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The geochemistry of mafic gneisses from the Renzy terrane, western Grenville Province, Quebec: Implications for the geodynamic setting of the early Mesoproterozoic Laurentian margin

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A B S T R A C T

This study presents new geochemical data on mafic gneisses from the Renzy terrane (RT), located in the Grenvillian Parautochthonous Belt of western Quebec. This region is of particular interest since it contains one of the rare Ni–Cu–Co massive sulfide deposits ever mined in the Grenville Province. RT mafic gneisses have been divided into 3 groups based mainly on major element compositions, trace element profiles normalized to the primitive mantle, and incompatible trace element ratios. The behaviour of high field strength elements (HFSE) (Ta, Zr, Hf, Ti, Th) and large ion lithophile elements (LILE) (Ba, Rb) are particularly useful for discriminating RT mafic gneisses. Major and trace element compositions of group 1 mafic/ultramafic gneisses are very similar to those of the RT ultramafic sheets; the mafic gneisses are therefore interpreted as melagabbroic sills cogenetic with these sheets. The trace element composition of group 1 mafic gneisses is typical of magmas formed from a previously metasomatized depleted mantle source. These rocks have high Th/Ta ratios and show strong to moderate negative anomalies in Ti, Zr, and Hf on multi-element plots normalized to the primitive mantle. Mafic gneisses of group 2 show geochemical features transitional between extensional and compressional settings. These rocks generally have low concentrations of HFSE and high concentrations of LILE, typical features of mafic rocks formed in a compressional environment; however, some of them are Fe–Ti rich, with minor or no negative anomalies in HFSE and low to moderate concentrations of LILE on multi-element diagrams normalized to primitive mantle, features more typical of an extensional environment. Mafic gneisses of group 3 have a geochemical signature typical of extensional environments or of ocean island basalt (OIB). These gneisses have no negative anomalies in HFSE and have low concentrations of LILE. RT mafic gneisses are similar in composition to mafic granulites in the Bondy gneiss complex in the Central Metasedimentary Belt and to Shawanaga Domain amphibolites from the Central Gneiss Belt, two paleoarc/back-arc environments in the Grenville Province. Based on the contrasting geochemical signatures found in the RT mafic gneisses and the similarities with known arc/back-arc settings in the Grenville Province, we propose that the RT was formed by arc/back-arc magmatic activity most likely associated with a period of arc magmatism along the Proterozoic Laurentian margin. OIB-like mafic gneisses found in the RT are similar to those from the Kipawa region, formed by intraplate continental magmatism in the Parautochthonous Belt of the Grenville Province.

1. Introduction

Knowledge of the evolution of the Grenville orogen has advanced greatly in the last two decades particularly with the publication of combined tectonic, geochemical and geochronological studies (Carr et al., 2000; Davidson, 2008; Gower and Krogh, 2002; Martignole et al., 2000; Rivers, 1997, 2008). Less well known are the geological events that preceed the beginning of the Grenville orogeny (older than ~1.1 Ga according to the definition of Rivers, 2008). In several places in the Grenville Province, early Mesoproterozoic terranes of unknown origin overlie the Archean rocks of the Parautochthonous Belt. An example is the Renzy terrane (RT), which is located in the southwestern part of this belt in Quebec (Fig. 1) and is mainly known for a Ni–Cu–Co massive sulfide deposit exploited in the early 1970s (Johnson, 1972). The Renzy terrane was first identified as a distinct geological entity by Indares and Martignole (1990), who linked many small lenses of gneiss–amphibolite–ultramafic sequences scattered on both sides of a regional, senestral shear zone, which they named the Renzy shear zone. Later, based on a U–Pb zircon age from a pegmatite dike cutting the shear zone, Martignole and Friedman (1998) established a minimum age for the shearing

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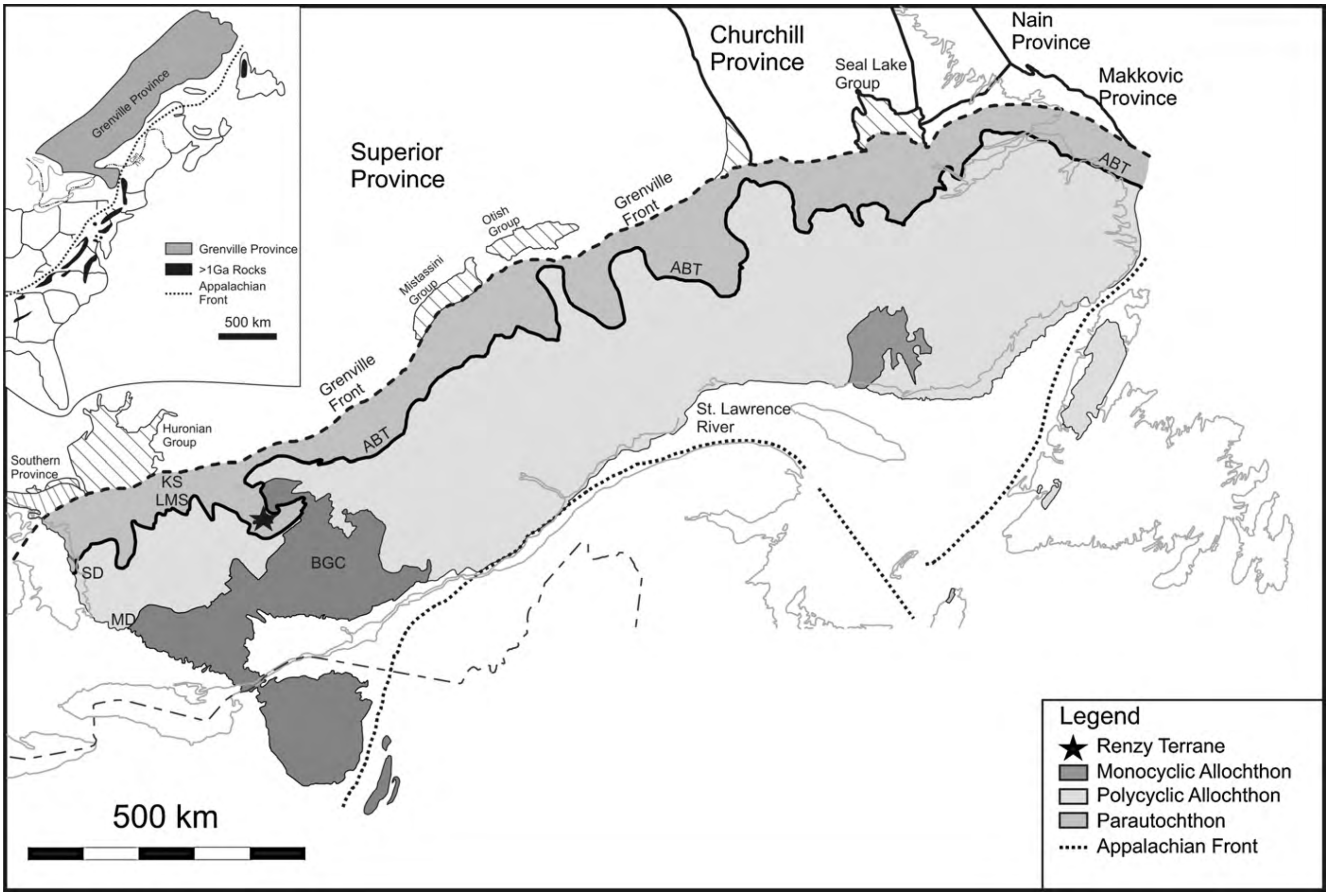

Fig. 1. Simplified geologic map showing the three major lithotectonic domains of the Grenville Province (after Rivers et al., 1989; Carr et al., 2000; Davidson, 2008). The location of the Renzy terrane is indicated by a star. Four other localities with amphibolites or mafic granulites discussed in the text are also shown. *Abbreviations*: ABT, Allochthon boundary thrust; BGC, Bondy gneiss complex; SD, Shawanaga domain; MD, Muskoka domain; KS LMS, Kikwissi suite and the Lac McKillop sequence.

at 1.00 Ga. Also in the 1990s, Indares and Martignole (1990) and Childe et al. (1993) demonstrated that the timing and intensity of the main metamorphic phase were different in the RT than in the surrounding gneisses of the Parautochthonous Belt. More temporal constraints came from neodymium isotope data (Guo and Dickin, 1996) which showed that the RT has Proterozoic Nd model ages, whereas the surrounding rocks of the Parautochthonous Belt have Archean Nd model ages. Laser ablation ICP-MS $^{207}Pb/^{206}Pb$ dating of zircons hosted in quartzite and garnet–biotite–sillimanite gneiss conducted in the western Grenville by Martignole and Ringuette (1998) supported the conclusions based on the Nd model ages. The terranes surrounding the RT yielded $^{207}Pb/^{206}Pb$ ages ranging from Archean to 1.3 Ga, whereas the RT yielded $^{207}Pb/^{206}Pb$ ages ranging from 1.40 to 1.05 Ga, with a peak at 1.2 Ga, indicating that the RT probably originated from a fragment of juvenile crust (Martignole and Ringuette, 1998) accreted to Laurentia. Based on these data, we believe that an approximate age of 1.40 Ga is likely for the minimum age for the RT, as the younger ages are probably from metamorphic zircons in the gneiss. These observations led Martignole et al. (2000) to describe the Renzy terrane as a sequence of ultramafic intrusions, mafic gneisses (previously called amphibolites), and other gneisses overlying Archean orthogneisses of the Parautochthonous Belt. The RT sequences are located on both sides of the Renzy shear zone (Indares and Martignole, 1990; Martignole et al., 2000).

One of the key questions remaining regarding the Renzy terrane is whether or not its formation is linked to the arc activity inferred to have occurred along the Laurentian margin during most of the Proterozoic (Rivers, 1997; Rivers and Corrigan, 2000; Gower and Krogh, 2002; Davidson, 2008). This knowledge is of great importance for placing the Renzy terrane within the evolutionary models of the eastern Laurentian margin during the Proterozoic. The Renzy terrane contains several mafic gneisses bands and lenses, rocks that are good indicators of ancient geodynamic settings in high-grade metamorphic sequences (Culshaw and Dostal, 2002; Van Boening and Nabelek, 2008). Mafic gneisses, amphibolites, and granulites in various regions of the Parautochtonous and Allochthonous belts have been used to identify their ancient geodynamic setting (Culshaw and Dostal, 2002; Blein et al., 2003; van Breemen and Currie, 2004); similar attempts have also been made in other ancient geological provinces (Sandeman et al., 2006; Van Boening and Nabelek, 2008). Mafic gneisses are resistant to partial melting during high-grade metamorphism and usually preserve their original immobile element compositions as partial melting in these rocks rarely exceeds the critical percentage (>8% for local percolation) for significant magma extraction (Vigneresse et al., 1996; Vigneresse, 2007). In this paper we present new geochemical analyses for 33 samples of mafic gneiss from the Renzy terrane, and we will show that the Renzy terrane is the result of Proterozoic arc activity temporally correlated with ongoing arc activity along the eastern Laurentian margin (Sappin et al., 2009).

