Nd isotopic and trace element constraints on the source of Silurian-Devonian mafic lavas in the
Chaleur Bay Synclinorium of New Brunswick (Canada): tectonic implications

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Abstract

Upper Silurian to Lower Devonian volcanic rocks of the Gander Zone, from the northern mainland Appalachians of northern New Brunswick, occur in the Chaleur Bay Synclinorium which forms the southeastern part of the Middle Paleozoic Matapedia cover sequence. These rocks, which are parts of shallow marine to subaerial sequences (Dalhousie, Dickie Cove and Tobique groups), were erupted in a continental rift environment between ca. 422 and 407 Ma. The volcanic rocks are mostly bimodal with mafic types corresponding predominantly to continental tholeiites inferred to be generated by partial melting of subcontinental lithospheric mantle (SCLM). The mafic rocks of all three groups have age-corrected ϵ_{Nd} values ranging from +3.4 to +5.3, and depleted model mantle ages ranging from 0.65 to 0.95 Ma that are interpreted to represent mantle enrichment ages associated with ancient Neoproterozoic subduction. This Neoproterozoic SCLM shows no contributions from juvenile Silurian mantle, suggesting that rifting was of limited extent and did not result in the replacement of the old SCLM by upwelling juvenile asthenosphere beneath the rift. These Nd isotopic data do not support the generation of the volcanic rocks by slab break-off, which would have likely introduced a juvenile asthenospheric mantle source for some of the Silurian-Devonian basaltic rocks. The ranges in ϵ_{Nd} values and depleted mantle ages in northern New Brunswick are similar to those recorded in penecontemporaneous mafic lavas in Avalonia suggesting that the Neoproterozoic SCLM was common to both Avalonia and Ganderia.

1. Introduction

The Appalachians of eastern North America have been subdivided into a number of zones and terranes (Keppie, 1985; Williams, 1995; Hibbard et al., 2006), either native Laurentian or exotic terranes. The suture between the Laurentian paleocontinent (North American Craton) and exotic terranes (the Red Indian Line) is believed to lie beneath Chaleur Bay (e.g., van Staal et al., 2009), which separates New Brunswick from the Gaspé Peninsula of Quebec (Fig. 1). The peri-Gondwanan Gander zone (Ganderia terrane) lies immediately south of the Red Indian Line (Fig. 1). Currently, there is some debate about the number of oceans between the exotic terranes; e.g. van Staal and Barr (2012) favour three oceans whereas Keppie (1985) and Keppie et al. (2003) infer that the exotic terranes are merely dispersed parts of one terrane with no intervening oceans (Fig. 2). Thus, the Gander zone is considered to represent either a passive-active margin adjacent to and underlain by Avalonia (Keppie et al., 2012), or that Ganderia and Avalonia represent distinct terranes (e.g. van Staal and Hatcher, 2010, Waldron et al., 2014, and references therein). This has had implications for Cambrian-Ordovician paleocontinental reconstructions: Keppie et al. (2012) place Ganderia and Avalonia adjacent to one another (Fig. 2A), whereas van Staal and Hatcher (2010), van Staal and Barr (2012), and Waldron et al. (2014) place them at different locations along the northwestern Gondwanan margin with an intervening seaway between them (Fig. 2 B). This peri-Gondwanan picture becomes more complex with the application of paleomagnetic and faunal constraints, which suggest that the Gander and Avalon zones (i.e. Greater Avalonia) originated as an island chain possibly off Baltica (Keppie and Keppie, 2014).

Neodymium isotopes as well as the trace elements of within-plate mafic volcanic rocks may provide information on the nature of the mantle source (e.g., DePaolo, 1988). These data have considerable potential for characterizing the composition of the subcontinental lithospheric

mantle (SCLM) beneath different tectonostratigraphic terranes. SCLM may exist for a long time without significant modification (Griffin et al., 2004, 2009). Alternatively, it may be removed during delamination (e.g., Gutierrez-Alonso et al., 2011; Murphy et al., 2011), replaced by a mantle plume (Murphy et al., 2011), or changed by mantle metasomatism (Carlson et al., 2005; Lee, 2006). The Nd isotopic and trace element data for the Silurian-Devonian rift-related mafic volcanic rocks of northern New Brunswick are important because they may help resolve the Ganderian controversy. However, Nd isotopic data from this part of the Appalachian orogeny are sparse.

The sampled Upper Silurian (Pridolian) - Lower Devonian (Lockhovian and Pragian) mafic lavas occur in the Chaleur Bay Synclinorium, which forms the southeastern part of the Matapedia cover sequence (Fig. 3). These 422-407 Ma lavas (Wilson et al., 2005; Wilson and Kamo, 2008, 2012) are parts of bimodal, felsic-mafic suites. The mafic volcanic rocks have within-plate characteristics and are inferred to have been erupted either in a continental rift (Dostal et al., 1989), or as a result of slab break-off (van Staal et al., 2009). The rocks of the Matapedia cover sequence were deposited unconformably on Early to Middle Ordovician rocks of the Popelogan arc and Brunswick subduction complex, an accretionary wedge formed during subduction-related closure of the Tetagouche backarc basin (van Staal et al., 2003, 2009).

