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GEOCHEMICAL EVIDENCE FOR A GANDERIAN ARC/BACK-ARC REMNANT IN THE NASHOBA TERRANE, SE NEW ENGLAND, USA

ANDREW KAY*, J. CHRISTOPHER HEPBURN*,†, YVETTE D. KUIPER**, and ETHAN F. BAXTER*

ABSTRACT. New geochemical data including Sm/Nd isotopic data show evidence for an early Paleozoic arc/back-arc complex in the Nashoba terrane of southeastern New England. The Nashoba terrane lies between rocks of Ganderian affinity to the northwest and Avalonian affinity to the southeast. It consists of early Paleozoic mafic to felsic metavolcanic and metasedimentary rocks that were intruded by intermediate to felsic plutons and metamorphosed to upper amphibolite facies conditions in the mid-Paleozoic. Major and trace element geochemical data indicate that the early Paleozoic igneous rocks contain a mix of arc, MORB, and alkaline signatures, and that the terrane formed as a primitive volcanic arc/back-arc complex built on thinned continental crust. Amphibolites have +4 to +7.5$\varepsilon_{Nd(500)}$ values consistent with formation in a primitive volcanic arc with minimal crustal contamination. Intermediate and felsic gneisses have $\varepsilon_{Nd(500)}$ values between +1.2 and −0.75 indicating a mixture of juvenile arc magmas and an evolved (likely basement) source. Depleted mantle model ages of 1.2 to 1.6 Ga point to a Mesoproterozoic or older age for this source. Metasedimentary rocks yielded −6 to −8.3 $\varepsilon_{Nd(500)}$ values and 1.6 to 1.8 Ga model ages, indicating an isotopically evolved source (or sources) that included Paleoproterozoic or older material. The $\varepsilon_{Nd(500)}$ values and model ages of the intermediate and felsic and metasedimentary rocks indicate that the basement to the Nashoba terrane is Ganderian rather than Avalonian. The Nashoba terrane therefore represents a Ganderian arc/back-arc complex similar to the Cambrian Penobscot arc/back-arc seen in Maritime Canada and Newfoundland, and particularly in the Annidale and New River terranes of southern New Brunswick. This correlation has not previously been recognized in southeastern New England. The Ganderian affinity of the Nashoba terrane also extends Ganderia farther SE in New England than previously established and indicates that the Nashoba terrane did not originate as a separate oceanic arc/back-arc complex or microcontinent.

Keywords: Appalachians, Sm/Nd, Penobscot arc, early Paleozoic, Peri-Gondwanan terrane

INTRODUCTION

The northern Appalachians formed during a sequence of orogenic events as a result of accretion of geological terranes onto Laurentia during the middle and late Paleozoic (for example, Hibbard and others, 2007a, 2007b; Zagorevski and others, 2007a; van Staal and others, 2009; Hatcher, 2010; van Staal and Hatcher, 2010). Unraveling the origin, current distribution and evolution of these terranes is critical to understand the processes behind the evolution of this orogen. In this contribution we

* Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, Massachussetts 02467

** Department of Geology and Geological Engineering, Colorado School of Mines, 1516 Illinois St., Golden, Colorado 80401

† Corresponding author: john.hepburn@bc.edu

focus on the Nashoba terrane (fig. 1), which forms part of the eastern margin of the Appalachian orogenic belt in southeastern New England. High-grade metamorphic rocks of the Nashoba terrane lie between rocks of lower grade both to the east in the Avalon terrane and to the west in the Merrimack belt of the Ganderian terrane (fig. 1A). The earliest rocks in the Nashoba terrane are early Paleozoic metaigneous and metasedimentary rocks (Bell and Alvord, 1976) interpreted to have formed in an arc environment (Bell and Alvord, 1976; Skehan and Abu-Moustafa, 1976; Goldsmith, 1991b; Hepburn and others, 1995). Deformation and metamorphism to upper amphibolite facies conditions occurred during several discrete periods from the Late Silurian to the Early Carboniferous (Goldsmith, 1991c; Hepburn and others, 1995; Stroud and others, 2009; Walsh and others, 2015; Buchanan and others, 2015). The terrane was intruded by dioritic and granitic plutons in the Silurian, Devonian and Early Carboniferous (Bell and Alvord, 1976; Zen and others, 1983; Wones and Goldsmith, 1991; Hepburn and others, 1995). The origin of the Nashoba terrane and its relationships to other terranes in the northern Appalachians has previously been unclear. Some specific questions to address include: (1) Does the terrane have a Gondwanan affinity, or did it originate as an oceanic arc/back-arc complex? (2) If the terrane has Gondwanan affinity, is it related to Avalonia or Ganderia, or is it a separate terrane? And (3) are there equivalents of the Nashoba terrane in the northern Appalachians other than the contiguous along-strike Putnam terrane in Connecticut (Goldsmith, 1991b) (fig. 1A)? Herein we use new Sm-Nd isotopic data for metaigneous and metasedimentary rocks and compilations of published and unpublished major and trace element geochemical data, in order to unravel the origin of the Nashoba terrane and to place it in context with other northern Appalachian arc terranes amalgamated to Laurentia in the early to middle Paleozoic.

BACKGROUND

General Geology of SE New England

From the Neoproterozoic until the late Paleozoic, Laurentia was separated from West Gondwana (hereafter simply referred to as Gondwana) by the Iapetus and Rheic ocean basins and lithotectonic terranes, such as volcanic arcs and ribbon continents (for example, Murphy and others, 2006; van Staal and others, 2009, Hatcher, 2010; van Staal and Hatcher, 2010; van Staal and others, 2012). These terranes can be grouped into those that formed in the peri-Laurentian, Iapetan, or peri-Gondwanan realms (Hibbard and others, 2006, 2007b). The peri-Gondwanan realm in the northern Appalachians comprises at least three major terranes: Ganderia, Avalonia and Meguma (from west to east, present-day coordinates, fig. 1A), all of which formed on or near the margin of Gondwana in the early Paleozoic (for example, van Staal and others, 1998, 2012; Murphy and others, 2006). Progressive accretion to the Laurentian margin of peri-Laurentian volcanic arcs, Ganderia, Avalonia, Meguma, and finally the remainder of supercontinent Gondwana led to the Ordovician Taconic, Silurian Salinic, Late Silurian-Devonian Acadian, Middle Devonian-Early Carboniferous Neoacadian and Permian Alleghanian orogenies, respectively (for example, Hibbard and others, 2007a; Zagorevski and others, 2007a; van Staal and others, 2009, 2012; Hatcher, 2010; van Staal and Hatcher, 2010; Hibbard and others, 2010; Pollock and others, 2012). In New England these events produced a sequence of north to northeast striking terranes outboard from the Laurentian margin. In eastern Massachusetts these terranes are, from west to east, (1) the Silurian-Devonian metasedimentary rocks of the Central Maine and Merrimack belts, presumably overlying Ganderian basement, (2) the Nashoba terrane, and (3) the Southeastern New England Composite Avalon terrane (fig. 1B).