2. Geological setting of the Renzy terrane

2.1. Regional geology

The Renzy terrane is located on both sides of the Renzy shear zone (Fig. 2). On the south side, RT gneisses overlie the

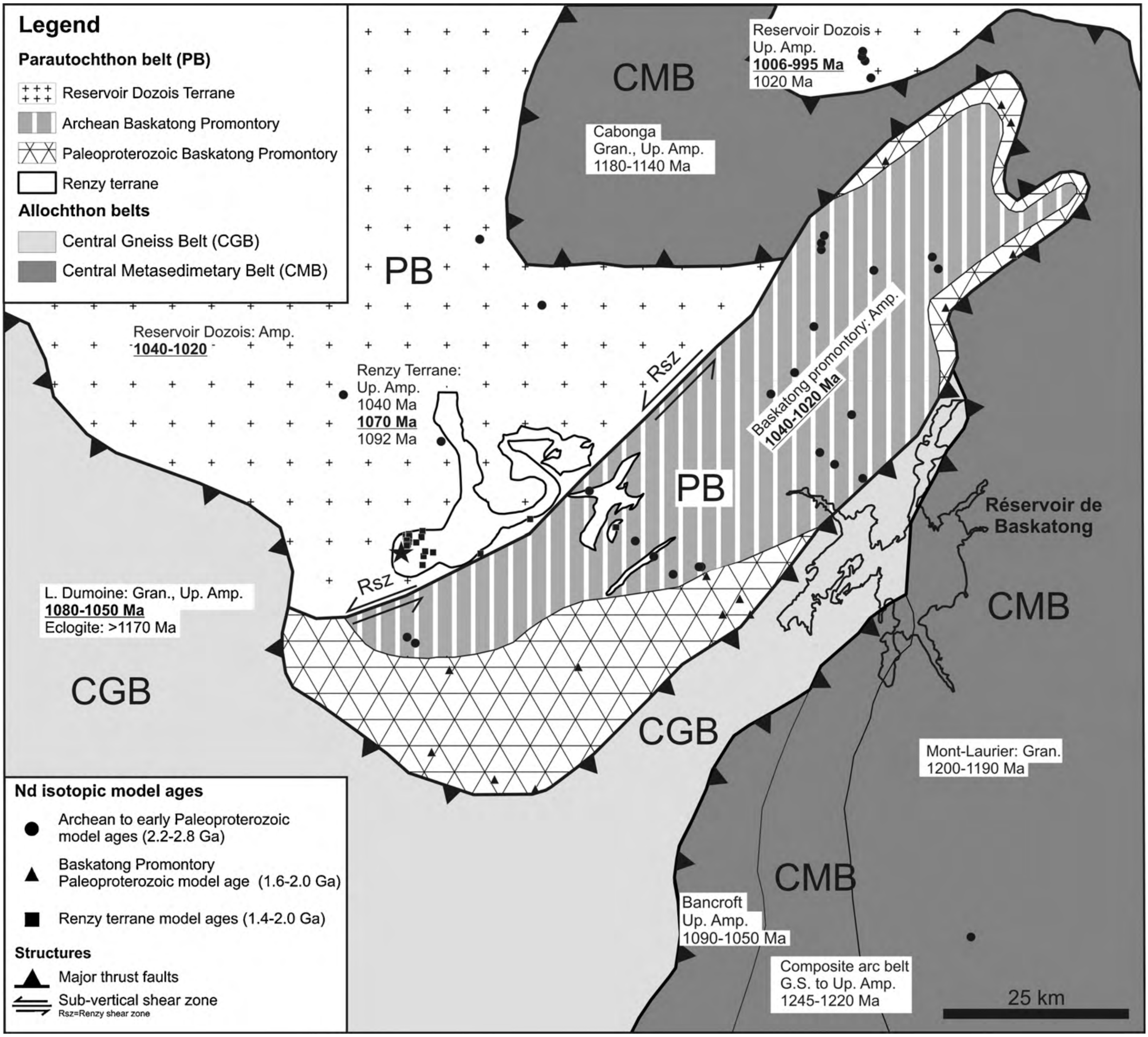

Fig. 2. Simplified geologic map of the western Grenville Province, Quebec (after Lyall, 1957, 1958; Sabourin, 1962; Guo and Dickin, 1996; Martignole et al., 2000; Rivers et al., 2002). Nd model ages from Guo and Dickin (1996) and Constantin et al. (2008) are shown. Metamorphic ages and intensities are indicated for each geologic terrane in the region. The star indicates the location of the Renzy mine. *Abbreviations*: G.S., greenschist facies; Amp., amphibolite facies; Up. Amp., Upper amphibolite facies; Gran., granulite facies.

Baskatong Promontory, whereas on the north side they overlie the Reservoir Dozois terrane; these are the two main terranes in the Parautochthonous Belt in this area. In the region where the RT is located, the Parautochthonous Belt forms a wide promontory into the allochthonous belts of the Grenville Province, with the allochthon boundary thrust marking the limit between the Parautochthonous and Allochthonous belts (Rivers et al., 1989). The Central Metasedimentary Belt (CMB), part of the allochthonous monocyclic belt of Rivers et al. (1989), marks the southeastern and eastern boundary of the Parautochthonous Belt, whereas the Central Gneiss Belt (CGB), part of the allochthonous polycyclic belt (Rivers et al., 1989), is adjacent to the southwestern and western boundary of the Parautochthonous Belt (Fig. 2) (Indares and Martignole, 1990; Martignole et al., 2000).

2.2. *Attributes of the Renzy terrane*

Four main criteria differentiate the Renzy terrane from the surrounding rocks of the Parautochthonous Belt. The first criterion relies on Nd model ages measured in the region (Guo and Dickin, 1996; Constantin et al., 2008) (Fig. 2). Using the depleted mantle model of DePaolo (1981), Guo and Dickin (1996) calculated Nd model ages, which are Paleoproterozoic (>1.8–2.0 Ga) in the Baskatong Promontory and near Archean (>2.4 Ga) in both the Baskatong Promontory and the Reservoir Dozois terrane. In contrast, five samples from the RT gave Nd model ages ranging from Mesoproterozoic (1.4 Ga) to Paleoproterozoic (2.0 Ga). Current work by Constantin et al. (2008) on thirty samples of felsic to ultramafic rocks from the RT gives an average Nd model age of 1.78 ± 0.14 Ga for the southwestern part of the RT, somewhat younger (within error) to those obtained by Guo and Dickin (1996) on 10 samples of biotite gneiss and plutonic rocks in the southwestern part of the Baskatong Promontory (mean: 1.92 ± 0.04 Ga). The model age difference between the RT, the Baskatong Promontory and the Reservoir Dozois terrane imply a more juvenile source for the RT formation.

The second criterion is based on metamorphic ages and grade (Fig. 2). In the Parautochthonous Belt, peak metamorphic conditions reached amphibolites facies around 1.04–1.02 Ga (late Ottawan orogeny) (Indares and Martignole, 1990; Rivers et al., 2002; Rivers, 2008). In the RT, peak metamorphic conditions reached upper amphibolites to granulite facies around 1.07 Ga (early Ottawan pulse) (Indares and Martignole, 1990; Childe et al., 1993). Pressure–temperature estimates obtained on a metagabbro of the RT define a maximum of 750 °C and 0.98 GPa (Indares and Martignole, 1990). A major contrast is seen in terms of timing and intensity of peak metamorphism between the RT and the Parautochthonous Belt. However, some similarities are observed between the RT and the Central Gneiss Belt. As in the case of the RT, the timing of the peak metamorphic event in the Central Gneiss Belt corresponds to the early Ottawan pulse (between 1.09 and 1.05 Ga), with maximum intensity at the granulite to upper amphibolite facies (Rivers et al., 2002).

The third criterion is based on the lithologic composition of the RT. The RT consists of a mixture of gneiss, amphibolite, and ultramafite, rocks that are not present in the Reservoir Dozois terrane nor the Baskatong Promontory of the Grenvillian Parautochthonous Belt (Indares and Martignole, 1990).

The fourth criterion is the distinctive aeromagnetic signature of the southwestern Renzy terrane compared to the regional Archean background. On filtered aeromagnetic maps, the southwestern part of the RT forms a strong positive and circular anomaly surrounded by the low aeromagnetic signature of the Archean orthogneisses of the Parautochthonous Belt (Fig. 3). However the strong aeromagnetic intensity is present only in the southwestern part of the Renzy terrane, possibly because of the occurrence of mafic and ultramafic lithologies and regional aeromagnetic maps do not help to distinguish the remaining sections of the RT from the Parautochthonous Belt and they are mainly defined based on the mapping done in the 1950s and 1960s by Lyall (1957) and Sabourin (1962).

The exact nature of the contacts between the RT and the surrounding Archean basement is poorly known. However our field observations in the southwestern part of the RT indicate shear zone boundaries between the RT and the Parautochthonous Belt. In this area, the boundaries are marked by mylonitic rocks, similar to those found in the Renzy shear zone. In addition, high-resolution aeromagnetic maps help to define the boundaries of the southwestern RT, which are generally represented by a high-intensity magnetic signature (Fig. 3).

The following parts of this paper focus on the southwestern part of the RT because detailed geologic maps and Nd model ages are available, partly as a result of the presence of Ni–Cu–Co–PGE prospects (Constantin et al., 2008).

2.3. *Geology of the southwestern Renzy terrane*

A diverse package of undifferentiated gneisses containing bands of mafic gneiss and ultramafic intrusions, with less abundant metagabbro and pegmatite, defines the southwestern RT (Fig. 4). The undifferentiated gneisses, initially identified as paragneiss during early mapping (Forrester, 1957; Lyall, 1958), possibly represent a volcanosedimentary sequence with compositions ranging from intermediate to felsic and they represent the dominant rock type found in the RT. The possible volcanic origin for some of the rocks is now inferred because no significant metamorphosed pelitic, quartzite, or carbonate units have been observed in the southwestern RT. Mafic gneisses form bands and lenses of sub-kilometre size; most of them have an apparent width of less than a few hundred meters, but they can extend laterally for ~5 km and be tightly folded within the gneiss sequence (Fig. 4). The surface geometry of the mafic gneiss units indicates that their protoliths could be volcanic flows, small sills or intrusive sheets intercalated within the undifferentiated gneiss sequence. This is confirmed by the high-resolution aeromagnetic map, in which the trends of the mafic gneiss bands and undifferentiated gneiss are concordant, implying that the mafic gneisses were formed prior to the episodes of deformation affecting the RT and may be contemporaneous with the undifferentiated gneiss sequence. The mafic gneisses are very diverse (Fig. 5B and C), and descriptions of the various facies follow this section. Ultramafic rocks generally form small intrusive sheets hosted in gneiss, but also small bands, especially in the southern part the southwestern RT. Ultramafic intrusions are generally composed of partially amphibolitized websterite, locally olivine bearing, with minor amounts of chromite-bearing peridotite. Intrusives sheets, host to Ni–Cu–Co–PGE occurrences, contain significant peridotite and locally show magmatic layering (Constantin, 2006b). A strongly foliated metagabbro unit, situated in contact with the Archean orthogneisses of the Reservoir Dozois Terrane, is interpreted as associated with the boundaries of the RT. A rare, late pegmatitic granitoid unit crosscuts all the other rock types at the Renzy mine. This lone occurrence might be an artefact of the detailed mapping carried out in the immediate surroundings of the mine.