In this paper, we present Nd isotopic as well as major and trace element data for Upper Silurian- Lower Devonian mafic volcanic rocks from the Gander Zone of northern New Brunswick. We use these data (a) to evaluate the nature of the SCLM beneath Ganderia in northern New Brunswick, and (b) to compare them with data for time equivalent basaltic rocks from the Nova Scotian part of Avalonia. The comparison of the characteristics of SCLM of the

two neighboring exotic terranes reveals that both terranes could have been underlain by the same SCLM during the Paleozoic and thus imposes constraints on the Ganderian controversy.

2. Geological Setting

The Upper Silurian to Lower Devonian volcanic rocks in northern and western New Brunswick underlie the southeastern part of a broad Middle Paleozoic successor basin referred to as the Matapedia cover sequence (Fyffe and Fricker 1987; van Staal and de Roo 1995), which extends from the eastern Gaspé Peninsula, southwest through northern New Brunswick (Fig. 3) into northern and central Maine. The Matapedia cover sequence consists of three structural zones, namely, from northwest to southeast, the Connecticut Valley – Gaspé Synclinorium, Aroostook – Percé Anticlinorium containing the oldest rocks, and Chaleur Bay Synclinorium (Rodgers 1970; Wilson et al., 2004; Fig. 3). Rocks of the Chaleur Bay Synclinorium lie disconformably on, or are in fault contact with, those of the Aroostook – Percé Anticlinorium to the west, and unconformably overlie Cambrian to Upper Ordovician rocks (Miramichi Group, and Bathurst and Fournier supergroups) in the Miramichi and Elmtree inliers to the east (Fig. 3). Compared to the other two zones, the Chaleur Bay Synclinorium displays much greater stratigraphic and tectonic complexity, manifested in transgressive-regressive sedimentary cycles, unconformities, and extensive magmatic activity, all related to crustal events that accompanied and followed Silurian accretion of Ganderian arc and back-arc terranes to Laurentia during the Salinic orogenic cycle (Wilson et al. 2004; Wilson and Kamo 2008, 2012). The Chaleur Bay Synclinorium is divided into two parts by the Rocky Brook – Millstream Fault (Fig. 3): the Chaleur zone to the north and the Tobique zone to the south. The Chaleur zone is underlain by Upper Silurian rocks of the Dickie Cove and Petit Rocher groups, Upper Silurian to Lower

Devonian rocks of the Chaleurs Group, and Lower Devonian rocks of the Dalhousie and Gaspé Sandstones groups (Fig.4). The Tobique zone is dominantly underlain by the Upper Silurian Petit Rocher Group and the Upper Silurian to Lower Devonian Tobique Group (Figs. 3 and 4).

The sampled volcanic rocks occur as subaerial to subaqueous lava flows in the Dickie Cove (422 to 420 Ma) and Dalhousie (earliest Lochkovian ~ 420 to 407 Ma) groups north of the Rocky Brook – Millstream Fault, and the Tobique Group south of the fault. Volcanic rocks dominate the Dickie Cove Group, the lower part of the Tobique Group (~421 to late Lochkovian ~ 412 Ma), and the Dalhousie Group in the Restigouche Syncline (Fig. 3), whereas the Dalhousie Group in the Jacquet River Syncline (Fig. 3) and the upper part of the Tobique Group consist mainly of sedimentary rocks, and volcanic rocks (mainly basalt) are subordinate. Fossil ages indicate that the Tobique Group was deposited over approximately the same time interval as the Dalhousie Group (Wilson and Kamo, 2008); however, U-Pb (zircon) dating has shown that volcanic rocks in the lower part of the Tobique Group are older than those in the Dalhousie Group, and may overlap the age of the Dickie Cove Group (Wilson and Kamo, 2008, 2012; Fig. 4).

3. Analytical Methods

The analyzed basaltic samples of the three groups (Dalhousie, Dickie Cove and Tobique) were selected from the set of several hundreds of volcanic rocks collected during regional mapping of northern and western New Brunswick (e.g., Wilson et al., 2005; Walker and Wilson, 2013). Locations of the samples analyzed for Nd isotopes are shown in Fig. 3. Whole rock major and trace elements (Table 1) were determined using lithium metaborate - tetraborate fusion at the Activation Laboratories Ltd. in Ancaster, Ontario, Canada. Major elements were analyzed by an

inductively coupled plasma-optical emission spectrometer whereas trace elements were determined by an inductively coupled plasma-mass spectrometer. Based on replicate analyses, the precision is generally between 2 and 10 % for trace elements and 2 % for major elements. The additional analyses of basaltic rocks are available on-line (Supplementary Files).