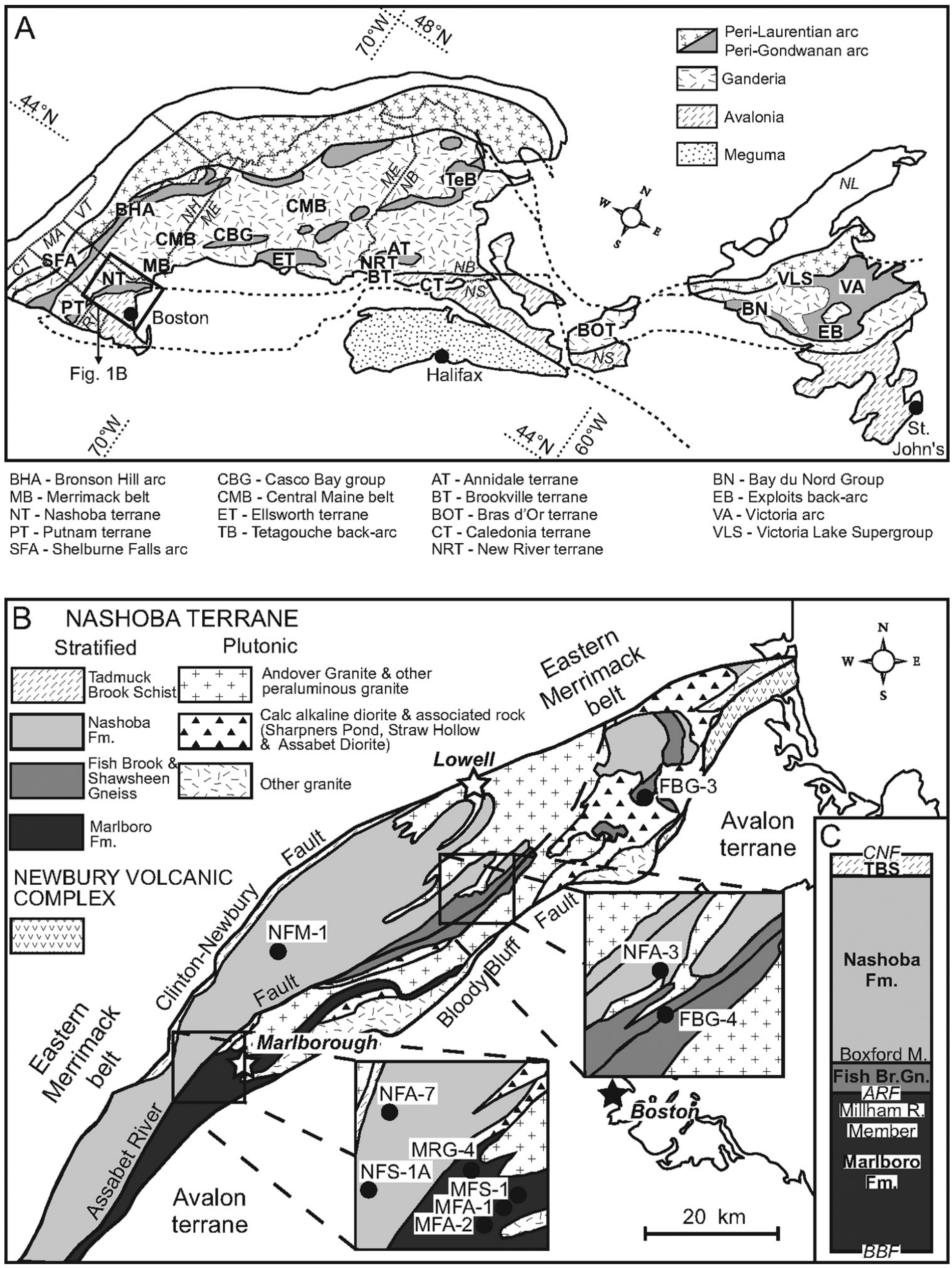

Fig. 1. (A) Simplified geological map of the northern Appalachians (after Hibbard and others, 2006). States/provinces: CT – Connecticut, MA – Massachusetts, ME – Maine, NB – New Brunswick, NH – New Hampshire, NL – Newfoundland, NS – Nova Scotia, RI – Rhode Island, VT – Vermont. (B) Generalized geological map of the Nashoba terrane, eastern Massachusetts (after Zen and others, 1983) with Sm-Nd sample locations. Sample descriptions and UTM coordinates are given in Appendix A. (C) Simplified schematic tectonostratigraphic column for the Nashoba terrane of units from SE to NW, based on Bell and Alvord (1976) and Zen and others (1983). Avalon terrane – Southeastern New England Composite Avalon terrane. Fault zones: ARF – Assabet River fault, BBF – Bloody Bluff fault, CNF – Clinton-Newbury fault; Unit names: Fm. – Formation, M – Member; Boxford M. – Boxford Member of the Nashoba Formation, Fish Br. Gn. – Fish Brook Gneiss, Millham R. Member – Millham Reservoir Member of the Marlboro Formation, TBS – Tadmuck Brook Schist.

Ganderia is typified by a tectonic evolution that includes early Paleozoic volcanic arc - back-arc systems along its leading (northern) edge as well as a sequence of distinctive early Paleozoic clastic sedimentary cover rocks (for example, Hibbard and others, 2007a, 2007b, 2010; van Staal and others, 2009, 2012; Fyffe and others, 2011; Pollock and others, 2012; van Staal and Barr, 2012). Between rifting from Gondwana and accretion to Laurentia these early Paleozoic volcanic arcs were modified by back-arc spreading and back-arc basin closures accompanied by ophiolite obduction and orogenesis (Hibbard and others, 2007b; van Staal and others, 2009; Fyffe and others, 2011; van Staal and Barr, 2012; Pollock and others, 2012). Geochemical evidence indicates that most Ganderian rocks were derived from, or incorporated, Neoproterozoic or older evolved continental sources or materials (Samson and others, 2000; Rogers and others, 2006; Fyffe and others, 2009; Pollock and others 2012).

The Southeastern New England Composite Avalon terrane (Milford-Dedham Zone of Zen and others, 1983) is correlated with the type Avalon terrane of eastern Newfoundland (O'Brien and others, 1983; Rast and Skehan, 1983; Williams and Hatcher, 1983), hereafter grouped as Avalonia. Avalonia is characterized by a tectonic evolution from Late Neoproterozoic juvenile arc magmatism to early Paleozoic passive margin sedimentation via rifting along the Gondwanan margin (Murphy and others, 2004; Hibbard and others, 2007a; Pollock and others, 2009, 2012). Paleozoic rocks eroded or melted from Neoproterozoic Avalonian igneous source material generally share this juvenile geochemical signature (for example, Samson and others, 2000; Murphy and Nance, 2002; Murphy and others, 2004), with a possible exception being the Caledonia terrane of southern New Brunswick (Murphy and others, 2004; Satkoski and others, 2010). The Southeastern New England Composite Avalon terrane in Massachusetts (fig. 1B) consists of unmetamorphosed to low-grade Neoproterozoic calc-alkaline plutonic and volcanic rocks and scattered exposures of Cambrian and Ordovician platformal sedimentary rocks (for example, Williams and Hatcher, 1983; Skehan and Rast, 1990; Goldsmith, 1991a). This terrane experienced bimodal alkaline plutonism in the late Ordovician, early Silurian, and middle to late Devonian (Wones and Goldsmith, 1991; Hermes and Zartman, 1992).

The younger Merrimack belt, directly northwest of the Nashoba terrane in Massachusetts (fig. 1), is a thick sequence of metamorphosed Silurian-Devonian basin deposits (for example, Robinson and Goldsmith, 1991; Sorota and others, 2011; Sorota, ms, 2013). It consists of phyllite, schist, quartzite and calcareous metasedimentary rocks, metamorphosed from lower greenschist facies in the east to upper amphibolite facies toward the west (for example, Robinson and Goldsmith, 1991).

Nashoba Terrane

The Nashoba terrane can be divided into a series of early Paleozoic metamorphosed magmatic (largely volcanic) and volcanogenic sedimentary rocks, which together are the focus of this paper, and a series of younger plutons. The early Paleozoic units include the Marlboro Formation, Nashoba Formation, Fish Brook Gneiss, and other minor schist or paragneiss units (Bell and Alvord, 1976; Zen and others, 1983; Goldsmith 1991b; Hepburn and others, 1995) (fig. 1C). Bell and Alvord (1976) interpreted these older metamorphosed rocks as forming a coherent stratigraphic package dipping to the northwest. However, the terrane has been significantly deformed, metamorphosed and partially melted during the late Silurian, Devonian and early Carboniferous (Goldsmith 1991c; Stroud and others, 2009; Buchanan and others, 2015; Walsh and others, 2015) and the boundaries between major stratigraphic units are now generally faults or shear zones (Goldsmith, 1991c; Hepburn and others, 1995). Therefore, the units may more closely represent lithodemic units of similar lithologies than actual stratigraphic formations. However, since these units can be mapped over 10's of kilometers along strike, the long-standing formational designations have been retained herein as useful guides in describing the rocks and placing their geochemistry in a lithological context. Furthermore, while there are few reliable age dates in the terrane, those available suggest a general younging to the northwest (see below). The classical tectonostratigraphic column for the Nashoba terrane that represents the sequence of the units from SE to NW is shown as figure 1C (Bell and Alvord, 1976; Goldsmith, 1991b).

The Marlboro Formation.—The Marlboro Formation is the southeastern most of the stratified units in the Nashoba terrane in Massachusetts (fig. 1B), although it either thins stratigraphically and pinches out or it is structurally cut out to the northeast (Zen and others, 1983). It is chiefly magmatic in origin and consists largely of hornblende-plagioclase amphibolite interlayered with intermediate composition to felsic gneiss and less common rusty-weathering pelitic schist. The amphibolitic rocks are typically fine- to medium-grained and commonly composed of hornblende (50% to 60%) and plagioclase feldspar (An_{47}-An_{55}, determined petrographically), with minor amounts of quartz, epidote and biotite. Pelitic schist is fine-grained and composed largely of muscovite and quartz, with minor amounts of biotite, garnet, and oligoclase (Goldsmith, 1991b; Kopera and others, 2006). The Quinnebaug Formation of the Putnam terrane in Connecticut is considered correlative (Goldsmith, 1991b; Wintsch and others, 2007).