2.4. *Subdivision of Renzy terrane mafic gneisses*

In order to define the geodynamic context of the RT, the mafic gneisses were used as pathfinder lithologies because they are reliable for such work. Petrographic and geochemical data obtained from mafic gneiss samples collected mainly in the southwestern RT but also in the eastern part are presented below. Mafic gneisses were discriminated from the intermediate and felsic volcanosedimentary sequence of the RT on the basis of their silica content. All samples with less than 54 wt.% SiO_2 from the previously identified amphibolite units on RT geologic maps were classified as mafic gneisses. Detailed petrological and geochemical characteristics of the intermediate and felsic sequences of the RT are found in Montreuil (2010).

On the basis of geochemical and petrological observations, mafic gneisses of the RT are subdivided into three groups (Fig. 4) (Table 1). Group 1 comprises gabbroic sills closely related to the ultramafic intrusions in the RT. They are melanocratic, with a mineralogy dominated by amphibole, clinopyroxene, and orthopyroxene, along with garnet and minor plagioclase. Accessory minerals include sulfides, titanite, and apatite (Fig. 5D). Group 2 is dominant in the RT, and these mafic gneisses show contrasting geochemical and petrological characteristics. Group 2 mafic gneisses consist mainly of an assemblage of amphibole, plagioclase, and clinopyroxene or orthopyroxene, with accessory biotite, oxides/sulfides, quartz, apatite, and titanite, or of an assemblage of plagioclase, biotite, and amphibole with accessory K-feldspar, apatite, quartz, sulfides, and oxide (Fig. 5E). Group 3 mafic gneisses are characterized by abundant garnet and poikiloblastic clinopyroxene. The poikiloblastic clinopyroxene with vermicular plagioclase inclusions and clinopyroxene/ilmenite symplectites might represent relicts of an eclogitic metamorphic event (Indares, 1993; Indares and Rivers, 1995) (Fig. 5F).

Relative compositional homogeneity of the groups 2 and 3 mafic gneisses occurring in the same band and their fine to medium grained texture precludes that these rocks are the product of fractional crystallization process, implying that their composition is close to the initial magma composition except for those of group 1 which look to be evolved product of the RT ultramafic sequence.

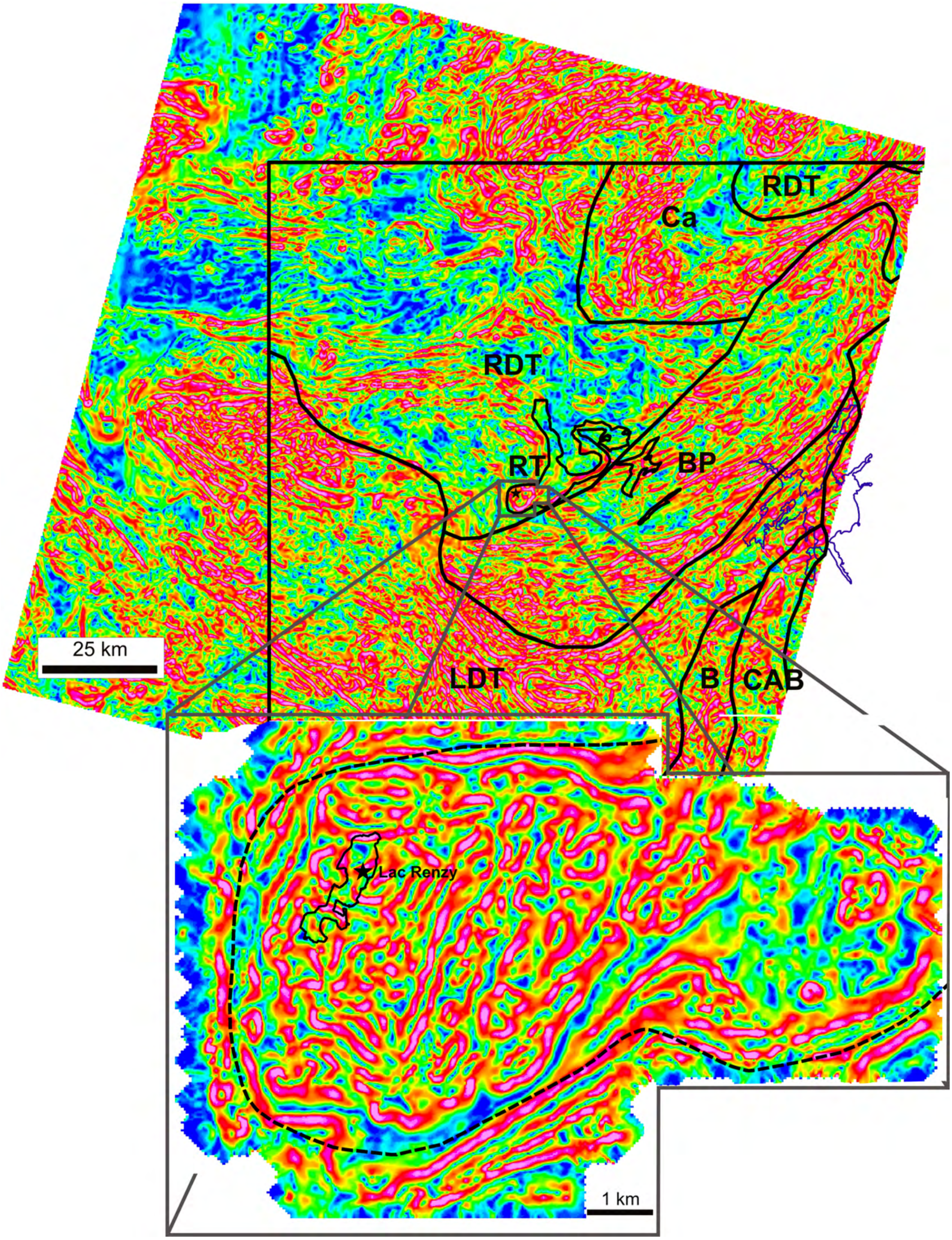

Fig. 3. Aeromagnetic map of the western Grenville Province and high-resolution magnetic map for the southwestern RT. Note the strong positive magnetic anomaly in the southwestern part of the RT. The star represents the Renzy mine. The dashed line indicates the approximate contact between the southwestern RT and the RDT. The red and blue colors stand for high and low magnetic intensity, respectively. The grids were filtered with a horizontal derivative filter. The raw data for the regional map were obtained from the Canadian Aeromagnetic Data Base, Regional Geophysics Section, GSC – Central Canada Division, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada; the raw aeromagnetic data for the high-resolution magnetic map were provided by Matamec Exploration.

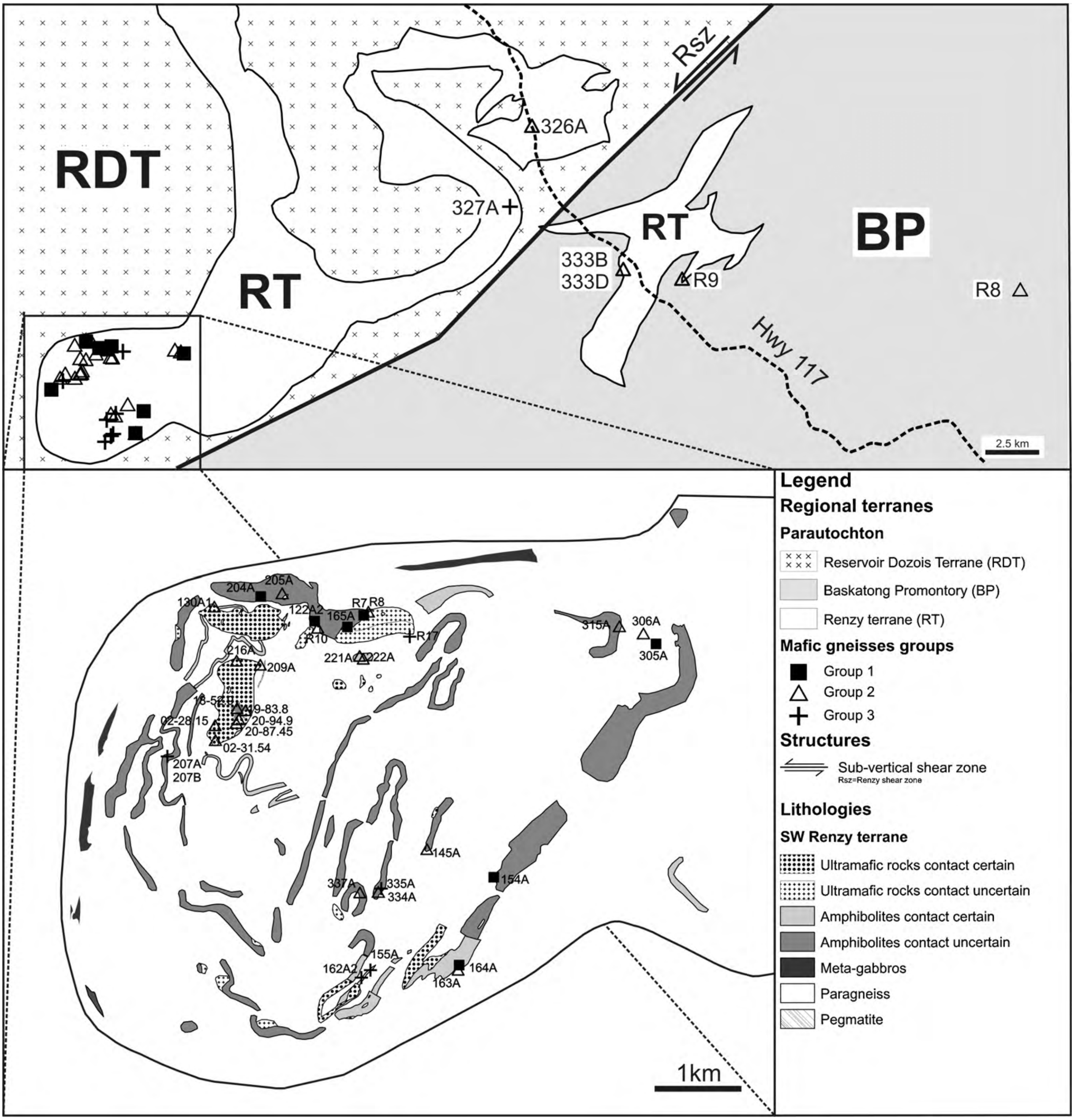

Fig. 4. Sample-distribution map of mafic gneisses in the RT and detailed geologic map of the southwestern part of the Renzy terrane. Modified from Lyall (1957, 1958) and Forrester (1957).