Abundances of Sm and Nd and Nd-isotope ratios of the basaltic rocks (Table 2) were determined at the Atlantic Universities Regional Facility at the Department of Earth Sciences of Memorial University of Newfoundland (St. John's, Newfoundland, Canada). Concentration data are standard ICP-MS analyses and are precise to $\pm 5\%$ (2σ). Ratios of $^{147}\text{Sm}/^{144}\text{Nd}$ were measured directly by high-precision ICP-MS with an estimated precision of $\pm 0.5\%$ (2σ). The isotopic ratios of $^{143}\text{Nd}/^{144}\text{Nd}$ were determined using a multicollector Finnigan MAT 262V thermal ionization mass spectrometer operated in a static mode. Measured $^{143}\text{Nd}/^{144}\text{Nd}$ values were normalized to a $^{146}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219. An average value for $^{143}\text{Nd}/^{144}\text{Nd} = 0.511849 \pm 9$ resulted from replicate analyses of the LaJolla standard, which was determined repeatedly throughout the study. The 2σ values for all samples are less than or equal to 0.000008 for $^{143}\text{Nd}/^{144}\text{Nd}$ and are given in Table 2. $\epsilon_{\text{Nd}}(t)$ values were calculated with respect to CHUR using a present-day $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512638 and $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.196593 and subsequently age-corrected. T_{DM1} model age was calculated using a linear evolution for a mantle separated from the CHUR at 4.55Ga and having a present day Epsilon value of +10. T_{DM2} model age was calculated according to the model of DePaolo (1988).

4. Petrography

The mafic volcanic rocks of all three suites are phaneritic, mostly porphyritic or microporphyritic. Some medium-grained basalts display sub-ophitic to ophitic textures.

Plagioclase is the most common phenocryst phase and forms typically subhedral to euhedral lath-shaped and compositionally zoned (andesine-labradorite) crystals. Clinopyroxene phenocrysts are less abundant than plagioclase phenocrysts. They are euhedral to subhedral to anhedral augites with a composition characteristic of rift-related continental tholeiites and alkali basalts (Dostal et al. 1989). In some samples, clinopyroxene and plagioclase phenocrysts form glomerophenocrysts. Phenocrysts are set in a groundmass of plagioclase, clinopyroxene and Fe-Ti oxides. The groundmass can also be aphanitic. Some rocks are vesicular (amygdaloidal). The volcanic rocks were affected by low-grade to very low-grade (zeolite to lower greenschist facies) metamorphism (e.g., Mossman and Bachinski, 1972). Secondary minerals including chlorite, epidote and saussuritized plagioclase replaced most of the primary magmatic minerals. Vesicles are commonly filled by chlorite, calcite, epidote and quartz.

5. Geochemistry

5.1. Alteration

All the investigated samples were affected to varying degrees by secondary processes, including low-grade regional metamorphism and alterations that modified the chemical composition of these rocks (e.g., Dostal et al., 2008). This is indicated by the highly variable LOI values (weight loss on ignition to 900°C) and the wide range of Na, K and Rb contents. However, the concentrations of most major elements, high-field-strength elements (HFSE), rare earth elements (REE), Th and transition elements, were probably not affected and are thought to reflect the primary magmatic history of the studied rocks. Similarly, Sm and Nd, which are involved in a radiogenic isotope system as parent and daughter isotopes, respectively, as well as

Nd isotopic ratios, display a very high degree of chemical congruence. This implies a much reduced relative mobility and great resistance of the Sm-Nd isotopic pair to geological disturbances (e.g., DePaolo, 1988). Thus, it is inferred that the Nd isotope features can also be ascribed to magmatic processes.

5.2 Whole-Rock Geochemistry

Three investigated Upper Silurian-Lower Devonian volcanic suites from northern New Brunswick (Dalhousie, Dickie Cove and Tobique groups; Table 1) are bimodal although locally intermediate rocks are present in not insignificant amounts (Dostal et al., 1989; Wilson et al., 2004, 2005). The mafic rocks are mostly basaltic with $\text{SiO}_2 < 55$ wt.% and a wide range of Mg# ($\text{MgO}/[\text{MgO}+\text{FeO}^{\text{tot}}]$ in mol.%). The mafic rocks display typical tholeiitic trends of increasing TiO_2 and P_2O_5 but constant SiO_2 with increasing $\text{FeO}^{\text{tot}}/\text{MgO}$ ratio (Fig. 5). They have low Zr/ TiO_2 and Nb/Y (< 0.65) ratios (Fig. 6) characteristic of sub-alkaline suites, although some samples have higher Nb/Y ratios, suggesting that they are transitional to alkali basalts. The decrease of Mg, Ni and Cr with increasing degree of differentiation indicates fractionation of clinopyroxene and olivine (Dostal et al., 1983). Compared to primitive basalts that have Mg# of ~ 0.70 (Hanson and Langmuir 1978), the Mg# values of the New Brunswick basalts are low (0.26-0.66; Table 1). The low Mg# values as well as the low MgO (< 9 wt.%), Cr and Ni contents suggest that all samples analyzed are not primary magmas but have undergone varying degrees of fractional crystallization. According to various discrimination diagrams and compositional characteristics (Dostal et al., 1989), the basaltic rocks are within-plate types. Their composition resembles that of many continental tholeiites (e.g., Dostal and Dupuy, 1984; Pegram, 1990; Dostal et al., 1986, 1992; Peate and Hawkesworth, 1996).

There are subtle compositional differences among the mafic rocks of the three suites. For example, compared to the Dalhousie and Tobique groups, basalts of the Dickie Cove Group contain, on average, higher abundances of TiO_2 , $\text{Fe}_2\text{O}_3^{\text{tot}}$, P_2O_5 , Zr and light REE (LREE) but lower concentrations of Cr, Ni as well as lower Mg#, indicating that these tholeiitic rocks are more differentiated.