The Millham Reservoir Member of the Marlboro Formation, which occurs along the boundary with the Nashoba Formation (fig. 1C), is typically fine-grained and composed of plagioclase feldspar (An_{35}-An_{45}), biotite and quartz, with minor amounts of hornblende and augite (Hepburn and DiNitto, 1978; DiNitto and others, 1984). Based on this unit's intermediate composition, along with the presence of interlayered rusty-weathering schist and amphibolite, the Millham Reservoir Member has been interpreted as a metamorphosed andesitic tuff or flow roughly contemporaneous with the amphibolite units of the Marlboro Formation (Hepburn and DiNitto, 1978; Kopera and others, 2006).

The metavolcanic rocks within the Marlboro Formation and its equivalent in the Putnam terrane to the south were dated as forming between 543 ± 7 Ma and 501 ± 3 Ma (U-Pb zircon SHRIMP), and a granitic gneiss that intrudes some of these metavolcanic rocks as 515 ± 4 Ma (U-Pb zircon SHRIMP; Walsh and others, 2009, 2011a, 2011b, 2015), so they are Cambrian in age.

The Fish Brook Gneiss.—The 499 +6/−3 Ma (U-Pb zircon TIMS; Hepburn and others, 1995) Fish Brook Gneiss is an intermediate composition to granitic orthogneiss with a distinctive "swirled" foliation (Bell and Alvord, 1976; Hepburn and others, 1995). It has previously been interpreted as either a metamorphosed felsic volcanic rock (Bell and Alvord, 1976) or a deformed granitic pluton (Castle 1964, 1965; see Goldsmith, 1991b for discussion). Meter-scale pods of amphibolite occur sporadically throughout the unit. The contact relationships between the Fish Brook Gneiss and the adjacent Marlboro and Nashoba Formations are unclear. In the central portion of the Nashoba terrane the Fish Brook Gneiss occurs along the north side of the Assabet River fault zone in contact with the Boxford Member of the Nashoba Formation, but to the northeast the contacts are not exposed and are obscured by younger plutons (fig. 1B). Castle (1964, 1965) interpreted the contact as faulted or unconformable, whereas Bell and Alvord (1976) considered the Marlboro, Fish Brook Gneiss, and Nashoba Formations to be gradational.

The Nashoba Formation.—The Nashoba Formation (fig. 1B) comprises a thick sequence of pelitic and feldspathic biotite schist and gneiss, migmatite, and amphibolite with minor amounts of calc-silicate and rusty-weathering sillimanite schist (Bell and Alvord, 1976; Hepburn and DiNitto, 1978; Goldsmith, 1991b; Kopera and others, 2006). Amphibolite is distributed sparsely throughout the Nashoba Formation in general, but it is the major component of the Boxford Member, which occurs along the formation's southeastern edge near the Assabet River fault zone (figs. 1B and 1C). The Tatnic Hill Formation of the Putnam terrane in Connecticut is considered correlative with the Nashoba Formation (Goldsmith, 1991b; Wintsch and others, 2007).

The Nashoba Formation has previously been interpreted to have formed in a near-arc basin based on the abundance of metasedimentary rocks with presumed volcanogenic protoliths, interlayered amphibolite and its proximity to the Marlboro Formation metavolcanic rocks (Abu-Moustafa and Skehan, 1976; Goldsmith, 1991b and references therein). In general, the abundance of amphibolite decreases to the northwest, away from the Marlboro Formation, while the abundance of the metasedimentary rocks increases. None of the metaigneous rocks in the Nashoba Formation have yet been successfully dated. However, preliminary U-Pb laser ablation inductively coupled mass spectrometry (LA-ICPMS) detrital zircon analyses of a Nashoba Formation paragneiss sample yielded a minimum age of 461 ± 19 Ma (1 sigma error) (Loan and others, 2011; Loan, ms, 2011) and indicates that at least some of the Nashoba Formation metasedimentary rocks could be as young as Ordovician.

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Methods

Major and trace element concentrations were compiled for forty-nine samples (Marlboro Formation 18, Fish Brook Gneiss 8, Nashoba Formation 23) analyzed by X-Ray Fluorescence at the University of Massachusetts, Amherst or the Nova Scotia Regional Geochemical Centre, and by Instrumental Neutron Activation Analysis at Boston College (table 1). Geochemical data used include that of Durfee (ms, 1983), Hill and others (1984), Raposa (ms, 1985), Oakes-Coyne and others (1996), Oakes-Coyne (personal communication, 1996), and Turner (ms, 1996).

Because the older rocks of the Nashoba terrane experienced amphibolite facies metamorphism, the discussion focuses largely on the more immobile elements (with the exception of the AFM diagrams and some spiderdiagram elements). Volcanic rock names are used for the igneous rocks for easy comparison, regardless of their intrusive or extrusive origin and subsequent metamorphism. For simplicity, we refer to extended incompatible element spider diagrams normalized to primitive mantle concentrations as "extended element plots," and to rare earth element plots normalized to chondritic concentrations as "REE plots."

Mafic Rocks

Marlboro Formation.—Amphibolite compositions from the Marlboro Formation (fig. 2) are tholeiitic on the AFM plot (fig. 3A), but include calc-alkaline basalts and basaltic andesite when plotted on a Th-Co diagram for determination of rock type in altered or metamorphosed igneous rocks (Hastie and others, 2007) (fig. 3B). On extended element plots these rocks show variable LILE enrichment but are otherwise typically fairly flat (fig. 3C). Strong negative Nb and Ta anomalies are not typical but present in one sample. Most samples have small negative P and Ti anomalies. Although strong LILE enrichment commonly indicates a subduction component, it may be somewhat equivocal for these rocks because these elements could have been mobilized during later metamorphism.

REE plots show flat to moderately negative patterns (fig. 3D; $[La/Yb]_N$ 1.29 – 3.93, with one sample at 0.86). There is also a general trend of decreasing enrichment in HREEs with increasing $[La/Yb]_N$. HREE patterns remain consistent throughout this trend ($[Tb/Yb]_N$ ~1 – 2), suggesting that LREE enrichment rather than HREE fractionation is the major contributing factor. None of the samples show a significant negative Eu anomaly.

TABLE 1

Major and trace element data

	Marlboro Formation *Amphibolites*									
Wt.%	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
SiO_2	48.98	50.86	49.70	48.20	45.90	48.38	47.31	47.09	49.55	45.29
Al_2O_3	15.13	15.09	14.45	16.27	17.22	16.13	18.14	18.38	15.40	16.36
FeO	11.36	10.18	12.55	10.93	11.53	11.29	9.95	9.10	10.89	12.12
MgO	8.62	8.64	6.74	5.25	10.11	6.65	7.26	7.71	7.20	6.54
CaO	9.62	8.61	8.98	12.66	8.71	11.01	12.07	12.29	10.00	14.55
Na_2O	3.04	3.76	4.61	3.04	2.93	3.79	3.09	3.34	3.65	2.32
K_2O	0.37	0.38	0.21	0.97	1.45	0.18	0.35	0.28	0.28	0.25
TiO_2	2.20	1.83	2.29	2.04	1.65	2.04	1.49	1.33	2.29	2.08
MnO	0.43	0.39	0.25	0.39	0.29	0.35	0.18	0.20	0.44	0.28
P_2O_5	0.24	0.26	0.21	0.27	0.20	0.18	0.16	0.28	0.31	0.21
PPM										
Ba	72	102	50	127	368	89	27	18	37	30
Rb	7	7	4	19	51	<5	<5	<5	<5	<5
Sr	276	261	218	378	336	381	354	345	241	423
Y	29	32	32	24	19	40	28	25	39	37
Zr	177	140	141	155	126	138	130	118	220	168
Nb	10.0	<5	7.0	10.0	7.0	2.6	2.7	2.8	8.4	4.5
Zn	70	64	111	88	99	93	77	88	102	98
Ni	64	91	54	38	132	115	77	109	68	81
V	303	288	341	273	207	275	231	193	275	273
La	10.29	5.72	8.01	14.08	7.54	4.80	4.98	4.67	11.74	8.87
Ce	26.93	15.24	19.73	34.34	20.11	15.60	16.30	15.40	33.84	26.30
Nd	18.32	14.31	17.24	20.84	13.39	14.10	14.48	13.50	26.60	22.00
Sm	4.70	4.16	5.04	5.07	3.56	4.55	3.55	3.20	6.77	5.87
Eu	1.21	1.70	1.74	1.84	1.29	1.79	1.36	1.27	2.10	2.12
Tb	0.53	0.72	1.02	0.92	0.63	0.93	0.89	0.72	1.40	1.40
Yb	2.32	2.54	3.67	2.57	1.97	4.00	2.10	2.05	3.40	3.30
Lu	0.28	0.43	0.59	0.40	0.27	0.52	0.37	0.36	0.56	0.54
Cr	61.6	231.4	181.3	47.7	81.0	399.0	365.0	269.0	185.0	153.0
Co	31.4	28.9	41.5	37.2	51.5	43.0	50.7	51.6	44.7	46.9
Hf	4.3	3.4	4.1	4.2	3.3	3.3	3.6	2.7	0.5	3.8
Sc	36.9	36.7	47.9	33.4	27.0	42.7	44.0	37.9	41.5	44.9
Ta	1.0	0.5	0.3	0.9	0.4	0.2	0.3	0.1	0.6	0.3
Cs	0.4	0.4		1.5	8.1					
Th	0.4	0.6	0.6	1.7	0.4	0.5	0.5	0.6	0.9	0.4

