^{144}Nd$=0.512638. Pl. plagioclase, Ol, olivine, Cpx. clinopyroxene, Hb. hornblende, Fe-Ti Fe-Ti oxides, Chl. Chlorite, Rt. Rutlile, C. carbonate, Ep. Epidote. UTMs are NAD83 (zone 20N).

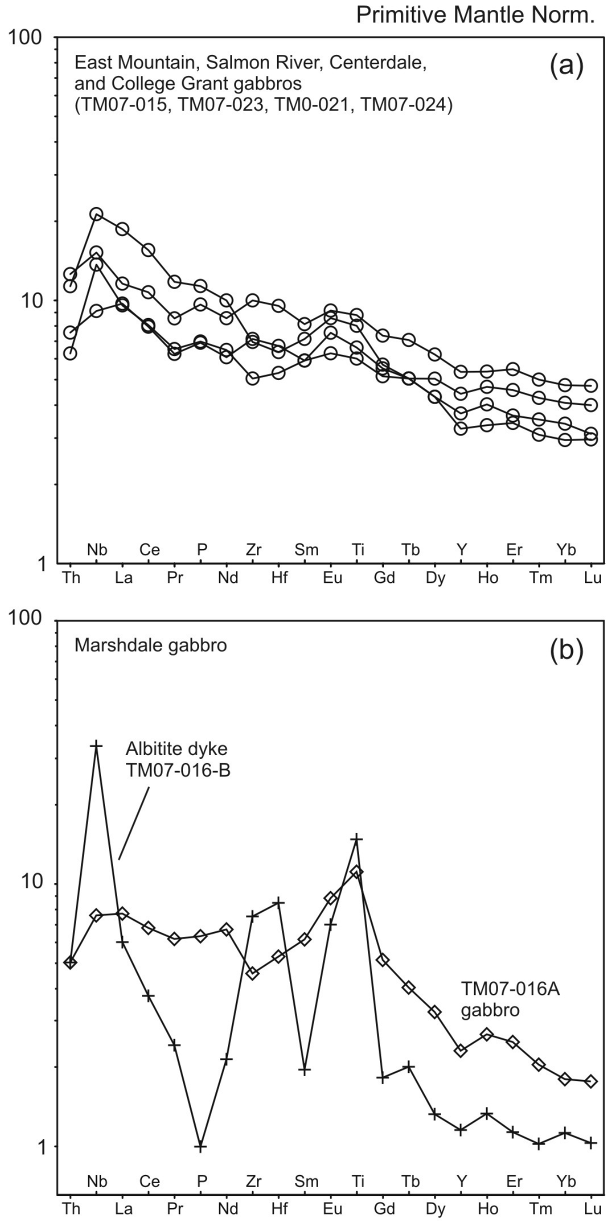

Figure 4. Primitive mantle-normalized (Sun and McDonough, 1995) extended trace element plots for gabbros and the albitite dyke. (a) Samples included in the group-1a gabbro group. (b) The Marshdale gabbro (group-1b) and the albitite dyke.

beyond the scope of this contribution, this source component is interpreted, at least in part, to reside within the subcontinental lithospheric mantle. This interpretation is based on the broadly similar enriched isotopic and chemical characteristics displayed in the CCFZ gabbros and remnants of older mafic magmatic events recognized in the Avalon Terrane at ca. 370, 460, 530 and 610 Ma (Murphy and Dostal, 2007).

Significance of the Albitite Dyke Within the Marshdale Gabbro

Petrographic and chemical data suggest that the origin of the albitite dyke is genetically related to the main phase gabbro and that it was ultimately formed directly or indirectly from a late-stage, volatile-rich, alkaline melt/hydrothermal fluid derived from a highly evolved and differentiated phase of the gabbro.

The following petrographic observations suggest that a Si-Na-Fe-Ti-CO_2-H_2O-rich fluid/melt is required to generate the principal phases found in the albitite: (1) numerous saline fluid inclusions contained within albite crystals (Fig. 3h), (2) the locally pegmatitic texture of plagioclase crystals (up to several cm long), and (3) evidence for the co-precipitation of euhedral, ~100 µm-scale hydrothermal albite (Fig. 3i) with both acicular rutile (Fig. 3j) and a high-relief carbonate (C.-1 possibly dolomite-ankerite/siderite). Late, interstitial chlorite and a secondary carbonate phase (C.-2 calcite; Fig. 3g and k) are interpreted to have replaced previous ferromagnesian phases (possibly hornblende and/or biotite) and fill voids, respectively.