The chondrite-normalized REE patterns of the basalts (Fig. 7) show a negative slope with an enrichment of LREE although the basalts of the Dickie Cove Group have steeper slopes (typically $[\text{La/Yb}]_n \sim 3-9$) than those of the Dalhousie and Tobique groups ($[\text{La/Yb}]_n \sim 1-6$). The patterns do not commonly show noticeable negative Eu anomalies despite the presence of plagioclase, possibly reflecting oxygen fugacity conditions. V/Sc ratios have been used to constrain the relative oxidation conditions of basalts (Lee et al., 2005). Despite some scatter, the the V/Sc ratio of the New Brunswick basalts is ~ 8 , suggesting that the relative oxidation state is around the FMQ (fayalite-magnetite-quartz) buffer. Plots of selected incompatible trace elements, normalized to normal mid-ocean ridge basalts (N-MORB), are also given in Figure 7. They display strong enrichment in Th, La, and Ce accompanied by relative depletion in high-field strength elements Ta and Nb, although these two elements are still enriched relative to MORB.

5.4. Nd Isotopic Data

Nd isotopic data for the Dickie Cove, Dalhousie and Tobique basaltic rocks yield age-corrected ϵ_{Nd} values that are lower than the values of contemporaneous depleted mantle (Table 2). $\epsilon_{\text{Nd}(t)}$ values (t = time of crystallization) range from $\sim +3.4$ to $+5.3$ with the T_{DM2} (depleted

mantle model age, after DePaolo, 1988) ranging from 0.65 to 0.95 Ga (Table 1). The T_{DM2} value for sample 202 (Table 2) is not reliable due to high $^{147}\text{Sm}/^{144}\text{Nd}$ (>0.165 ; Stern, 2002). High positive ϵ_{Nd} values of the basaltic rocks are inconsistent with a significant contribution from substantially older continental crust or sedimentary rocks derived from it (DePaolo, 1988). The consistent Sm-Nd depleted mantle ages of DePaolo (1988; Table 2) for both New Brunswick and Nova Scotia (see below) basaltic rocks suggest that the model ages represent a bulk weighted average of the source composition, rather than mixing between older crust and juvenile magma (Murphy et al., 2008). In the case of the basaltic rocks, the model ages could represent mantle enrichment ages associated with ancient subduction.

6. Discussion

6.1. Comparable Rock Suites

Comparable rift-related Upper Silurian-Lower Devonian basaltic rocks also occur in the Nova Scotian part of the Avalon Terrane. There, these rocks are part of three bimodal volcanic suites (Keppie and Dostal, 1980, 1991; Keppie et al., 1997). They include the basaltic rocks at the base of the Arisaig Group (~430 Ma) in the Antigonish Highlands (Keppie et al., 1979; Murphy et al., 1991) as well as the basalts of the Money Point Group (~428 Ma) and Sarah Brook Metamorphic Suite (~430 Ma) in the Cape Breton Highlands (Barr and Jamieson, 1991; Dunning et al., 1990; Keppie et al., 1992, 1997). Each mafic suite exhibits a positive covariation of $\text{FeO}^{\text{tot}}/\text{MgO}$ with FeO^{tot} , TiO_2 , P_2O_5 , V and Zr, trends typical of differentiated continental tholeiites. Their high content of Zr is accompanied by a high Zr/Y ratio (>4) characteristic of rift-related rocks. The Arisaig basalts are tholeiites showing alkaline affinities with Nb/Y ratios of

0.5 to 0.9. They have LREE- enriched chondrite-normalized patterns with $(La/Yb)_n$ of 4.0-5.5 and N-MORB-normalized trace element plots do not show negative Nb and Ti anomalies. The Sarah Brook and Money Point suites are tholeiitic with Nb/Y ratios ~ 0.3 , fractionated chondrite-normalized REE patterns with $(La/Yb)_n$ ranging from 3.5 to 7.0 and N-MORB-normalized plots showing distinct negative Nb-Ta anomalies (Fig. 8).

6.2. Petrogenesis

The variations in major elements, Mg#, Ni and Cr in the mafic rocks of individual groups together with their petrography are consistent with fractional crystallization of plagioclase, clinopyroxene and olivine. Slightly lower Mg#, and Ni and Cr concentrations of the mafic rocks of the Dickie Cove Group indicate more advanced fractional crystallization relative to the Dalhousie and Tobique mafic rocks. However, the Dickie Cove basalts have also higher ratios of Zr/Y, La/Yb, La/Sc, Ti/Y and Ti/V, which are not modified during fractional crystallization, suggesting minor compositional differences in the mantle sources and/or a different degree of partial melting (Dostal et al. 1989, 1993).