Oxides in weight %, trace elements in PPM.

^{B}=samples from the Boxford Member of the Nashoba Formation; samples from the same locality as Sm-Nd samples: ^{1}= NFA-3; ^{2}=NFA-7; ^{3}=FBG-3.

Table 1
(continued)

	Marlboro Formation							
	Amphibolites					*Gneisses*		
Wt.%	M11	M12	M13	M14	M15	M16	M17	M18
SiO_2	46.22	45.96	47.63	49.32	48.63	64.30	66.92	57.23
Al_2O_3	16.80	16.87	17.07	13.34	15.82	16.88	15.72	15.20
FeO	11.35	11.35	10.17	11.20	10.94	5.21	4.36	9.53
MgO	10.26	10.45	8.57	10.15	8.61	2.22	1.86	4.52
CaO	9.85	9.81	10.67	11.30	9.73	4.82	3.71	7.37
Na_2O	2.75	2.78	3.52	2.36	3.84	3.15	3.31	2.50
K_2O	0.60	0.61	0.22	0.19	0.15	2.36	3.24	1.94
TiO_2	1.65	1.65	1.76	1.75	1.86	0.82	0.66	1.40
MnO	0.34	0.33	0.21	0.25	0.22	0.07	0.06	0.12
P_2O_5	0.18	0.02	0.17	0.14	0.21	0.17	0.15	0.17
PPM								
Ba	105		25	25	16	411	814	374
Rb	16		<5	<5	<5	88	117	67
Sr	319		355	327	403	402	282	265
Y	25		30	34	35	21	24	30
Zr			133	145	141	146	158	172
Nb	5.5		3.0	3.3	3.2	10.0	11.0	13.0
Zn	116		84	97	83	70	54	67
Ni	131		105	84	85	10	11	59
V	198		222	295	245	109	76	190
La	7.54	7.10	5.30	4.60	5.78	29.13	34.00	21.56
Ce	20.43	20.60	16.30	12.50	18.80	54.12	63.39	48.13
Nd	14.33	14.10	15.40	10.94	17.90	22.48	24.81	24.43
Sm	3.51	3.70	4.09	3.73	4.80	3.41	4.76	5.49
Eu	1.39	1.39	1.60	1.34	1.63	1.15	1.46	1.60
Tb	0.83	0.64	1.05	0.68	1.40	0.46	0.81	0.89
Yb	2.00	2.17	2.50	2.56	2.90	1.76	2.17	2.73
Lu	0.32	0.33	0.40	0.46	0.46	0.29	0.34	0.48
Cr	189.0	128.0	190.0	100.0	129.0	17.7	21.9	105.1
Co	53.2	51.4	51.7	47.0	54.9	9.9	10.2	29.8
Hf	2.9	3.1	3.6	3.0	3.8	4.0	4.8	5.3
Sc	29.7	28.4	39.7	68.3	42.0	9.9	11.1	23.5
Ta	0.4	0.4	0.3	0.3	0.2	0.8	0.9	1.1
Cs						3.1	4.4	3.0
Th	0.8	0.8	0.5		0.4	9.3	11.2	5.1

Oxides in weight %, trace elements in PPM.
[B]=samples from the Boxford Member of the Nashoba Formation; samples from the same locality as Sm-Nd samples: [1]= NFA-3; [2]=NFA-7; [3]=FBG-3.

TABLE 1
(continued)

	Nashoba Formation *Amphibolites*										
Wt.%	N1	N2[1]	N3	N4	N5	N6	N7	N8[2]	N9	N10	N11[2]
SiO_2	49.58	49.58	50.16	52.50	46.64	44.95	46.55	42.81	45.92	50.28	47.77
Al_2O_3	14.13	13.73	14.39	13.89	14.98	16.65	14.37	12.31	18.97	14.35	13.78
FeO	12.66	13.00	13.80	12.52	12.07	14.64	11.27	20.34	12.20	10.89	13.70
MgO	7.10	6.53	5.08	5.47	7.61	5.44	13.49	7.18	7.01	8.47	7.45
CaO	11.75	11.62	8.76	8.08	12.06	9.87	9.16	10.10	10.45	11.74	10.73
Na_2O	1.84	3.15	3.96	3.37	2.56	3.05	1.46	2.28	1.43	2.48	3.14
K_2O	0.45	0.26	0.53	1.26	0.75	1.10	1.37	0.45	1.76	0.48	0.42
TiO_2	2.04	1.80	2.87	2.47	2.75	3.61	1.84	3.83	1.54	0.97	2.34
MnO	0.24	0.19	0.21	0.18	0.19	0.20	0.18	0.33	0.38	0.21	0.36
P_2O_5	0.20	0.13	0.24	0.25	0.39	0.50	0.31	0.37	0.35	0.13	0.32
PPM											
Ba	64	31	109	301	132	77	385	43	498		
Rb	6		17	34	13	29	37	11	59		
Sr	162	252	249	255	385	634	157	99	485		
Y	45	37	43	35	30	30	18	62	39		
Zr	141	111	148	200	197	255	132	228	99		
Nb	5.0	5.0	5.0	17.0	26.0	37.0	21.0	16.0	9.0		
Zn	97	98	88	96	84	111	78	208	118		
Ni	81	42	25	46	125	27	312	48	23		
V	349	350	458	350	337	351	260	622	284		
La	5.94	3.50	7.10	18.76	18.90	28.08	15.79	10.31	13.62	3.69	8.71
Ce	16.53	9.83	18.67	45.78	44.92	62.61	35.75	30.87	39.52	20.24	21.56
Nd	11.72	8.87	17.28	27.21	25.11	32.22	18.49	25.87	29.50	15.68	13.37
Sm	4.75	3.66	4.94	6.20	5.45	6.76	4.26	8.49	7.78	3.13	4.91
Eu	1.78	1.36	1.95	1.88	1.95	2.34	1.49	2.67	2.24	0.70	1.88
Tb	1.20	0.70	1.30	0.83	0.69	0.88	0.63	1.94	1.30	1.96	0.88
Yb	3.86	3.34	3.79	2.63	2.30	2.06	2.14	7.68	3.13	2.49	4.66
Lu	0.64	0.48	0.66	0.40	0.33	0.31	0.35	1.16	0.47	0.39	0.63
Cr	230.8	62.2	45.8	85.2	304.0	3.4	877.1	83.8	64.7	289.4	237.1
Co	38.2	47.2	36.4	41.0	43.9	46.4	55.2	53.2	32.6	51.7	
Hf	3.7	2.8	4.1	5.7	4.6	6.0	3.4	6.6	2.6	2.0	3.8
Sc	41.4	47.8	40.4	32.3	32.5	21.8	31.1	54.8	35.3	43.9	43.1
Ta	0.3	0.4	0.6	1.3	2.1	2.9	1.8	0.8	0.5		1.2
Cs	0.9		0.2	0.9	1.5	12.3	4.8		2.0	2.3	1.4
Th	0.2	1.2	0.7	3.3	1.4	2.6	1.2	1.2	0.6		

Oxides in weight %, trace elements in PPM.
[B]=samples from the Boxford Member of the Nashoba Formation; samples from the same locality as Sm-Nd samples: [1]= NFA-3; [2]=NFA-7; [3]=FBG-3.