3. Geochemistry

3.1. Analytical methods

Thirty-three mafic gneiss samples collected from outcrops and six from drill cores have been analyzed (Table 2). All rock specimens were cut to remove weathered portions. The fresh interiors were subsequently crushed in a steel-plated jaw crusher and powdered using an agate ball mill. Whole rock major oxides and some trace elements (Ba, Sr, Zr, Y) were determined at Acme Labs (Vancouver, Canada) by ICP-AES after dilute nitric acid digestion and lithium metaborate/tetraborate fusion. Rare earth and other trace elements were determined by instrumental neutron activation analysis (INAA) at the Université Laval following the method of Constantin (2006a, 2009). Results for reference materials are given in Table 3.

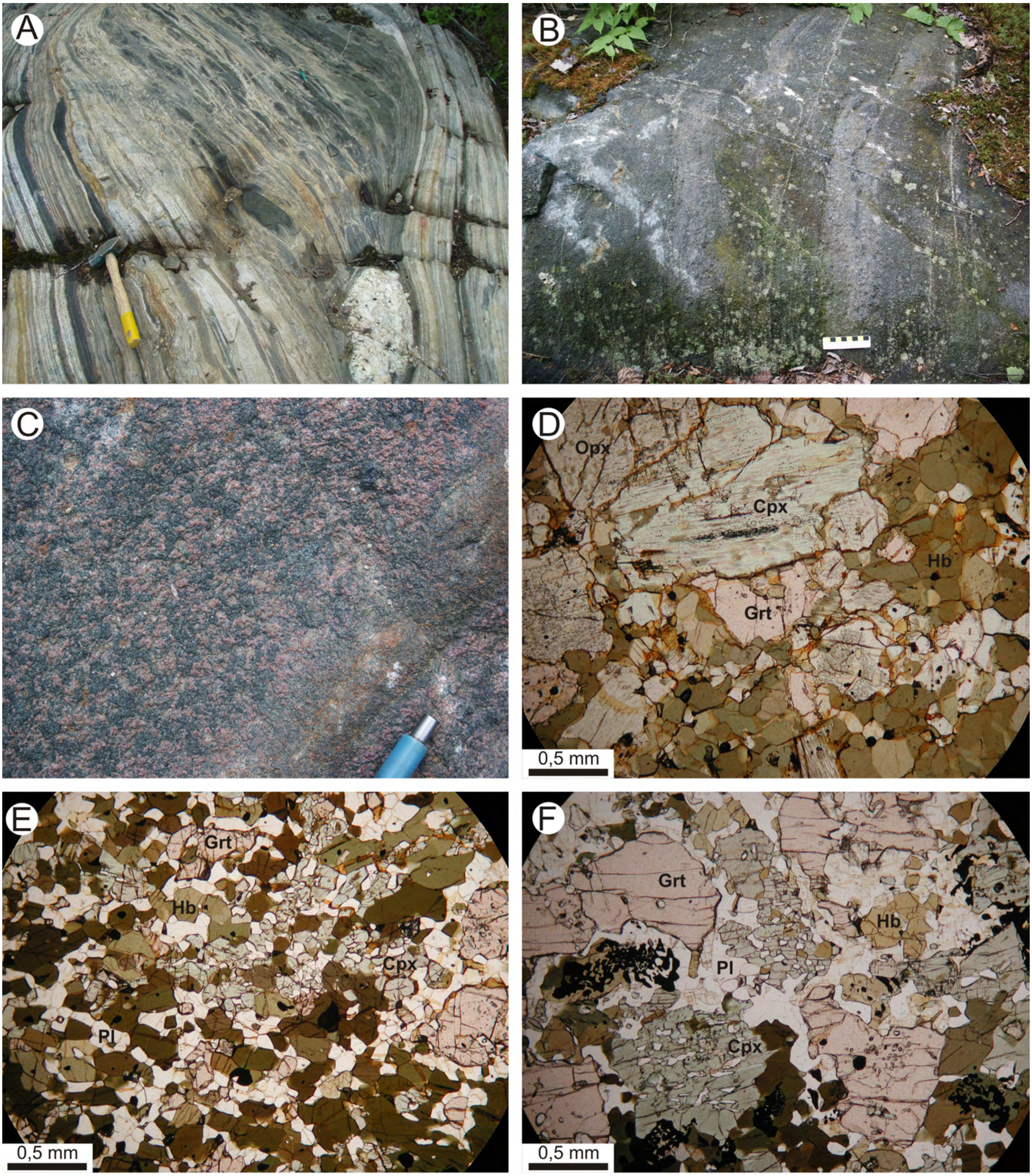

Fig. 5. (A) Mylonitic fabric characteristic of the ductile Renzy shear zone; (B) Melanocratic amphibolite with small lenses of ultramafic material; (C) typical appearance of a garnet amphibolite in the field; (D) typical texture in thin section of group 1 mafic gneisses coming from the same outcrop shown in (B); (E) typical texture in thin section of group 2 mafic gneisses; (F) typical texture in thin section of group 3 mafic gneisses. Mineral abbreviations after Kretz (1983).

All the Nb values presented in this paper were calculated from Ta concentrations measured by INAA. The Ta to Nb conversion factor used is $(16.5)^{-1}$, a ratio representative of their terrestrial reservoir abundances (Jochum et al., 2000).

3.2. Results

The immobile trace element discrimination diagrams of Winchester and Floyd (1977) and Pearce (1996) indicate that the

Table 1
Synthesis of petrographic descriptions for each RT mafic gneiss group.

Mafic gneiss group	Important features	Paragenesis[a]	Textures
Group 1	Strong recrystallization, Melanocratic	Hbl–Opx–Cpx–Pl ± Grt ± sulfides Hbl–Pl–Grt–Cpx ± sulfides	Granoblastic, nematoblastic
Group 2	Strong recrystallization, pale green to green–brown hornblende	Hbl brown–green/Hbl pale green–Pl–Cpx/Opx–Grt–sulfides–oxides ± Qtz	Granoblastic, nematoblastic
		Hbl–Pl–Cpx–Bt–Grt–oxides ± Qtz Hbl–Cpx–Pl–Bt–sulfides Pl–Hbl–Bt–Kfs–Ap–Qtz ± Grt ± Cpx ± Zrn	Lepidonematoblastic
Group 3	Strong alteration, garnet abundant (up to 35 wt.% of the rock), poikiloblastic clinopyroxene, brown–green hornblende	Cpx–Grt–Hbl brown green–Pl–Qtz–Ilm ± Ap	Granoblastic, nematoblastic

[a] Mineral abbreviations after Kretz (1983).

RT mafic gneisses are subalkaline and range in composition from basaltic to andesitic, except for one sample from group 2 that falls in the dacite field (Fig. 6A).

3.2.1. Major elements and chromium

The (Fe + Ti)–Al–Mg triangular diagram of Jensen and Pykes (1982) illustrates some differences between the mafic gneiss groups (Fig. 6B). Group 1 mafic gneisses fall mainly in the komatiitic field close to the RT ultramafic pole and along the boundary between the magnesian tholeiite and komatiitic fields. Group 2 mafic gneisses mainly fall in the Fe-tholeiite field of the diagram, whereas the remaining samples fall in the magnesian tholeiite or in the calc-alkaline fields. All group 3 mafic gneisses fall in the Fe-tholeiite field in the diagram.

The Jensen and Pyke diagram along with binary diagrams of Mg# (molecular MgO/(FeO + MgO) × 100), ($Fe_2O_3 + TiO_2$), CaO, and Cr vs.

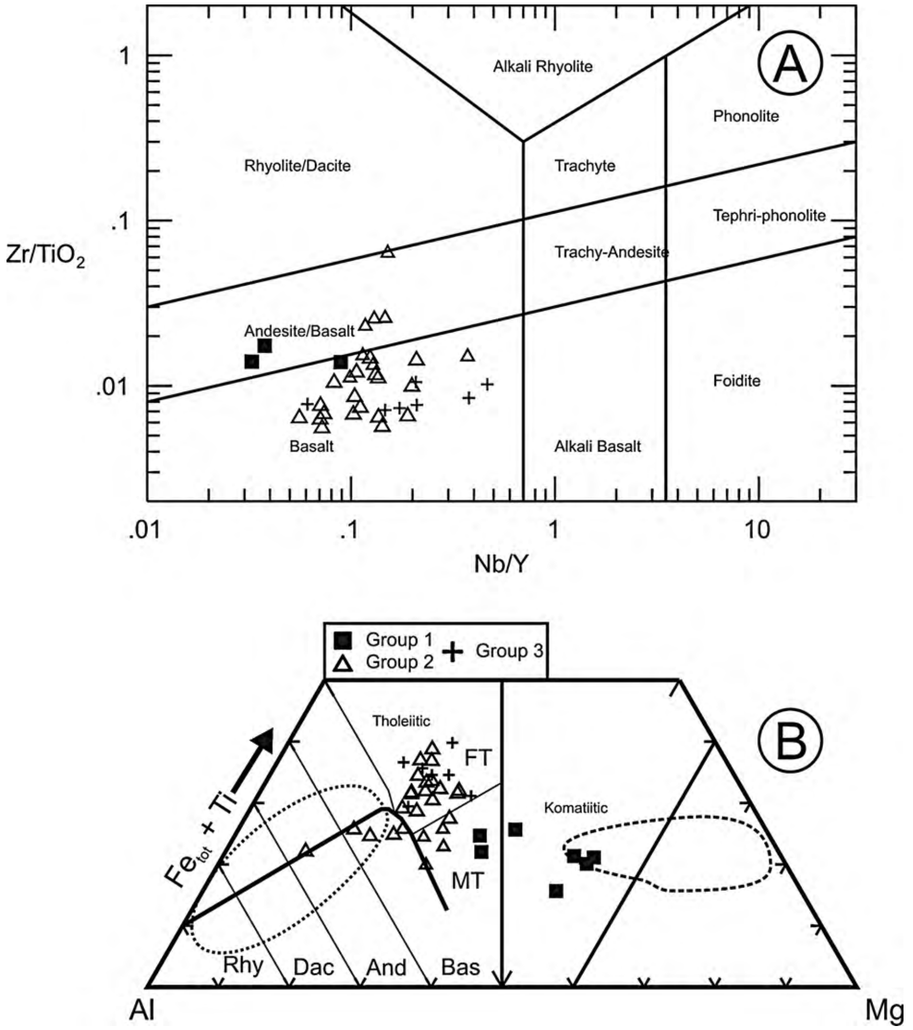

Fig. 6. (A) Zr/TiO_2 vs. Nb/Y plot of Winchester and Floyd (1977) modified by Pearce (1996); (B) Renzy terrane mafic gneisses projected on the Al–(Fe + Ti)–Mg triangular plot of Jensen and Pykes (1982). Note that Nb values = Ta (measured) × $(16.5)^{-1}$, using the conversion factor for the Nb/Ta primitive mantle ratio determined by Jochum et al. (2000). *Key*: dashed line – RT ultramafic rocks field; dotted line – RT intermediate and felsic rocks field; heavy line – tholeiitic/calc-alkaline field boundary. *Abbreviations*: FT, ferrian tholeiite; MT, magnesian tholeiite; Rhy, rhyolite; Dac, dacite; And, andesite; Bas, basalt.