The La/Yb versus Yb plot (Fig. 9), which highlights the differences in behaviour of these two elements, is useful to differentiate among the compositional changes due to fractional crystallization, degrees of partial melting and source heterogeneity (Fan et al., 2008; He et al., 2010). The negative correlation between La/Yb and Yb for the basalts of the Dalhousie Group points to a slightly heterogeneous mantle source although fractional crystallization also played a role. Similarly, the basalts of the other two groups were derived from a similar, but heterogeneous, mantle source. The ratios of some incompatible trace elements can also provide

constraints on other melting conditions such as degree of partial melting and pressure (depth) of melting. The abundances of REE in the basalts are particularly useful to evaluate the melting degrees and the composition of the mantle sources since heavy REE (HREE) are preferentially partitioned into garnet whereas all REE are strongly incompatible in spinel (Kelemen, 1990). Thus, magma derived from a garnet-bearing source will have higher Gd/Yb and Sm/Yb ratios than those formed from a spinel-bearing source. Whereas these ratios are related to the depth of the melting, ratios such as La/Sm and Nb/Zr (Fig. 10) reflect the degree of partial melting. Figure 10 indicates that there are differences in the melting depth and degrees of melting of the three suites, although their sources have rather similar chemical compositions. The Tobique basalts were generated at a shallow depth by a high degree of melting whereas the Dickie Cove basalts were derived at a greater depth by a smaller degree of melting. The Dalhousie basalts are intermediate. There are also differences in the slopes of the REE patterns as shown in Figure 7. The shapes of the REE patterns suggest that the bulk of the Dickie Cove basalts were formed by melting of garnet-bearing peridotites or are from a transition zone between spinel and garnet stability fields, whereas the shallow slopes of the REE patterns of Dalhousie and Tobique basalts were derived from a spinel-bearing peridotite. The garnet-to-spinel transition is generally placed at a depth between 80 and 60 km (McKenzie and O'Nions, 1991).

Mafic volcanic rocks of the Dalhousie, Tobique and Dickie Cove groups are rift-related basalts that have the chemical characteristics of continental tholeiites, which have been inferred to be generated by partial melting of SCLM (e.g., Pegram, 1990; Dostal and Greenough, 1992; Turner and Hawkesworth, 1995; Peate and Hawkesworth, 1996; Pearce, 2008). The overall negative slopes on the N-MORB-normalized plots (Fig. 7) are typical of basaltic magmas generated by partial melting of an enriched mantle. The Th/Yb versus Nb/Yb diagram (Fig. 11) of

Pearce (2008) can help to constrain the nature of such an enriched mantle source. The graph is useful for an evaluation of the enrichment processes including mantle metasomatic enrichment and lithospheric inputs (subduction and crustal contamination). MORB and ocean island basalts (OIB) form a diagonal array centred on average N-MORB, enriched-type MORB (E-MORB) and OIB with a principal axis of dispersion along the array. On this graph, basalts that have interacted with continental crust during ascent or have a subduction component are displaced to higher Th/Yb values because Th is mobile and Nb is immobile during these processes. Assimilation-fractional crystallization (AFC) processes lead to an enrichment trend intermediate between the mantle array and subduction enrichment (Pearce, 2008). As the mantle array also reflects variable degrees of melting (Pearce, 2008), some of the array-parallel trends may be attributed to this process. The basaltic rocks of northern New Brunswick display elevated Th/Yb relative to the mantle array. To evaluate the role of continental crust, ϵ_{Nd} values are plotted against Th/La, a sensitive indicator of crustal contamination (Fig. 12). This figure shows a general trend of lower $\epsilon_{\text{Nd(t)}}$ with higher Th/La, suggesting the involvement of continental crust in basalts with lower $\epsilon_{\text{Nd(t)}}$. Crustal assimilation and AFC processes tend to modify pre-existing trace element ratios and/or produce mixing trends between the original magma and crustal components. However, the strong enrichment of Fe, Ti and V in the differentiated basalts argues against extensive crustal contamination by felsic material. These elements are being enriched during fractional crystallization but should decrease during assimilation of silicic material. This is also consistent with a lack of correlation of Th/La with SiO_2 (Fig. 13). Thus, enrichment of Th, negative anomalies for Nb-Ta and $\epsilon_{\text{Nd(t)}}$ values of $\sim +3$ to $+5$ probably represent the compositional characteristics of the mantle source. A mechanism that can be invoked for the origin of “subduction” or “crustal” signature of the basalts and SCLM is recycling of crustally

derived sediments through subduction, resulting in the incorporation of crustal material into the SCLM (Hofmann and White, 1982; Cox, 1983). Thus, crustal contamination is a result of ancient subduction and the relatively high contents of Th and relative depletions of Nb and Ta probably reflect subduction-related contamination of the mantle.

An alternative model for the origin of “subduction” signature of the basalts and the mantle source is an interaction of plume-derived melts with melts or materials derived from the arc lithospheric mantle (e.g., Saunders et al., 1992; Lassiter and DePaolo 1997). However, without evidence for a large thermal anomaly accompanying volcanism in New Brunswick during this period, a mantle plume origin for these basalts is unlikely. Likewise, the consistent Nd isotopic systematics in the New Brunswick and Nova Scotia Silurian-Devonian basalts argues against melt mixing.