Table 1
(continued)

	Nashoba Formation											
	Amphibolites										*Gneisses*	
Wt.%	N12[1B]	N13[1B]	N14[1B]	N15[B]	N16[B]	N17	N18	N19	N20[B]	N21[B]	N22	N23
SiO_2	47.29	47.28	46.10	52.75	56.35	48.07	50.30	48.80	45.87	45.31	68.67	66.06
Al_2O_3	15.73	17.46	16.38	17.77	13.67	13.21	14.60	15.30	16.46	15.60	14.06	15.07
FeO	11.64	8.79	11.43	8.64	7.64	12.27	11.39	12.23	11.70	12.24	6.27	6.65
MgO	7.02	8.02	6.58	7.99	9.31	8.83	8.11	6.65	6.60	6.82	1.85	2.61
CaO	12.73	13.24	13.18	9.04	7.85	13.54	10.78	10.55	11.57	12.76	2.22	2.11
Na_2O	3.19	3.23	3.85	1.67	2.68	2.30	3.07	3.22	3.59	3.21	3.38	3.28
K_2O	0.26	0.61	0.22	0.85	1.57	0.53	0.50	0.58	0.66	0.38	2.51	3.04
TiO_2	1.74	1.14	1.85	1.01	0.63	0.97	0.98	2.07	2.94	3.02	0.85	0.89
MnO	0.19	0.15	0.20	0.17	0.20	0.23	0.21	0.22	0.19	0.19	0.11	0.14
P_2O_5	0.20	0.07	0.22	0.10	0.09	0.04	0.06	0.37	0.40	0.47	0.08	0.14
PPM												
Ba											409	481
Rb											154	150
Sr											132	193
Y											31	28
Zr											282	217
Nb											20.0	19.0
Zn											23	50
La	2.52	1.04	4.97	5.85	8.91	1.00	1.48	9.79	15.02	13.66	44.31	37.2
Ce	9.05	6.16	12.47	21.44	28.21	3.52	3.94	24.87	35.84	33.17	92.41	76.68
Nd	8.44	5.85	11.72	16.38	18.43	3.67	3.34	18.31	26.27	25.74	40.87	34.65
Sm	3.38	1.87	4.63	4.64	4.33	1.78	1.93	5.73	6.31	6.46	7.70	6.75
Eu	1.47	0.94	1.47	1.35	1.20	0.73	0.81	2.01	2.26	2.23	1.53	1.46
Tb	0.88	0.73	1.18	1.07	1.03	0.87	0.85	1.89	1.48	1.49	1.26	1.10
Yb	3.18	3.32	3.32	2.23	3.32	3.09	2.97	4.99	3.09	3.36	3.42	3.55
Lu	0.51	0.32	0.60	0.49	0.48	0.42	0.44	0.75	0.46	0.58	0.56	0.56
Cr	92.1	289.8	33.6	200.8	740.5	57.2	88.8	180.1	121.6	245.7	52.0	90.0
Co	45.3	39.8	45.7	35.2	36.2	51.3	48.0	42.4	43.9	43.6	13.6	18.2
Hf	2.7	1.7	3.4	1.8	2.2	1.3	1.2	5.2	5.0	5.5	8.3	7.0
Sc	45.9	35.6	44.6	29.6	33.3	47.6	45.3	38.4	41.1	36.3	14.8	18.8
Ta	1.1	0.3	0.4	0.5	0.8	1.1	1.1	1.1	1.2	0.8	1.2	1.3
Cs	1.4	0.9	1.1	2.89	2.7	1.3	1.3	1.7	1.0	1.9	4.9	4.4
Th											14.6	12.2

Oxides in weight %, trace elements in PPM.
[B]=samples from the Boxford Member of the Nashoba Formation; samples from the same locality as Sm-Nd samples: [1]= NFA-3; [2]=NFA-7; [3]=FBG-3.

TABLE 1

(continued)

	Fish Brook Gneiss							
	Northeastern Body				*Southwestern Body*			
Wt.%	FB1[3]	FB2[3]	FB3[3]	FB4[3]	FB5	FB6	FB7	FB8
SiO_2	76.07	78.54	77.36	78.32	66.71	72.17	73.29	78.54
Al_2O_3	12.59	11.55	12.07	11.98	14.92	13.99	14.10	13.32
FeO	2.08	1.46	2.02	1.49	5.20	3.23	2.62	2.01
MgO	0.40	0.37	0.34	0.15	1.80	0.75	0.50	0.33
CaO	0.95	0.64	0.81	0.67	2.91	2.32	3.45	1.47
Na_2O	5.76	5.62	5.74	5.80	3.78	3.74	4.00	5.08
K_2O	0.44	0.35	0.25	0.35	1.36	1.27	0.71	0.78
TiO_2	0.14	0.08	0.11	0.10	0.69	0.23	0.23	0.20
MnO	0.03	0.02	0.03	0.02	0.11	0.60	0.05	0.02
P_2O_5	0.02	0.01	0.02	0.01	0.13	0.04	0.05	0.03
PPM								
Ba	159	84	68	105	433	215	178	303
Rb	10	16	3	4	42	34	14	21
Sr	55	62	73	65	336	72	72	106
Y	96	47	19	60	20	18	18	29
Zr	164	145	122	169	159	99	83	135
Nb	8.0	5.0	5.0	10.0	8.0	7.0	4.0	8.0
Zn	78	28	48	21	84	45	33	15
Ni	4	5	4	4	20	6	9	6
V	7	9	0	2	93	34	20	6
La	17.62	13.72	8.57	18.22	21.66	9.20	7.18	15.80
Ce	42.51	32.13	19.22	44.48	48.73	17.18	14.32	31.71
Nd	24.61	15.17	9.53	22.79	23.34	8.30	7.28	15.70
Sm	7.68	3.73	2.19	4.99	4.75	1.85	1.68	3.52
Eu	0.65	0.47	0.55	0.47	1.26	0.44	0.50	0.75
Tb	2.50	1.12	0.51	1.40	0.68	0.45	0.42	0.77
Yb	12.53	6.17	2.99	7.86	2.50	2.46	2.50	3.51
Lu	1.82	0.93	0.47	1.14	0.37	0.40	0.38	0.53
Cr	2.9	1.0	1.4	2.1	39.4	3.3	2.2	1.3
Co	1.2	1.1	1.2	1.0	11.7	4.9	3.6	2.1
Hf	5.9	6.7	4.3	8.2	5.0	3.5	2.8	4.5
Sc	6.5	4.9	7.8	4.3	15.2	9.3	10.1	7.4
Ta	0.2	1.5	0.2	0.6	0.7	0.5	0.2	0.6
Cs	0.4	3.1	0.1	0.3	3.3	2.8	0.9	0.6
Th	8.0	5.0	0.1	8.0	5.0	7.0	2.0	9.0

Oxides in weight %, trace elements in PPM.
[B]=samples from the Boxford Member of the Nashoba Formation; samples from the same locality as Sm-Nd samples: [1]= NFA-3; [2]=NFA-7; [3]=FBG-3.

On tectonic discrimination diagrams, amphibolite samples of the Marlboro Formation plot in a range of MORB and arc-related fields (fig. 4). On the Th-Hf/3-Ta plot of Wood (1980; fig. 4A) about half the samples plot in the N-MORB and E-MORB fields while most of the others plot between the MORB and arc fields or in the island arc tholeiite field. By comparison, on the La/10-Y/15-Nb/8 diagram of Cabanis and Lecolle (1989) (fig. 4B) most samples plot in the back-arc and continental arc basalt

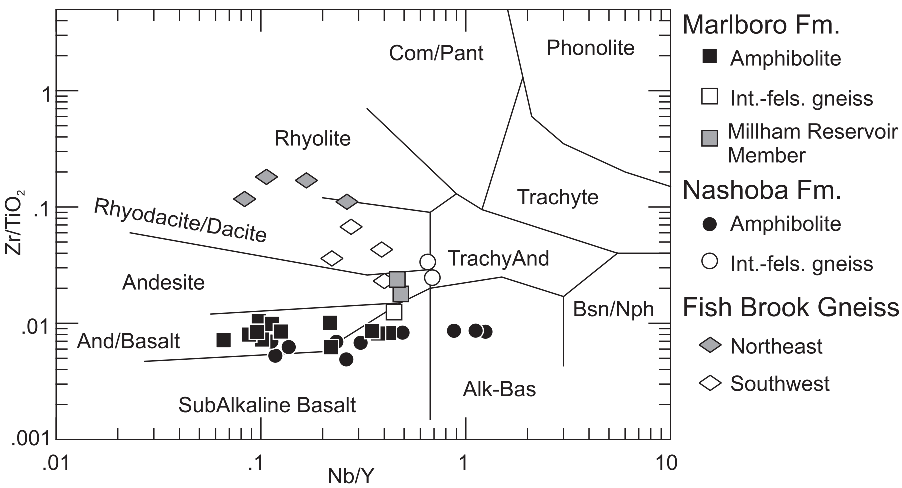

Fig. 2. Zr/TiO2 vs. Nb/Y diagram showing rock type for various units of the Nashoba terrane based on the more immobile trace elements (diagram from Winchester and Floyd, 1977).

fields. A plot of Ti/1000 versus V (fig. 4C) shows a consistent grouping in the back-arc basalt-MORB field. Although little evidence for Th enrichment is present in the incompatible element diagram (fig. 3C), figure 4D shows that approximately half of the Marlboro Formation amphibolite samples plot above the mantle array due to enrichment in Th over Nb (normalized to Yb to eliminate fractionation effects). This is consistent with contamination by either a continental or subduction zone source (Pearce, 2008).