Chemical similarities between the gabbro and albitite, such as their elevated TiO_2 contents and strikingly similar REE profiles (e.g. $(La/Yb)_N$; Fig. 6a), imply a genetic relationship. The low REE contents and significant positive Eu anomaly displayed by the albitite suggest plagioclase control and dilution of the REE with respect to its parental fluid/melt (Fig. 6b). The incompatible trace element contents of the albitite are shown increased by a factor of 2.25 in Fig. 6a to adjust for REE to examine REE/HFSE fractionations between the gabbro and albitite. This exercise demonstrates that the albitite contains excess Th, Nb, La, Zr, Hf, Ti and Eu, and low P with respect to the majority of REE. The excess La and Eu can be explained by the significant amount of plagioclase constituting the albitie (~80-90 vol.%), and the elevated HFSE contents by the abundance of rutile. The low P content suggests that apatite fractionation occurred at some stage in the generation of the Si-Na-Fe-Ti-CO_2-H_2O-rich fluid/melt that formed the albitite.

The albitite appears to have ultimately formed as a result of extreme differentiation and volatile concentration within the gabbro, as shown by the

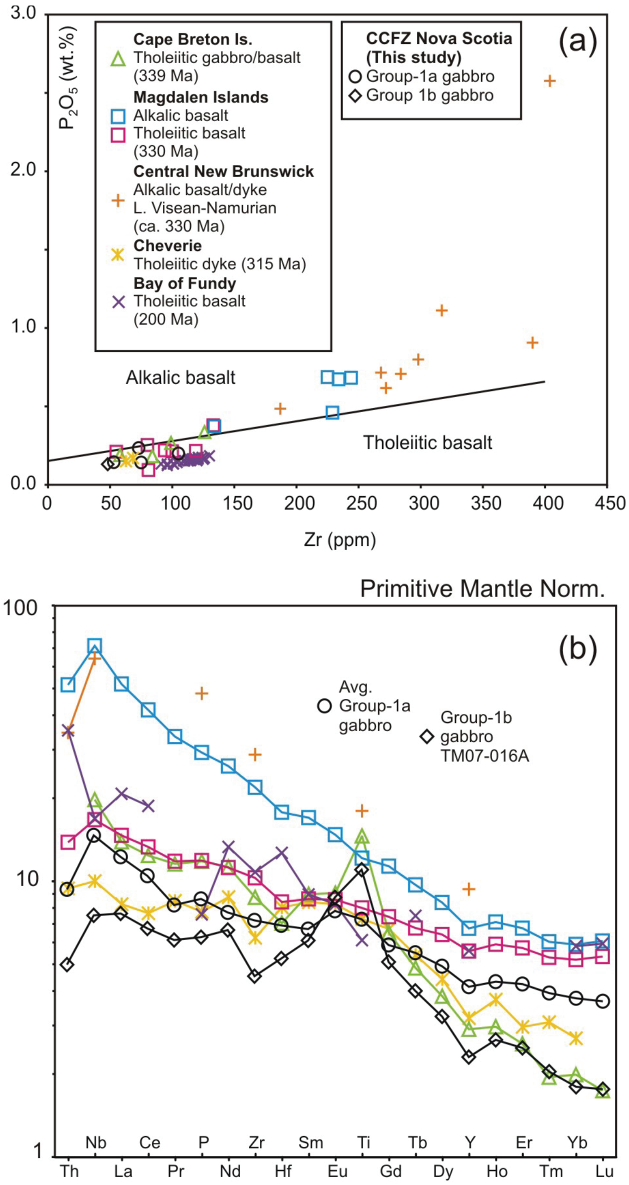

Figure 5. (a) P_2O_5-Zr alkalic-tholeiitic discrimination diagram (Winchester and Floyd, 1976) for Carboniferous and Jurassic mafic magmatism discussed in this contribution. (b) Primitive mantle normalized (Sun and McDonough, 1995) extended trace element plots for Carboniferous and Jurassic mafic magmatism discussed in this contribution. Average compositions employed in Figure 5b are of samples plotted in Figure 5a with the exception of the Magdalene Islands data (see below). For Cape Breton Island, the average is all four gabbro samples with REE data (samples 1, 3, 5 and 14; Barr *et al.,* 1994). Magdalen Islands averages in Figure 5b are those reported in La Flèche *et al.* (1998) and include 34 alkalic and 18 tholeiitic basalts. Those plotted in Figure 5a are the representative samples reported in La Flèche (1998). For central New Brunswick, the average is of 8 Late Viséan-Namurin basalts and diabase dykes (samples Q-1, M-1, M-4, B-1, B-2, B-3, RR-1 and RR-2; Fyffe and Barr, 1986). Bay of Fundy average is for 25 basalt samples reported in Greenough *et al.* (1989). Cheverie tholeiitic dyke is the average of two samples reported in Kontak *et al.* (2000).