6.3. Nd Isotopes

A comparison of Sm-Nd isotopic data from continental rift magmas of similar ages from neighbouring Avalonia can provide insights into the similarities and differences in the mantle source rocks (Murphy and Dostal, 2007). The range in $\epsilon_{\text{Nd}(t)}$ probably reflects the original mantle heterogeneity, and the range in $^{147}\text{Sm}/^{144}\text{Nd}$ can be, in part, also attributed to fractional crystallization. The Upper Silurian-Lower Devonian rift-related tholeiitic basalts of the three suites from Avalonia of Nova Scotia have $\epsilon_{\text{Nd}(t)}$ values between +3.2 and +5.8 and T_{DM2} of 0.62 to 0.84 Ga (Keppie et al., 1997; Murphy et al., 2008; Fig. 14). These data are similar to those for the basalts from northern New Brunswick, implying that the basalts from Ganderia were derived from SCLM that is isotopically indistinguishable from Avalonian SCLM. In fact, the New Brunswick data plot mostly within the envelope (Fig. 14) defined for Avalonian lithosphere of

Nova Scotia between the Neoproterozoic and Late Devonian (Murphy et al., 2008; Keppie et al., 2012). Thus, geochemical and isotopic similarities of the Silurian-Devonian mafic magmas indicate that all these mafic rocks could have been derived from the same enriched lithospheric mantle source. The mantle model ages suggest the enrichment likely took place between 0.6 and 1.0 Ga, i.e. the SCLM is of Neoproterozoic age like that of Avalonia (Murphy et al., 2011).

7. Tectonic Models and Conclusions

The tholeiitic (-alkalic) within-plate geochemistry of the Upper Silurian - Lower Devonian volcanic rocks (422 to 407 Ma) is consistent with their eruption in a continental rift (Dostal et al., 1989). The Nd isotopic data suggest that the source of the mafic volcanic rocks is a Neoproterozoic SCLM, with no contributions from juvenile, Silurian mantle. This suggests that rifting was of limited extent and did not result in replacement of the old SCLM by upwelling juvenile asthenosphere beneath the rift. These Nd isotopic data are inconsistent with the production of the volcanic rocks by slab break-off (van Staal et al., 2009), which would have introduced a juvenile asthenospheric mantle source for at least some of the Silurian-Devonian lavas. The range in $\epsilon_{\text{Nd}}(t)$ values in northwestern New Brunswick is very similar to that recorded in penecontemporaneous mafic lavas in Avalonia (Fig. 14), which suggests that the Neoproterozoic SCLM was common to both Avalonia (sensu stricto) and Ganderia. This is consistent with Nd isotopic data that indicate derivation of Silurian-Devonian granitoid rocks of northern New Brunswick from an Avalonian lower crust (Whalen et al., 1994, 1996). These data are also consistent with the inference that Ganderia formed along the margin of Avalonia, i.e. Greater Avalonia of Keppie and Keppie (2014). The Latest Neoproterozoic and Cambrian paleomagnetic and faunal data suggest that Avalonia (sensu stricto) was an island chain lying at

ca. 20°S, a long way from northwestern Gondwana, but at a similar paleolatitude as the Timanides of northern Baltica (Keppie and Keppie, 2014).

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Figure Captions

Figure 1. Map showing the major lithotectonic units of the Appalachian-Caledonian orogenic belt in an Early Mesozoic restoration (modified after Williams, 1984 and van Staal and Barr, 2012). Heavy dashed line is the boundary between Laurentia and Gondwana in Europe.

Figure 2. (A) 550 Ma paleogeographic reconstruction of Keppie and Keppie (2014); (B) Map showing the distribution of the main continents at 555 Ma according to van Staal et al. (1998). Note that this paleogeographic map shows Ganderia (Ga) and Avalonia (Av) originating in separate locations on the northwestern Gondwana margin (after van Staal et al., 1998). WAfr - Western African Craton; Kal - Kalahari Craton.

Figure 3. Simplified geology of the northern part of the Chaleur Bay Synclinorium, showing the location of samples collected for Sm-Nd analysis and previously published U-Pb (zircon) radioisotopic ages (numerical superscripts indicate data sources: 1-Wilson et al. 2005; 2-Wilson and Kamo, 2008; 3-Wilson and Kamo, 2012). The Chaleur zone is located north of the Rocky Brook – Millstream Fault and the Tobique zone is south of the fault. RS= Restigouche Syncline; JRS= Jacquet River Syncline. Uncoloured areas are underlain by Late Ordovician to Silurian rocks and by local Carboniferous rocks (Wilson, 2006). The inset at lower left showing the location of the geological map, also illustrates the three subdivisions of the Matapedia cover sequence: CB= Chaleur Bay Synclinorium; AP= Aroostook - Percé Anticlinorium; CG= Connecticut Valley - Gaspé Synclinorium. The inset on the right shows the location of New Brunswick.

Figure 4. Stratigraphic columns showing the age and correlation of Late Silurian – Early Devonian volcanic rocks of the Chaleur Bay Synclinorium. U-Pb zircon ages: 1-Wilson et al. 2005; 2-Wilson and Kamo, 2008; 3-Wilson and Kamo, 2012.