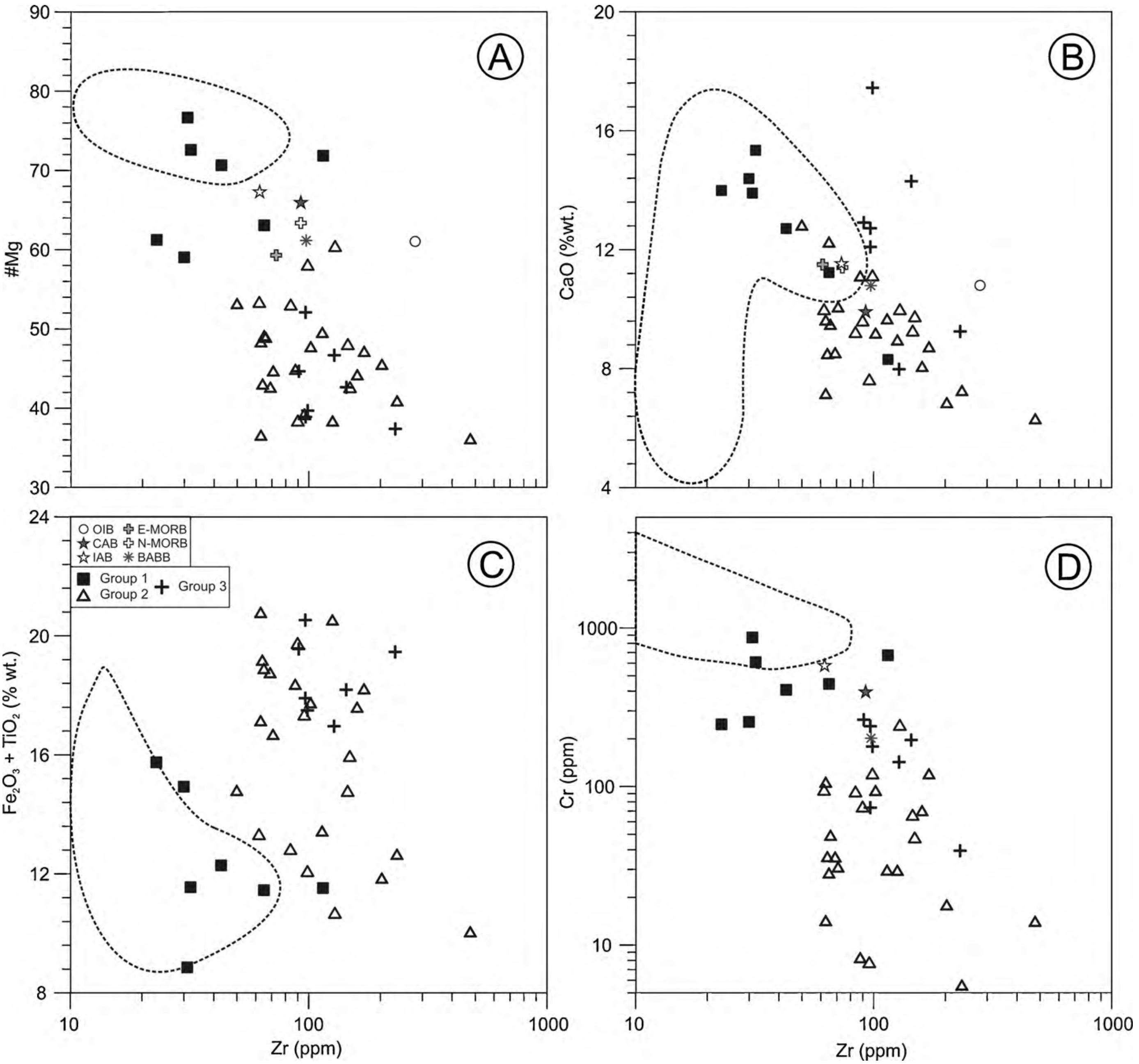

Fig. 7. Major and trace elements vs. Zr. Data for N-MORB, E-MORB, and OIB from Sun and McDonough (1989); data for IAB and CAB from Kelemen et al. (2004); data for BABB from Fretzdorff et al. (2002). *Key*: dashed line, field of RT ultramafic rocks.

Zr (zirconium is chosen because of its relative immobility under high-grade metamorphic conditions) highlight several differences between the groups of mafic gneisses (Fig. 7A–D and Table 2).

Group 1 mafic gneisses display high Mg# values and low ($Fe_2O_{3(TOT)} + TiO_2$), high CaO, and high Cr concentrations. They generally plot in continuity with or close to the RT ultramafic rock field, which distinguishes them from the other RT mafic gneisses.

Group 2 mafic gneisses show great dispersion in the Mg# values and in CaO, Cr, and ($Fe_2O_{3(TOT)} + TiO_2$) concentrations. Many samples of group 2 mafic gneisses show high concentrations of ($Fe_2O_{3(TOT)} + TiO_2$) (between 14% and 20%).

Group 3 mafic gneisses exhibit higher CaO values (mean 12.4%) compared to the other mafic gneisses with similar amounts of Zr (mean of 9.3% for group 2 mafic gneisses). Some of these high CaO concentrations could be the result of a previous episode of metasomatism affecting some of these rocks. Group 3 also has Mg# values comparable to those of group 2 mafic gneisses. The Cr concentrations of this group are generally higher than those in group 2. These mafic gneisses also display the highest values in ($Fe_2O_{3(TOT)} + TiO_2$) (mean 18.5 wt.%).

Although some groups 2 and 3 mafic gneisses are fairly primitive, none of them can be considered representative of primitive magmas because of their low Mg# and Cr values. In some group 2 samples and in all group 3 mafic gneisses, high concentrations of Fe_2O_3 and TiO_2 indicate that these rocks are probably derived from ferrogabbro/ferrobasalt protoliths, which are generally found in extensional settings (see Table 1) (Raveggi et al., 2007).

3.2.2. Trace elements

Trace element plots are shown in Fig. 8. The high field strength elements (HFSE), rare earth elements (REE), and Ba generally show positive covariation with Zr (Fig. 8A–C).

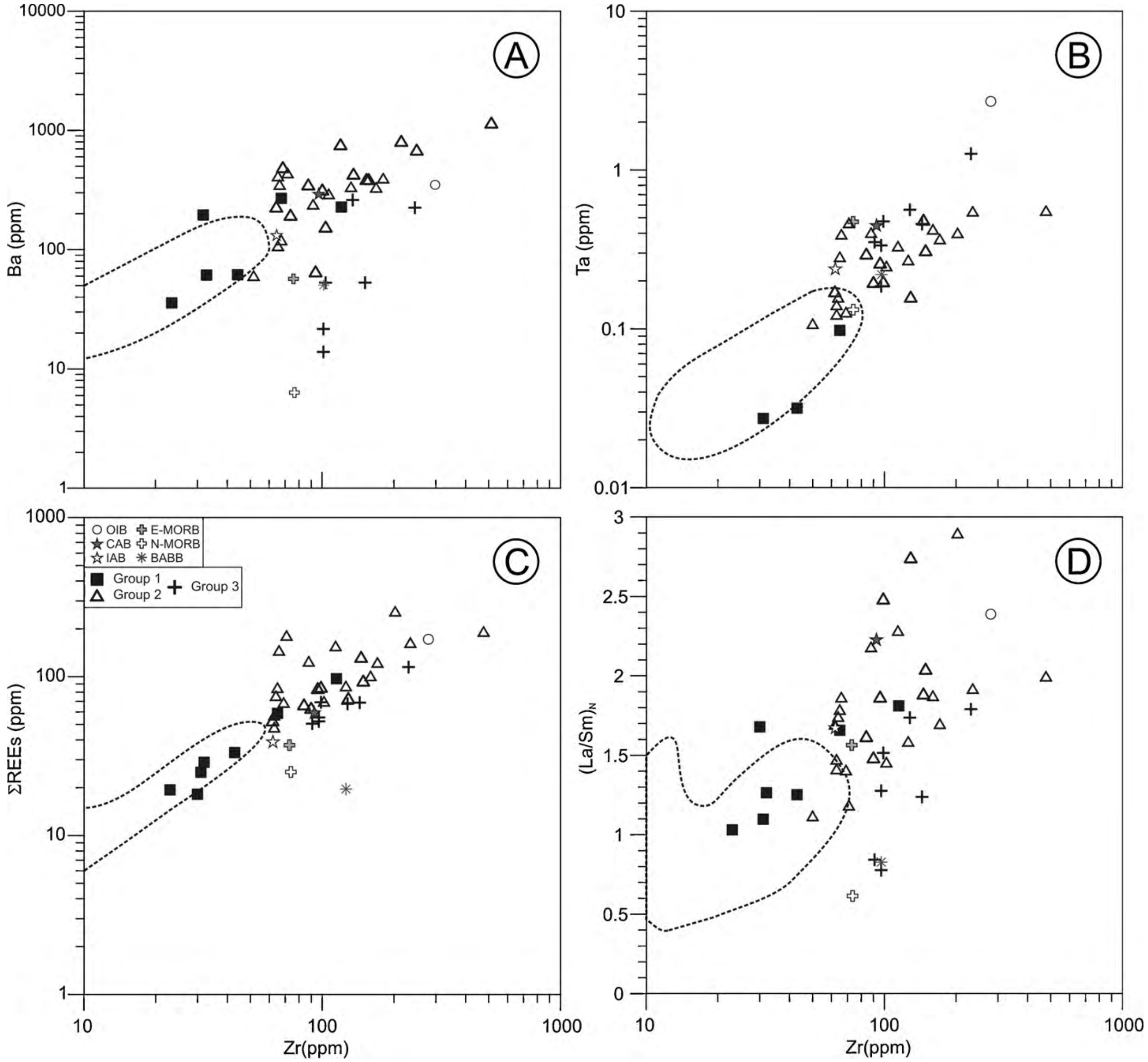

Fig. 8. Trace element contents and chondrite-normalized (Palme and Jones, 2004) La/Sm ratio vs. Zr. Data for N-MORB, E-MORB, and OIB from Sun and McDonough (1989); data for IAB and CAB from Kelemen et al. (2004); data for BABB from Fretzdorff et al. (2002). *Key*: dashed line – field of RT ultramafic rocks.