The geochemical and tectono-magmatic discrimination diagrams do not point strongly to a single tectonic setting for the Marlboro Formation but show a mix of MORB and arc-derived components. The REE plots are typical of primitive arc tholeiites but the incompatible elements show little evidence for a strong subduction component aside from the enrichment in LILEs. The lack of strong LREE depletion is not consistent with a pure MORB source, while the low enrichment in Th over Nb suggests minimal contribution from either a subduction or continental source. The largely tholeiitic character of the amphibolites, the low to moderate values of $[La/Yb]_N$, mixing of back-arc and arc magma signatures on tectonic discrimination diagrams, and minimal enrichment of Th over Nb and Ta do suggest, however, that the Marlboro Formation formed in a arc/back-arc setting on attenuated continental crust.

Nashoba Formation.—Amphibolite samples from the Nashoba Formation are generally similar in major element geochemistry to those of the Marlboro Formation (figs. 2, 5A and 5B), although they include three samples with somewhat more alkaline compositions (fig. 2). However, several of the Nashoba Formation amphibolites plot in the calc-alkaline field in figure 5A, while others have more evolved, Fe-enriched, tholeiitic compositions than any of the Marlboro Formation amphibolites. On extended element plots, Nashoba Formation amphibolite samples show similar patterns to those of the Marlboro Formation but with greater variations in enrichment, especially in Th, Nb, and Ta and some samples have concentrations 2 to 3 times higher in the Nashoba Formation (fig. 5C, table 1). As in the Marlboro Formation, LILE enrichment is high but variable, there is no strong Nb-Ta anomaly, and a small negative P anomaly is present in some samples.

REE patterns for amphibolite samples from the Nashoba Formation have a much wider range than those in the Marlboro Formation with both positive and negative

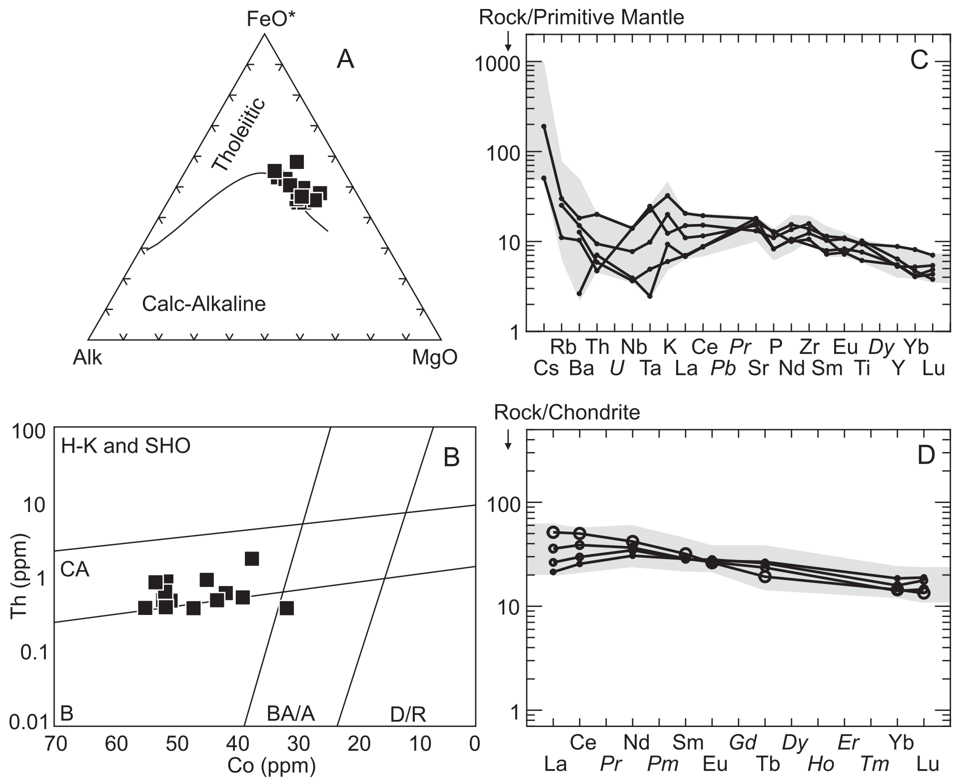

Fig. 3. Geochemical diagrams for Marlboro Formation amphibolite samples: (A) Alkalis-FeO-MgO diagram of Irvine and Baragar (1971) showing tholeiitic and calc-alkaline trends. (B) Th-Co diagram for determining rock type of altered or metamorphosed igneous rocks after Hastie and others (2007). Fields are (counter-clockwise from upper left) high-K and shoshonitic, calc-alkaline, island arc tholeiite and basalt, basaltic andesite and andesite, and dacite and rhyolite. (C) Extended element plot. The shaded area indicates the full range of values; five representative samples are shown. (D) REE plot. The shaded area indicates full range of values, solid lines are quartile averages based on $[La/Yb]_N$ values. Symbols on the average lines increase in size to highlight increasing $[La/Yb]_N$ values at similar $[Tb/Yb]_N$ values but decreasing HREE concentrations. Both (C) and (D) are normalized after Sun and McDonough (1989); italicized elements are not plotted.

slopes. For instance, La varies from 4 to 118 times chondritic values and $[La/Yb]_N$ ratios range from 0.2 to 9.8 (fig. 5D). While no strong negative Eu anomalies are present, three samples do have a slight negative Eu anomaly. The HREE patterns are generally flat, but the trend of decreasing HREEs as $[La/Yb]_N$ increases is less well developed than in the Marlboro Formation. A major difference between the amphibolite samples from the Nashoba and Marlboro Formations is that several from the Nashoba Formation show LREE depletion, typical of mid-ocean ridge basalts, while those of the Marlboro Formation do not. In the Boxford Member, near the structural base of the Nashoba Formation (Goldsmith, 1991b) LREE depleted and LREE enriched amphibolites occur in close proximity (table 1), which is consistent with an arc/back-arc basin origin.

The Nashoba Formation amphibolite samples, much like those in the Marlboro Formation, plot in a variety of arc and MORB related fields on tectono-magmatic discrimination diagrams. On the Th-Hf/3-Ta plot of Wood (1980; fig. 6A) most samples plot in the N-MORB or E-MORB fields while three plot in or near the OIB-rift field. Two samples plot toward the arc basalt field, and unlike similar amphibolite