612 Figure 5. Plots of SiO_2 (wt.%) and TiO_2 (wt.%) versus FeO^*/MgO ratios for New Brunswick
613 Upper Silurian- Lower Devonian basaltic rocks. Calc-alkaline and tholeiitic trends are after
614 Miyashiro (1974). FeO^* -total Fe as FeO.

615 Figure 6. Zr/TiO_2 versus Nb/Y discrimination diagram of Winchester and Floyd (1977) for New
616 Brunswick Upper Silurian-Lower Devonian basaltic rocks. A-Dalhousie Group; B- Dickie
617 Cove Group; C-Tobique Group. Alk-Bas - alkali basalt; Bsn/Nph - basanite, nephelinite;
618 TrachyAnd – trachyandesite.

619 Figure 7. N-MORB-normalized trace element plots (A-Dalhousie Group; B-Dickie Cove Group;
620 C-Tobique Group) and chondrite-normalized REE patterns (D-Dalhousie; E-Dickie Cove
621 Group; F-Tobique Group) plots for the New Brunswick Silurian-Devonian basaltic rocks.
622 Normalizing values after Sun and McDonough (1989). N-MORB- N-type mid-ocean ridge
623 basalt.

624 Figure 8. N-MORB- normalized trace elements plots for Upper Silurian- Lower Devonian
625 basaltic rocks of the Avalon Zone in Cape Breton Island (Sarah Brook Group – samples
626 1222 and 8011; Money Point Group – samples 731 and 740). Data from Keppie et al.
627 (1997); normalizing values are after Sun and McDonough (1989).

628 Figure 9. La/Yb versus Yb (ppm) variation diagram for basalts of the Dalhousie Group. Vectors
629 for fractional crystallization (FC), increase of the degree of melting and source heterogeneity
630 are after He et al. (2010).

631 Figure 10. (A) Sm/Yb versus Nb/Zr and (B) Gd/Yb versus La/Sm for the northern New
632 Brunswick Upper Silurian-Lower Devonian basaltic rocks (Dalhousie Group-solid triangle;

+ - Dickie Cove Group; solid circles-Tobique Group). Vectors for increase of melting depth and for an increase of the degree of partial melting are after He et al. (2010).

Figure 11. Th/Yb versus Nb/Yb diagram of Pearce (2008) for Upper Silurian-Lower Devonian basaltic rocks of northern New Brunswick. Vectors indicate the influence of a subduction component (S), within-plate enrichment (W), crustal contamination (C) and fractional crystallization (FC); N-MORB- N-type mid-ocean ridge basalt; E-MORB- enriched mid-ocean ridge basalt; OIB-ocean island basalt (after Sun and McDonough, 1989).

Figure 12. Th/La versus $\epsilon_{\text{Nd}(t)}$ plot for Silurian-Devonian basalts of northern New Brunswick. CC- average continental crust (Rudnick and Gao, 2003).

Figure 13. Th/La versus SiO_2 (wt.%) diagram for the basalts of the Dalhousie Group showing vectors for crustal contamination and fractional crystallization.

Figure 14. $\epsilon_{\text{Nd}(t)}$ versus time plot comparing new Sm-Nd isotopic data of the Upper Silurian-Lower Devonian basaltic rocks from northern New Brunswick with a compilation of Sm-Nd isotopic data for the Neoproterozoic to Devonian basaltic rocks of the Avalon terrane. Avalonian basalts (squares) are after Murphy et al. (2011). Solid thick line is the range of $\epsilon_{\text{Nd}(t)}$ of Upper Silurian-Lower Devonian basaltic rocks of New Brunswick (Ganderia). Shaded area is the Avalonian basement and SCLM (after Keppie et al., 2012; Murphy et al., 2011). The field for Mesoproterozoic rocks is from Murphy et al. (2008).

Table 1

Table 1. Major and trace element analyses of Silurian-Devonian basaltic rocks of the Chaleur Bay Synclinor