The good covariation between the REE, especially the LREE, and Zr contents indicates that the REE, like Zr, were relatively immobile during metamorphism (Fig. 8C). Large ion lithophile elements (LILE) generally exhibit either a weak positive correlation or a scattered distribution with respect to Zr, indicating the potential mobility of these elements after magmatic crystallization of the rocks. Group 2 mafic gneisses exhibit the largest variations in Ba and REE concentrations, whereas group 3 mafic gneisses have the lowest Ba and REE contents for equivalent Zr concentrations. In group 1 mafic gneisses, Ba and REE concentrations are not as scattered, are generally low, and correlate with the concentrations observed in the RT ultramafic rocks. Barium values of a few hundred ppm are elevated relative to N-MORB (6 ppm) or E-MORB (57 ppm) (Sun and McDonough, 1989), but closer to those found in (ocean island basalt) OIB (350 ppm) (Sun and McDonough, 1989) or primitive oceanic and continental arc basalts (respectively, 133 and 295 ppm) (Kelemen et al., 2004). Ba concentrations in group 2 mafic gneisses encompass Ba concentrations found in all known geodynamic settings; those in group 3 range from the N-MORB pole to the E-MORB pole, except for two samples closer to the OIB pole. Group 3 mafic gneisses also define a distinct trend on the $(La/Sm)_N$ vs. Zr diagram, whereas most of the other RT mafic gneisses follow a trend in continuity with that defined by the RT ultramafic intrusions in the $(La/Sm)_N$ vs. Zr diagram (Fig. 8D).

4. Discussion

The mafic gneiss groups identified so far have been found in all parts of the RT and in many cases are located in close proximity. As mentioned previously, Nd isotope compositions of most mafic gneisses and pyroxenites, as well as some gneisses from the southwestern RT, have similar crustal residence ages of 1.78 ± 0.14 Ga (Constantin et al., 2008, and unpublished data). If we assume that the oldest available U–Pb zircon age of 1.40 Ga obtained for the Renzy terrane by Martignole and Ringuette (1998) represents the minimum crystallization age of the mafic gneisses and pyroxenites, we obtain $\varepsilon_t(\mathrm{Nd}) = +2.5$ ($n = 27$), which indicates that the protoliths of these rocks were derived mostly from an enriched mantle source and only in minor proportion from continental crust. Coeval igneous ages of 1.39 Ga have been obtained from the Bondy gneiss complex (Wodicka et al., 2004) and the Portneuf-Mauricie Domain (Sappin et al., 2009). The Nd isotope results and the presence of primitive ultramafic rocks displaying no sign of extensive crustal contamination associated with the mafic gneisses strongly support a juvenile nature for the RT. Consequently, we believe that many of the features observed on chondrite- and PM-normalized diagrams reflect a mantle source for the mafic gneisses.

4.1. *Chemical characteristics of the mantle sources*

Observations about major and trace element contents point to various mantle sources for the igneous precursors of the RT mafic gneisses. Major element compositions indicate that the majority of the RT mafic gneisses correspond to tholeiite and, to a lesser extent calc-alkalic magmas. Trace element data indicate a covariation of both HFSE and REE contents with Zr, which implies the relative immobility of these elements after igneous crystallization of the rock; on the other hand, the results show that some LILE were more mobile.

Based on the variations of major and trace elements, group 1 mafic gneisses are the most primitive. On major and trace element diagrams (Figs. 7–10), they are usually in continuity or in close association with the compositional field of RT ultramafic rocks; furthermore, they are generally spatially related to the ultramafic intrusions (Fig. 4). On the chondrite- and PM-normalized diagrams (Figs 9A and 10A), these rocks also plot in the field of RT ultramafic rocks. These observations indicate that group 1 mafic gneisses may represent the gabbroic end-members of a suite of intrusions that includes the RT ultramafic bodies. This assertion implies that these mafic gneisses did not crystallize from primitive magmas but are the product of fractional crystallization; therefore, they are not plotted in discrimination diagrams for geodynamic environment. Group 1 mafic gneisses and associated ultramafic rocks have trace element profiles that closely match those of rocks formed from magmas generated in mantle that was previously metasomatized by subduction process; group 1 rocks have gently to moderately sloping REE profiles ($\mathrm{La/Yb_N} = 2.4–4.7$), negative anomalies in HFSE (Ta, Zr, Hf and Ti), slight positive anomalies in LILE (Th, Ba, Sr) and high Th/Yb ratios (Pearce et al., 1994; Elliott et al., 1997).

Group 2 mafic gneisses exhibit scattered trends on major element plots but rather continuous trends on trace elements plots. On chondrite- and PM-normalized diagrams, these rocks can be subdivided into two subcategories: those that exhibit no negative Ti anomalies and those with variable negative Ti anomalies (Figs 9B and C, and 10B and C). Group 2 mafic gneisses with no negative Ti anomalies are generally characterized by high concentrations of Fe and Ti, variable slopes on chondrite-normalized REE diagrams, low to high concentrations of LILE and variable nega-

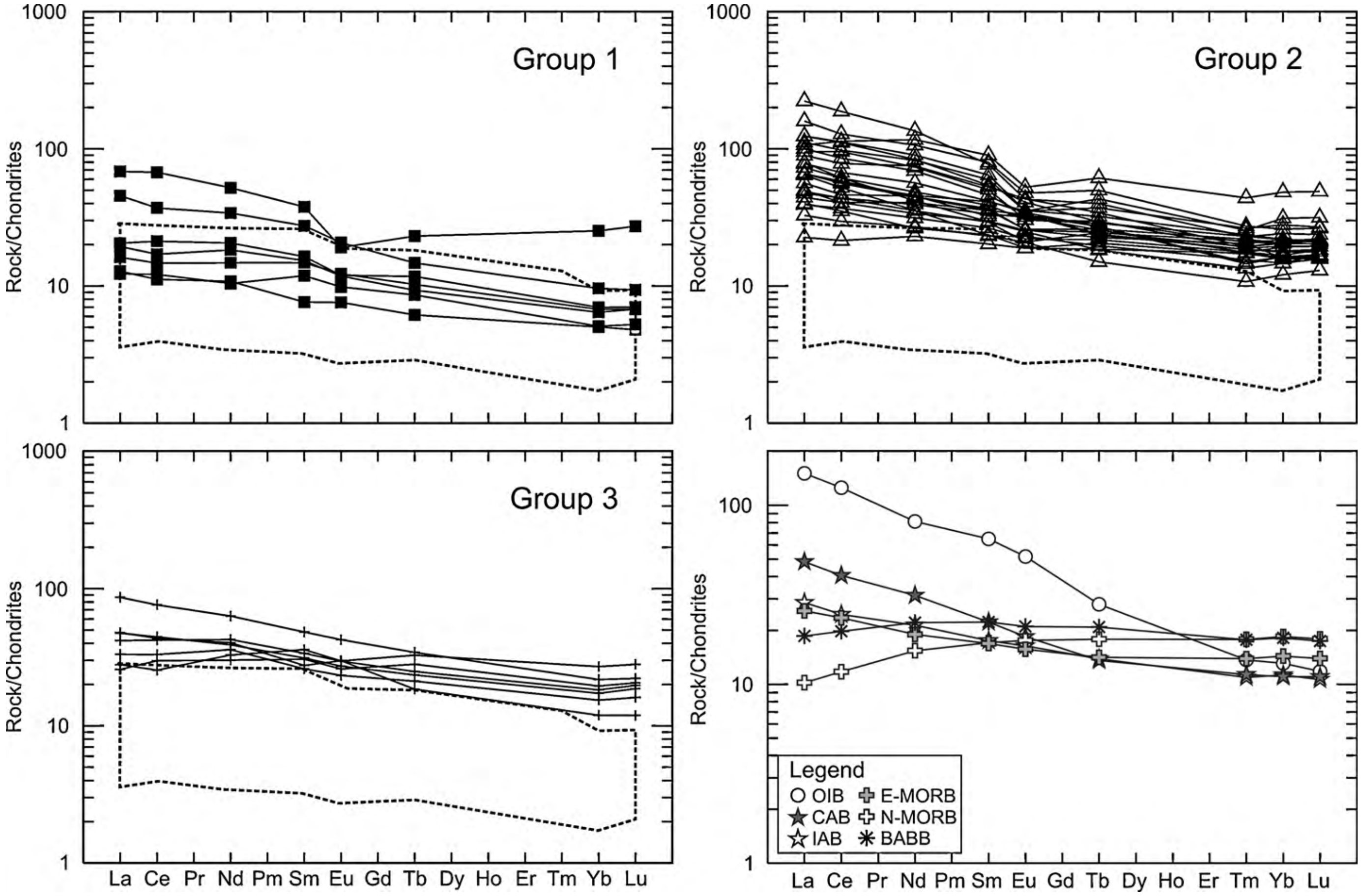

Fig. 9. Chondrite-normalized REE patterns. Data for N-MORB, E-MORB, and OIB from Sun and McDonough (1989); data for IAB and CAB from Kelemen et al. (2004); data for BABB from Fretzdorff et al. (2002). Chondrite normalization values are from Palme and Jones (2004). *Key*: dashed line – field of RT ultramafic rocks.