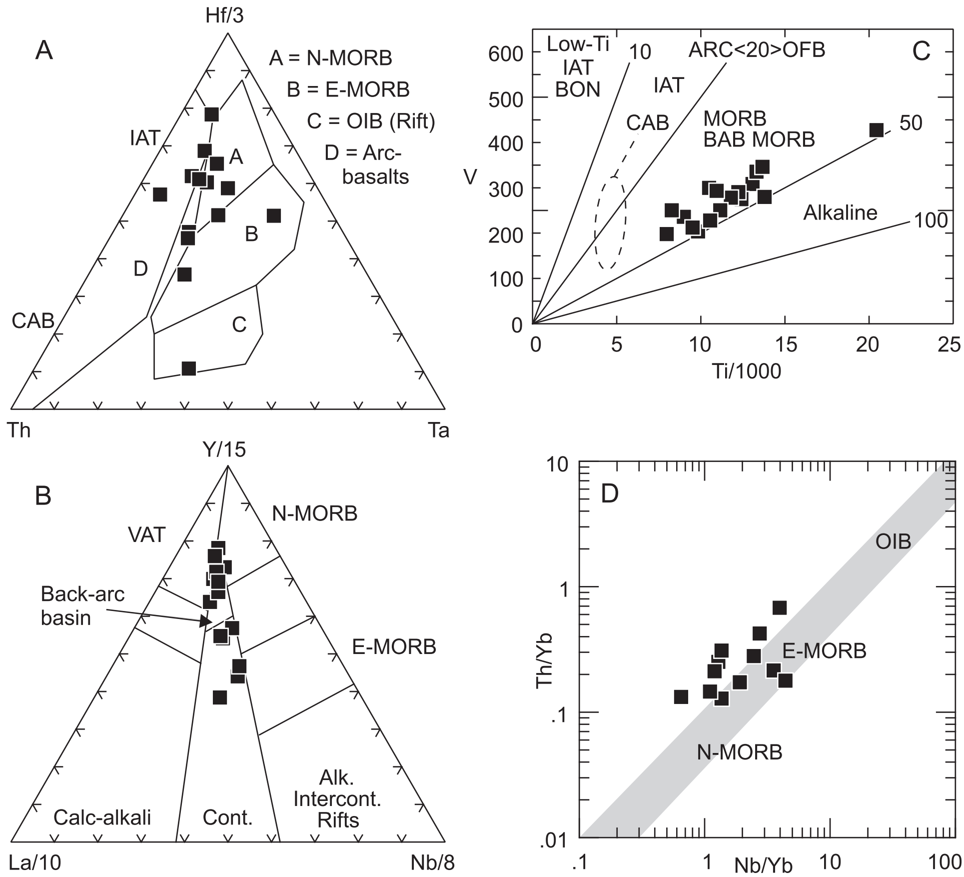

Fig. 4. Tectonic discrimination diagrams for Marlboro Formation amphibolite samples. (A) Th-Hf/3-Ta diagram for basalts and derivatives after Wood (1980). (B) La/10-Y/15-Nb/8 diagram for basalts after Cabanis and Lecolle (1989). (C) V vs. Ti/1000 diagram for basalts after Shervais (1982). (D) Th/Yb vs. Nb/Yb mantle array diagram after Pearce (2008). Shaded area indicates range of mantle array compositions. Abbreviations: BAB = back-arc basalt, BON = boninite, CAB = calc-alkaline basalt, Cont = continental, E-MORB = enriched mid-ocean ridge basalt, IAT = island arc tholeiite, N-MORB = normal mid-ocean ridge basalt, OFB = ocean floor basalt, OIB = ocean island basalt, VAT = volcanic arc tholeiite.

samples in the Marlboro Formation these trend toward the calc-alkaline basalt field rather than the arc tholeiite field. On the La/10-Y/15-Nb/8 diagram (Cabanis and Lecolle, 1989; fig. 6B) and in contrast to the Marlboro Formation, Nashoba Formation amphibolite samples plot mostly in the MORB and alkaline fields, with only three in the back-arc and continental arc fields (fig. 4B).

The plot of Ti-V (Shervais, 1982) for the Nashoba Formation amphibolite samples shows a broad range of compositions that are mostly within the back-arc and MORB field, with one sample in the alkaline field (fig. 6C). As indicated in the extended element plot (fig. 5C), enrichment in Th over Nb is minimal in the Nashoba Formation and only three amphibolite samples of nine plot above the mantle array (fig. 6D). The other six samples spread out on the mantle array, indicating N-MORB, E-MORB and OIB sources contributing to the amphibolites of the Nashoba Formation.

Geochemical data indicate greater source diversity in the Nashoba Formation amphibolites than in the Marlboro Formation. Samples with strong LREE depletion,

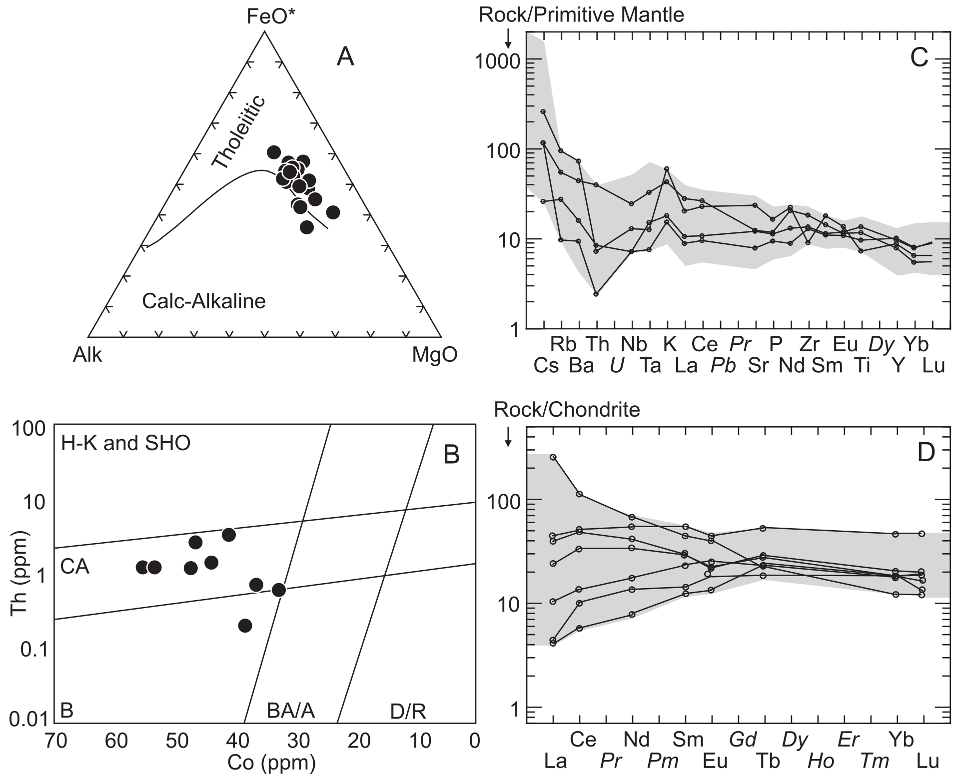

Fig. 5. Geochemical diagrams for Nashoba Formation amphibolite samples: (A) Alkalis-FeO-MgO diagram after Irvine and Baragar (1971) showing tholeiitic and calc-alkaline trends. (B) Th-Co diagram for determining rock type of altered or metamorphosed igneous rocks after Hastie and others (2007). Fields are (counter-clockwise from upper left) high-K and shoshonitic, calc-alkaline, island arc tholeiite and basalt, basaltic andesite and andesite, and dacite and rhyolite. (C) Extended element plot. (D) REE plot. Shaded areas on (C) and (D) indicate the full range of values with representative samples shown. (C) and (D) are normalized after Sun and McDonough (1989); italicized elements are not plotted.

low Th, Nb, and Ta values, and tholeiitic geochemistry, point to less overall contribution from subduction or continental crustal sources in the Nashoba Formation than in the Marlboro Formation; instead these are consistent with a MORB source. However, other samples with moderate LREE enrichment, elevated Th/Nb ratios, and calc-alkaline geochemistry indicate the opposite, being more consistent with a subduction and/or continental source. A small subset of three samples indicates an alkaline rift or OIB source may be present in addition to the arc and MORB sources.

A primitive arc/back-arc complex built on attenuated continental crust could produce magmas consistent with all of these sources. As with the Marlboro Formation, this provides a setting where arc-influenced magmas, uncontaminated depleted mantle melts, and mixes thereof can be emplaced in proximity to magmas derived from rifting.