Sample	Dalhousie Group						Dickie Cove Group			
	166	278	329	226A	513	225A	BP11	BP4	BP6	BP8
SiO ₂ (wt.%)	51.91	46.18	48.70	54.97	50.59	50.55	41.03	46.04	46.37	44.43
TiO ₂	1.64	1.85	1.58	2.39	1.12	1.43	2.01	2.96	2.73	3.82
Al ₂ O ₃	17.70	15.63	18.08	14.48	17.31	17.72	15.25	17.32	16.56	14.11
Fe ₂ O ₃	9.10	9.46	9.66	11.61	7.84	8.68	11.89	11.92	11.62	14.67
MnO	0.16	0.17	0.16	0.20	0.13	0.18	0.22	0.17	0.17	0.22
MgO	3.95	5.22	5.12	2.18	7.73	5.04	2.73	4.33	5.48	4.34
CaO	8.39	11.78	6.36	6.45	5.75	9.53	9.29	9.37	9.93	6.01
Na ₂ O	3.97	3.99	5.09	4.23	4.44	3.42	4.83	3.43	2.96	4.36
K ₂ O	1.25	0.12	0.27	1.31	0.95	0.55	1.34	0.30	0.45	0.28
P ₂ O ₅	0.25	0.28	0.34	0.40	0.16	0.17	0.33	0.38	0.42	0.86
LOI	1.68	4.52	3.97	1.53	4.24	3.11	9.60	3.83	2.91	7.07
Total	100.00	99.20	99.33	99.75	100.26	100.38	98.52	100.05	99.60	100.17
Mg #	0.46	0.52	0.51	0.27	0.66	0.53	0.31	0.42	0.48	0.37
Cr (ppm)	48	182	163	10	117	77	0	42	101	6
Ni	9	72	81	0	53	40	25	38	33	0
Co	22	33	31	21	33	28	0	40	39	31
Sc	23	34	28	30	27	27	0	30	35	34
V	260	262	266	170	177	206	118	320	291	283
Rb	23	0	0	27	25	10	36	3	8	6
Ba	306	34	137	255	573	164	0	175	199	252
Sr	535	92	240	305	1290	417	470	657	401	393
Ga	19	19	14	22	15	20	18	22	20	23
Ta	0.89	0.51	0.57	0.65	0.29	0.34	1.01	0.92	0.75	1.18
Nb	11.1	7.4	7.0	10.1	5.2	5.2	15.6	14.1	11.5	17.6
Hf	3.8	3.7	3.3	6.1	2.2	2.8	4.1	4.7	4.2	6.4
Zr	162	151	141	249	82	91	175	210	176	278
Y	28	31	25	51	16	19	30	30	32	54
Th	5.01	1.07	1.44	4.05	2.52	1.56	2.20	1.99	1.61	2.26
U	1.44	0.50	0.33	1.46	1.03	0.76	0.59	0.61	0.51	0.60
La	21.20	13.70	12.10	24.30	14.98	8.38	20.43	23.21	18.61	35.07
Ce	45.40	33.10	26.50	54.63	30.73	19.64	43.44	51.35	41.99	78.98
Pr	5.86	3.97	3.79	7.57	3.95	2.61	5.66	6.89	5.91	10.98
Nd	20.70	17.50	16.20	31.76	15.05	12.06	23.33	27.22	24.78	45.69
Sm	4.61	4.62	4.16	7.96	3.28	3.25	5.52	6.21	6.07	10.47
Eu	1.45	1.37	1.30	2.71	1.25	1.19	2.02	2.33	2.37	3.90
Gd	4.91	4.76	4.73	9.33	3.35	3.72	6.01	6.48	6.73	11.47
Tb	0.78	0.89	0.74	1.60	0.53	0.65	0.96	1.04	1.10	1.78
Dy	4.71	5.56	4.49	9.09	3.03	3.85	5.55	5.71	6.25	10.11
Ho	1.00	1.14	0.93	1.85	0.62	0.73	1.09	1.12	1.23	2.00
Er	2.95	3.27	2.74	5.44	1.77	2.12	3.20	3.24	3.55	5.75
Tm	0.42	0.47	0.40	0.81	0.26	0.33	0.45	0.46	0.50	0.81
Yb	2.64	2.85	2.46	4.93	1.57	2.09	2.73	2.76	2.99	4.89
Lu	0.38	0.42	0.36	0.73	0.23	0.31	0.40	0.41	0.44	0.73

Table 2

Table 2. Sm-Nd isotopic data for Silurian-Devonian basaltic rocks of the Chaleur Bay Synclinorium

Sample	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_m$	2σ	$^{143}\text{Nd}/^{144}\text{Nd}_i$	$\epsilon_{\text{Nd}(t)}$	T_{DM1} (Ma)	T_{DM2} (Ma)
Dalhousie Group									
166	21.99	4.64	0.1274	0.512652	6	0.512306	3.95	880	705
329	18.48	4.5	0.1474	0.512706	6	0.512305	3.94	1019	788
226A	30.37	7.71	0.1535	0.512737	7	0.512320	4.23	1043	789
513	14.75	3.15	0.1290	0.512664	7	0.512313	4.10	874	697
Tobique Group									
202	11.87	3.78	0.1923	0.512864	7	0.512341	4.65	2008	1260
71	24.20	6.5	0.1623	0.512726	6	0.512285	3.54	1253	948
117	18.59	4.98	0.1610	0.512754	7	0.512316	4.16	1142	849
Dickie Cove Group									
PB6	23.87	5.82	0.1475	0.512769	6	0.512362	5.21	876	652
247	28.01	6.48	0.1400	0.512653	7	0.512267	3.35	1027	818
748	18.35	4.25	0.1402	0.512694	6	0.512307	4.14	945	738

T_{DM1} -depleted mantle model age calculated using a linear evolution for a mantle separated from the CHUR at 4.55 Ga and having a present day ϵ_{Nd} value of +10; T_{DM2} - depleted mantle model age calculated using the model of DePaolo (1988); $\epsilon_{\text{Nd}(t)}$ values were calculated for the respective crystallization ages (t=421 Ma, Dickie Cove Group; t=415 Ma, Dalhousie and Tobique groups); $^{143}\text{Nd}/^{144}\text{Nd}_m$ – measured values; $^{143}\text{Nd}/^{144}\text{Nd}_i$ – initial, calculated; 2σ – uncertainty in measured $^{143}\text{Nd}/^{144}\text{Nd}$ – the value is the sixth decimal place.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14