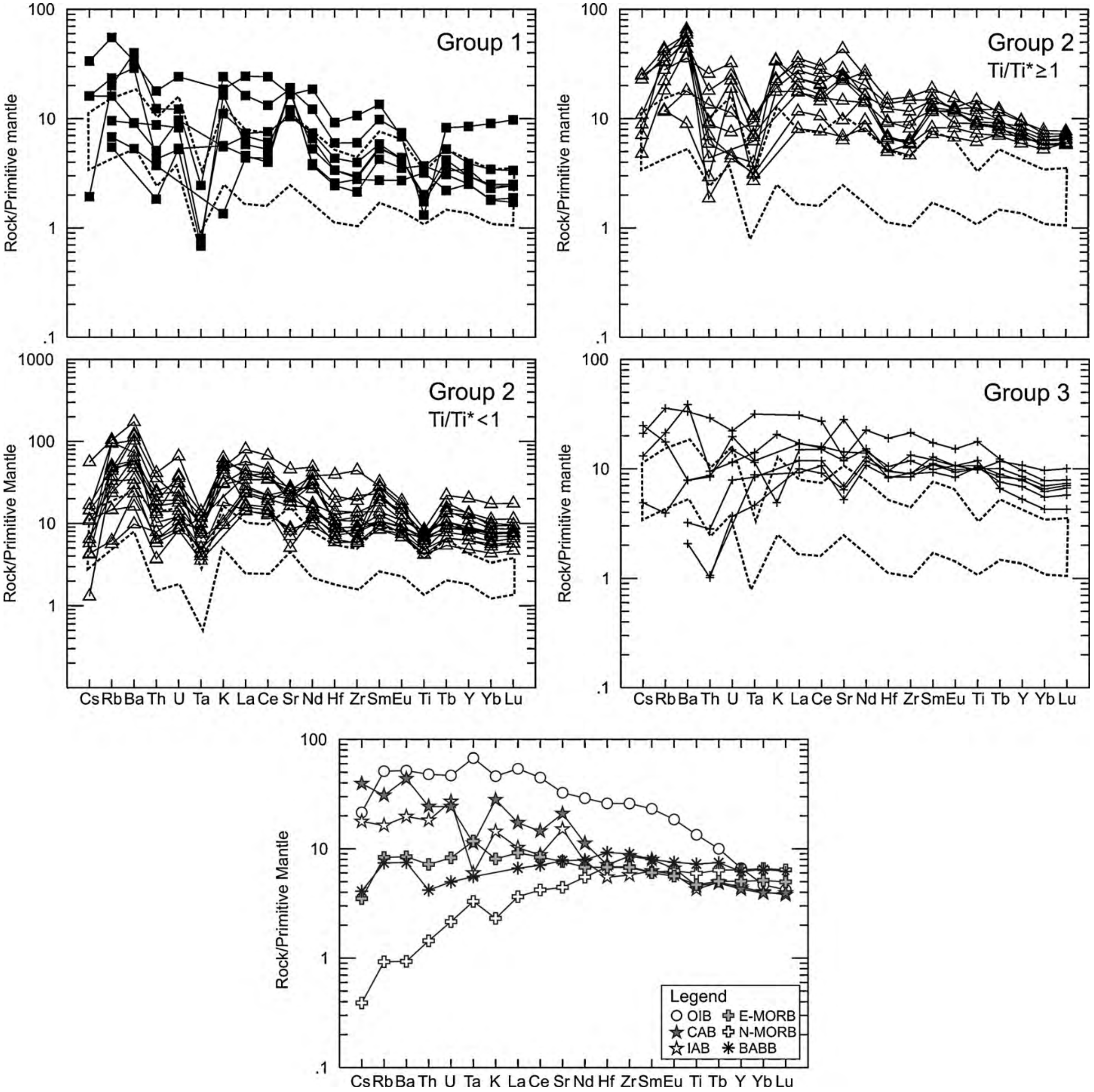

Fig. 10. Primitive mantle-normalized multi-element patterns. Data for N-MORB, E-MORB, and OIB from Sun and McDonough (1989); data for IAB and CAB from Kelemen et al. (2004); data for BABB from Fretzdorff et al. (2002). Primitive mantle normalization values are from Palme and O'Neill (2004). *Key*: dashed line – field of RT ultramafic rocks.

tive to no anomalies in HFSE on PM-normalized plots. Group 2 mafic gneisses with negative Ti anomaly are generally characterized by lower concentrations of Fe and Ti, gentle to abrupt slopes on chondrite-normalized REE diagrams, variable concentrations of LILE and negative anomalies in HFSE on PM-normalized diagrams. These rocks also exhibit low Th/La_N ratios, a feature typical of rocks formed in ensimatic, continental back-arc or arc-rift settings (Hollings and Kerrich, 2000; Culshaw and Dostal, 2002; Sandeman et al., 2006). These general characteristics indicate that group 2 mafic gneisses with and without positive Ti anomaly were derived from magmas formed in an extensional setting where the mantle source was previously modified by subduction-related metasomatism. Indeed, high concentrations of Fe–Ti and low Th/La_N ratios are characteristic of extensional settings (Hollings and Kerrich, 2000; Culshaw and Dostal, 2002; Sandeman et al., 2006; Raveggi et al., 2007). The variable depletion in HFSE (Ta, Zr, Hf) and enrichment in LREE indicate that these gneisses crystallized from magmas formed in a mantle modified by subduction processes (Pearce et al., 1994; Elliott et al., 1997). Since group 2 mafic gneisses are the most abundant and found everywhere in the RT, the igneous activity related to their formation was accordingly the most important magmatic stage in the RT.

Group 3 mafic gneisses exhibit different geochemical features from those of groups 1 and 2. They display either flat or gently sloping chondrite-normalized profiles, with negative anomalies in LILE and/or no negative anomalies in HFSE ($La/Yb_N = 1–1.3$, and 2.2–4) (Figs 9D and 10D). These rocks also show high concentrations of Fe and Ti. Enrichment in these elements is characteristic of rocks formed in an extensional setting, and as these rocks occur throughout the RT, it indicates that the extensional event affected the entire RT.

Mantle sources for the RT mafic gneisses can also be traced using the Th/Yb–Ta/Yb diagram of Pearce (1982), the Ta–Hf/3–Th triangular diagram of Wood (1980), and the Zr–Ti/100–Y*3 triangular diagram of Pearce and Cann (1973) (Fig. 11A–C). These diagrams, as well as the La/Sm_N ratio, indicate that the RT mafic gneisses were derived from a wide variety of mantle sources (Fig. 8D). Group 1 mafic gneisses, along with all the RT ultramafic rocks, came from a subduction-influenced mantle source as they show high Th/Yb ratios, well above the mantle array in Fig. 11C. Group 2 mafic gneisses exhibit a scattered distribution on the Pearce (1982) and Wood (1980) diagrams. On Fig. 11A, they form a continuous trend from the arc field to the N-MORB field. The same pattern is seen in Fig. 11C, where these rocks, with their low to high Th/Yb ratios, exhibit variable addition of "crustal" components (Sandeman et al., 2006). Group 2 mafic gneisses generally fall within or just slightly above the field for the East Scotia Ridge (a typical ridge formed in a back-arc basin setting with OIB influence) rocks, but they plot close to the Mariana Arc field (Fretzdorff et al., 2002). These characteristics indicate that group 2 mafic gneisses

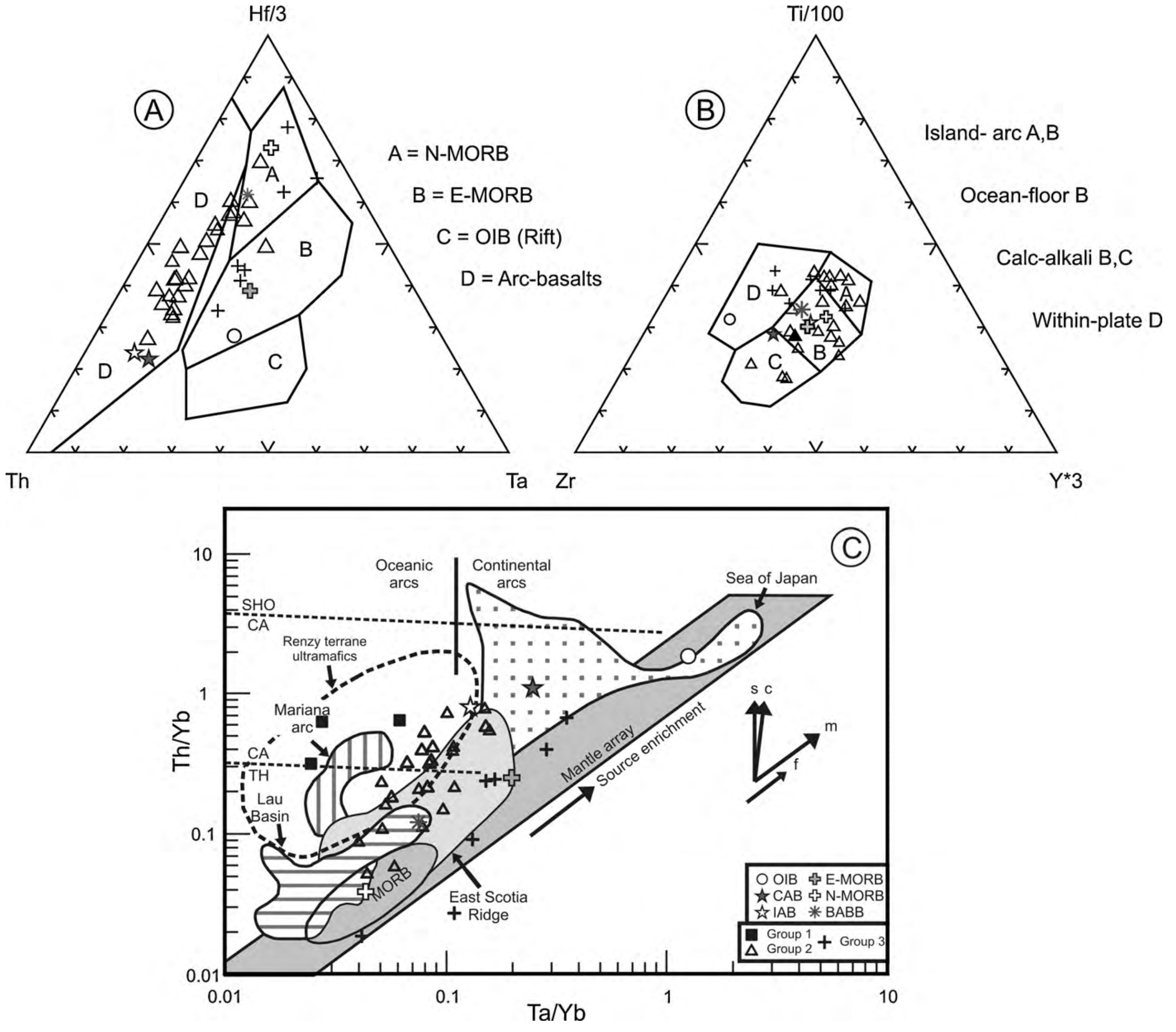

Fig. 11. (A) Th–Hf/3–Ta triangular diagram for discriminating tectonic environments (Wood, 1980); (B) Zr–Ti/100–Y*3 triangular diagram of Pearce and Cann (1973), which allows a better discrimination of the OIB-like rocks in the RT. *Key*: dashed field for RT ultramafic rocks; (C) Th/Ta vs. Ta/Yb diagram of Pearce (1982), modified from Sandeman et al. (2006) for basalts to illustrate their compositions relative to the mantle array. Group 1 plots close to the Mariana arc field, whereas the other groups are dispersed between the Mariana arc (MA) and East Scotia Ridge (ESR) fields, except for two group 3 samples which have a stronger OIB-like component and therefore plot closer to the OIB pole in the mantle array; light grey fill – East Scotia Ridge basalt (Fretzdorff et al., 2002); medium grey fill – mantle array (Pearce, 1982); horizontal ruled fill – Lau Basin (Pearce et al., 1994); vertical ruled fill – Mariana arc (Elliott et al., 1997); dotted fill – Sea of Japan (Pouclet et al., 1994). *Abbreviations*: TH, tholeiitic series; CA, calc-alkaline series; SHO, shoshonitic series; MORB, mid-ocean ridge basalts; s, subduction components; c, crustal contamination components; m, mantle source variation; f, fractional crystallization of olivine + clinopyroxene + plagioclase.