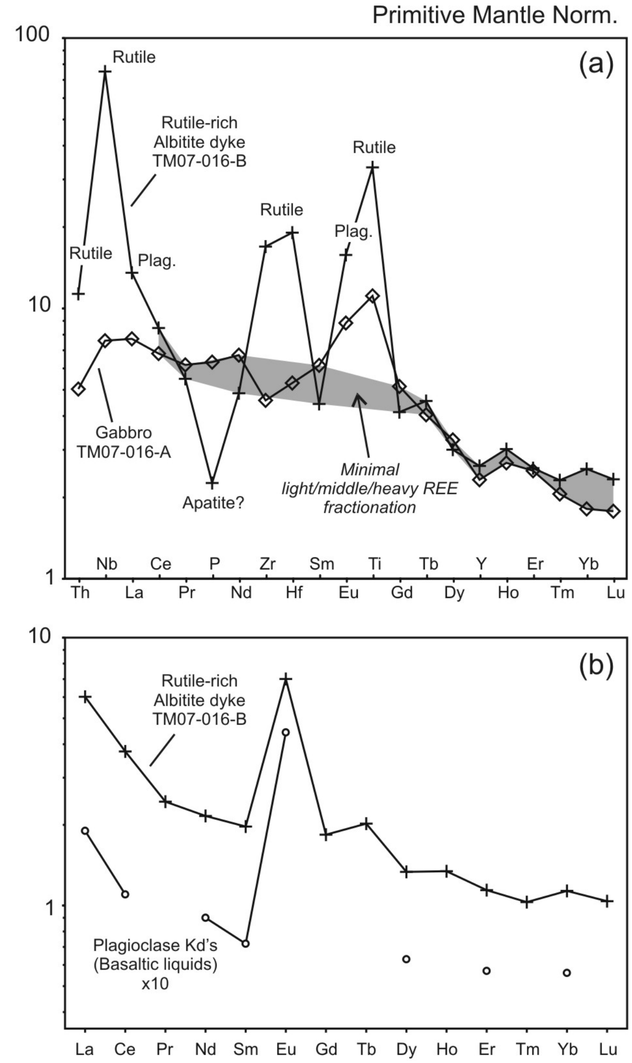

Figure 6. (a) Primitive mantle normalized (Sun and McDonough, 1995) extended trace element plot for the Marshdale gabbro (group-1b) and the albitite dyke with the abundances of all trace elements in the latter increased by a factor of 2.25. This factor increases the REE abundances of the dyke to those similar to the gabbro (grey field). After normalization, significant differences include excess La, Eu (plagioclase control) and Th, Nb, Zr, Hf, and Ti (rutile control), and low P (apatite fractionation(?)) in the dyke. (b) Primitive mantle normalized (Sun and McDonough, 1995) REE pattern for the dyke and plagioclase partition coefficents (x 10) for the REE in basaltic systems (see Rollinson, 1998).

primary volatile concentration in the gabbro which resulted in the formation of biotite- and hornblende-rich metasomatic clots gradational with the main phase gabbro (Fig. 3e).

Relationship Between Magmatism and IOCG-style Mineralization and Alteration in the CCFZ

The timing of IOCG-style mineralization in the CCFZ currently is only directly constrained by a single, absolute Re-Os age of ca. 325 Ma, determined for hydrothermal pyrite associated with chalcopyrite and bornite at the Copper Lake Cu-Au deposit (Kontak *et al.,* 2008). Abundant hydrothermal alteration and deformation occurring in the CCFZ between ca. 340 and 310 Ma, and the numerous Fe-carbonate-oxide occurrences hosted by Upper Carboniferous strata (see Fig. 1 and 2 in MacHattie and O'Reilly, 2009, and references therein) also constrain the timing.

The age suggested for IOCG-style mineralization and alteration in the CCFZ is coincident with the ca. 340-310 Ma maximum age constraint for gabbroic magmatism in the CCFZ. Both emplacement of these gabbros and IOCG-style mineralization are fault controlled and, therefore, probably genetically related. The spatial and temporal association of the gabbros and IOCG-style mineralization in the fault zone suggests that the gabbros may have been an important source of heat to drive hydrothermal circulation. The fact that the Marshdale gabbro appears to have generated an alkaline hydrothermal/magmatic fluid could also indicate that the gabbros were an important source for hydrothermal fluids and/or metals. This is consistent with the occurrence of late carbonate viens containing pyrite, chalcopyrite and specularite in the Marshdale Pluton (O'Reilly, personal communication), and that the College Grant Cu deposit is hosted by a highly altered gabbro (see O'Reilly, 1995).

Conclusions

The field relationships and geochemical signatures of gabbros in the CCFZ suggest that they are components of a regionally recognized, ca. 340-315 Ma alkalic-tholeiitic mafic magmatic event in the Maritimes Basin of Atlantic Canada. Their geochemical and isotopic signatures suggest they were generated by low degrees of mantle melting near the garnet stability field. Their Late Carboniferous to Permian(?) age, and spatial association with the CCFZ, suggest a possible genetic link to IOCG-style mineralization and alteration in the CCFZ. Furthermore, the evidence suggesting that metal-rich alkaline melts and hydrothermal fluids were exsolved from the Marshdale (and College Grant) gabbros implies that the gabbros may have also acted as an important direct source for hydrothermal fluids and metals.

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