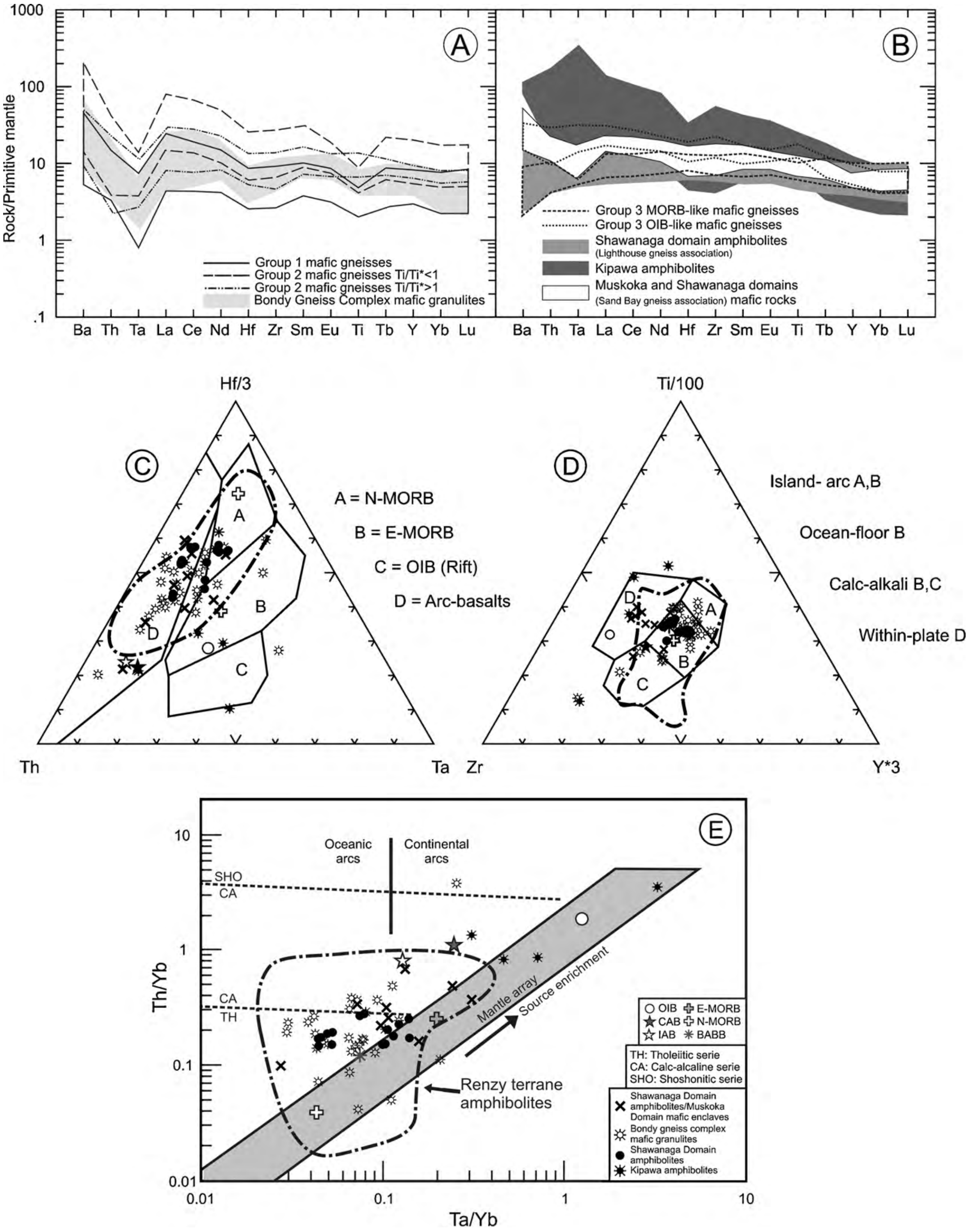

Fig. 12. (A) Primitive mantle – normalized multi-element patterns for the RT groups 1 and 2 mafic gneisses and the Bondy Gneiss Complex; (B) primitive mantle – normalized multi-element patterns for group 3 MORB-like and OIB-like mafic gneisses compared to Shawanaga domain amphibolites, the Muskoka domain mafic enclaves, and Kipawa amphibolites (Kikwissi suite and Lac McKillop sequence); (C) Th–Hf/3–Ta triangular diagram for discriminating tectonic environments, after Wood (1980); (D) Zr–Ti/100–Y*3 triangular diagram of Pearce and Cann (1973); (E) Th/Ta vs. Ta/Yb diagram of Pearce (1982), modified from Sandeman et al. (2006), illustrating the covariation between the mantle sources for RT mafic gneisses and mafic granulites of the Bondy Gneiss Complex, the Shawanaga domain amphibolites, and the Muskoka domain mafic enclaves. Note that the Kipawa amphibolites fall close to the OIB domain, next to the OIB-like mafic gneisses of group 3 from the RT. *Key*: the symbols in C and D are explained in E; the long-dashed field encompasses RT amphibolites in C and D. Data for the Bondy Gneiss Complex from Blein et al. (2003); data for the Shawanaga Domain from Culshaw and Dostal (2002) (full circle) and Slagstad et al. (2004) (X); data for the Kipawa amphibolites from van Breemen and Currie (2004). Abbreviations are the same that the ones used in Fig. 11C.

were probably formed in an extensional setting from a mantle source variably influenced by subduction processes, a feature typical of rocks formed in a back-arc setting. This is confirmed in Fig. 11B, where almost all samples overlap the arc/MORB fields, suggesting an environment transitional between compressional and extensional. Group 3 mafic gneisses fall within or close to the mantle array in Fig. 11C, indicating a mantle source not previously impacted by crustal input. Moreover, the mafic gneisses of group 3 mostly fall within E-MORB and N-MORB fields in Fig. 11A and B. These features are typical of mafic rocks formed in extensional environments. However, two samples from group 3 display higher Ta/Yb ratios and plot closer to the OIB pole, indicating that OIB-like magmatic activity may have occurred during RT evolution. This interpretation is supported by the Zr–Y/3–Ti/100 Pearce and Cann (1973) diagram, where these samples fall in the within-plate field, whereas the other RT mafic gneisses generally overlap the arc-MORB fields.

4.2. *Comparison with other Grenvillian mafic gneisses*

RT mafic gneisses share some similarities with those found in the southwestern part of the Grenville Province. We have compared our results with various metabasites from the following localities: (1) the Bondy gneiss complex mafic granulites located in the Central Metasedimentary Belt and identified as the product of a 1.4 Ga arc/back-arc basin at the Laurentian margin (Blein et al., 2003); (2) the Shawanaga domain amphibolites (Lighthouse and Sand Bay gneiss associations), an undated (although probably aged between 1.45 and 1.33 Ga) back-arc basin located in the Central Gneiss Belt (Culshaw and Dostal, 2002; Slagstad et al., 2004); (3) the Kikwissi suite and the Lac McKillop sequence amphibolites (undated but bracketed between 1.23 and 1.68 Ga), located in the Parautochthonous Belt of the Kipawa region and with a chemistry suggestive of intraplate continental magmatism (van Breemen and Currie, 2004); and (4) Muskoka domain mafic enclaves, whose age is probably between 1.48 and 1.43 Ga and whose chemistry is suggestive of a back-arc basin setting (Slagstad et al., 2004). On PM-normalized multi-element plots, profiles for mafic gneisses from groups 1 and 2 are generally similar to those of the mafic granulites of the Bondy gneiss complex (Fig. 12A). Most of the mafic gneisses from group 3 follow roughly the trend defined by the metabasites from both the Shawanaga and Muskoka domains, except for the OIB-like mafic gneisses from group 3 that get closer to the profiles of the Kipawa amphibolites (Fig. 12B). In Fig. 12C, mafic granulites from the Bondy gneiss complex and amphibolites from both the Shawanaga and Muskoka domains have a distribution transitional between the arc and MORB fields; their distribution is almost identical to that of the RT mafic gneisses of groups 2 and most of group 3. The Kipawa amphibolites fall in or close to the within-plate field, in a similar way to the OIB-like mafic gneisses of group 3 (Fig. 12C). The same relations are repeated in Fig. 12D and E, where mafic granulites from the Bondy gneiss complex and amphibolites from the Shawanaga domain are superimposed on the area defined by the RT mafic gneisses, in the depleted mantle and subduction-influenced mantle fields. Kipawa amphibolites plot closer to the OIB pole and consequently near the RT mafic gneisses with an OIB-like signature (Fig. 12D and E). An exception is seen in Fig. 12D, where amphibolites from the Sand Bay gneiss association of the Shawanaga domain plot mainly in the OIB field instead of the MORB/arc fields.

This comparison shows that the RT mafic gneisses are very similar to the mafic rocks in arc/back-arc settings previously identified in the Grenville Province, such as the Bondy gneiss complex and the Shawanaga and Muskoka domains. The comparison also suggests that the RT magmas probably locally tapped an OIB source during their evolution.

4.3. *Geodynamic setting of the Renzy terrane*

To account for the contrasting geochemical signatures found in the RT and the geochemical similarities between RT mafic gneisses and the Bondy Gneiss Complex/Shawanaga domain amphibolites, we propose that Renzy terrane rocks were formed in an arc/back-arc system related to a subduction zone. In fact, the proposed geodynamic environment must be able to produce a wide variety of rock signatures, ranging from MORB to arc. It is now known that in back-arc basins, rocks with signatures ranging from arc-like to MORB-like can be produced in a short lapse of time, depending in part on the distance between their site of emplacement and the subduction zone (Fretzdorff et al., 2002; Sandeman et al., 2006). The magmatic activity produced mafic magmas similar to those generated in the modern East Scotia Ridge, as was shown in Fig. 11C. OIB-like rocks also occur in the RT, indicating that during its evolution the RT tapped an OIB-like source. This is confirmed by the geochemical similarities between Kipawa amphibolites, ascribed to intraplate continental magmatism (van Breemen and Currie, 2004), and the OIB-like mafic gneisses from the RT. Identification of the RT as an arc/back-arc system indicates that subduction processes were active close to the Laurentian margin at the beginning of the Mesoproterozoic and that the RT represents one of the numerous arc/back-arc systems accreted to Laurentia during the one of the numerous orogenic events that impact this margin.

5. Conclusions

Four criteria can be used to differentiate the components of the RT from the parautochthonous (BP and RDT) terranes in the region. An important criterion is the Nd isotope model ages, but also the metamorphic signature, the distinct lithologic composition, and the high aeromagnetic intensity of the southwestern part of the RT. The chemistry of RT mafic gneisses indicates that they probably originated from arc/back-arc activity temporally correlated with coeval arc activity along the Laurentian margin during the late Paleoproterozoic to early Mesoproterozoic. This hypothesis is supported by the contrasting geochemical signatures found in RT mafic gneisses and the similarities between RT mafic gneisses and those from other localities in the Grenville Province previously identified as arc/back-arc basin systems (Bondy gneiss complex and Shawanaga Domain). Three mafic gneiss groups were identified on the basis of petrographic and geochemical criteria. Group 1 mafic gneisses are probably mafic sills related to the ultramafic rocks of the RT; they have a geochemical signature typical of rocks formed from a mantle source previously affected by subduction processes, as suggested by their high Th/Yb ratios and their strong depletion in HFSE. Group 2 mafic gneisses have a transitional signature between an arc and a rift environment. All these features need an arc/back-arc tectonic environment that is capable of producing a wide variety of magmatic products in a short lapse of time, and we suggest that the RT was formed in such a tectonic environment, in a similar fashion to the Bondy Gneiss Complex and the Shawanaga Domain. The RT represents a juvenile arc/back-arc fragment accreted as a thrust sheet over the Parautochthonous Belt of the Grenville Province.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2010.06.001.

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