Intermediate and Felsic Rocks

Marlboro Formation.—Andesitic to dacitic composition gneiss (figs. 2, 7A and 7B) occurs in several locations within the Marlboro Formation and within the Millham Reservoir Member. The same characteristics that indicate arc input in the Marlboro Formation amphibolites are present and more pronounced in the intermediate

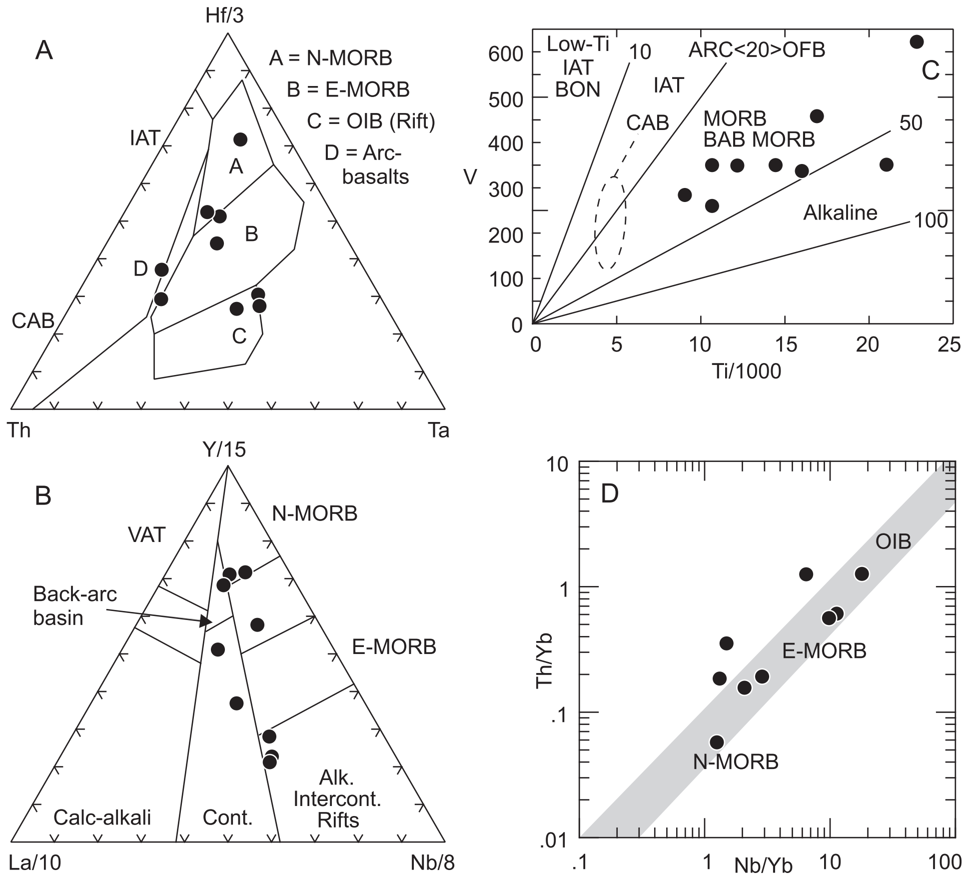

Fig. 6. Tectonic discrimination diagrams for Nashoba Formation amphibolite samples. (A) Th-Hf/3-Ta diagram for basalts and derivatives after Wood (1980). (B) La/10-Y/15-Nb/8 diagram for basalts after Cabanis and Lecolle (1989). (C) V vs. Ti/1000 diagram for basalts after Shervais (1982). (D) Th/Yb vs. Nb/Yb mantle array diagram after Pearce (2008). Shaded area indicates range of mantle array compositions. Abbreviations: BAB = back-arc basalt, BON = boninite, CAB = calc-alkaline basalt, Cont = continental, E-MORB = enriched mid-ocean ridge basalt, IAT = island arc tholeiite, N-MORB = normal mid-ocean ridge basalt, OFB = ocean floor basalt, OIB = ocean island basalt, VAT = volcanic arc tholeiite.

composition gneiss samples. For instance, these samples all have a calc-alkaline chemistry (fig. 7A), trace element characteristics typical of arc andesite with strong negative Nb, Ta, Ti, and P anomalies and significant enrichment in Th and the LILE (fig. 7C). The REE plots with their negative sloped LREE and MREE patterns and flat HREE patterns (fig. 7D), are likewise typical of intermediate composition arc magmas. The decreasing HREE content with increasing fractionation and enrichment in LREE is similar to that in the Marlboro Formation amphibolite samples. The volcanic rocks in the Millham Reservoir Member are the most fractionated igneous rocks in the Marlboro Formation, and thus it is likely that their magmas interacted with a greater thickness of crust.

On the granitic discrimination diagram of Pearce and others (1984; fig. 8A) the Marlboro Formation and Millham Reservoir Member gneiss samples plot in the volcanic arc granite field, consistent with their origin in a supra-subduction zone environment. The Th-Hf/3-Ta plot of Wood (1980; fig. 8B) shows a similar result, with all three samples in the calc-alkaline basalt field.

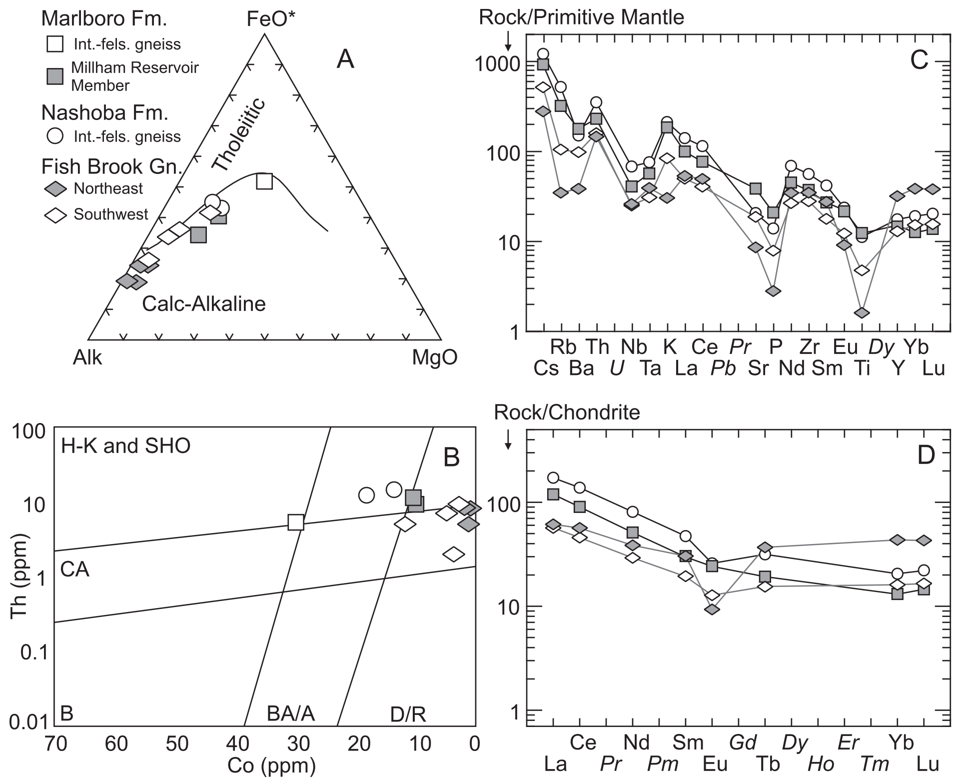

Fig. 7. Geochemical diagrams for the intermediate and felsic rocks from the Marlboro Formation, Nashoba Formation, and the northeastern and southwestern bodies of the Fish Brook Gneiss: (A) Alkalis-FeO-MgO diagram after Irvine and Baragar (1971) showing tholeiitic and calc-alkaline trends. (B) Th-Co diagram for determining rock type of altered or metamorphosed igneous rocks after Hastie and others (2007). Fields are (counter-clockwise from upper left) high-K and shoshonitic, calc-alkaline, island arc tholeiite and basalt, basaltic andesite and andesite, and dacite and rhyolite. (C) and (D) Extended element and REE plots for averages of the intermediate and felsic gneisses of the Marlboro and Nashoba Formations and the NE and SW bodies of the Fish Brook Gneiss. (C) and (D) are normalized after Sun and McDonough (1989); italicized elements are not plotted.

Nashoba Formation.—The two felsic gneiss samples from the Nashoba Formation have geochemical characteristics similar to the gneisses in the Marlboro Formation (figs. 2, 7A, 7B, 8A and 8B). Analogous to the amphibolites, felsic gneiss from the Nashoba Formation has higher overall enrichments in incompatible elements than gneiss from the Marlboro Formation and trends toward slightly more alkaline compositions. Extended element and REE plots for the Nashoba Formation gneiss samples differ from those in the Marlboro Formation only in detail (figs. 7C and 7D). Sr and P are slightly lower, and a small negative Eu anomaly exists in the Nashoba Formation samples. The presence of negative Eu anomalies in the felsic gneiss and in some of the amphibolite samples from the Nashoba Formation suggest that plagioclase fractionation, and by proxy subduction related fluids, exerted more influence on some of the rocks in the Nashoba Formation than those of the Marlboro Formation.

Nashoba Formation gneiss samples are also similar to the Marlboro Formation gneisses on tectonic discrimination diagrams. On the granitic discrimination diagram (Pearce and others, 1984; fig. 8A) the samples plot within the volcanic arc granite field, but tend to be slightly closer to the within-plate and ocean-ridge granite fields than the

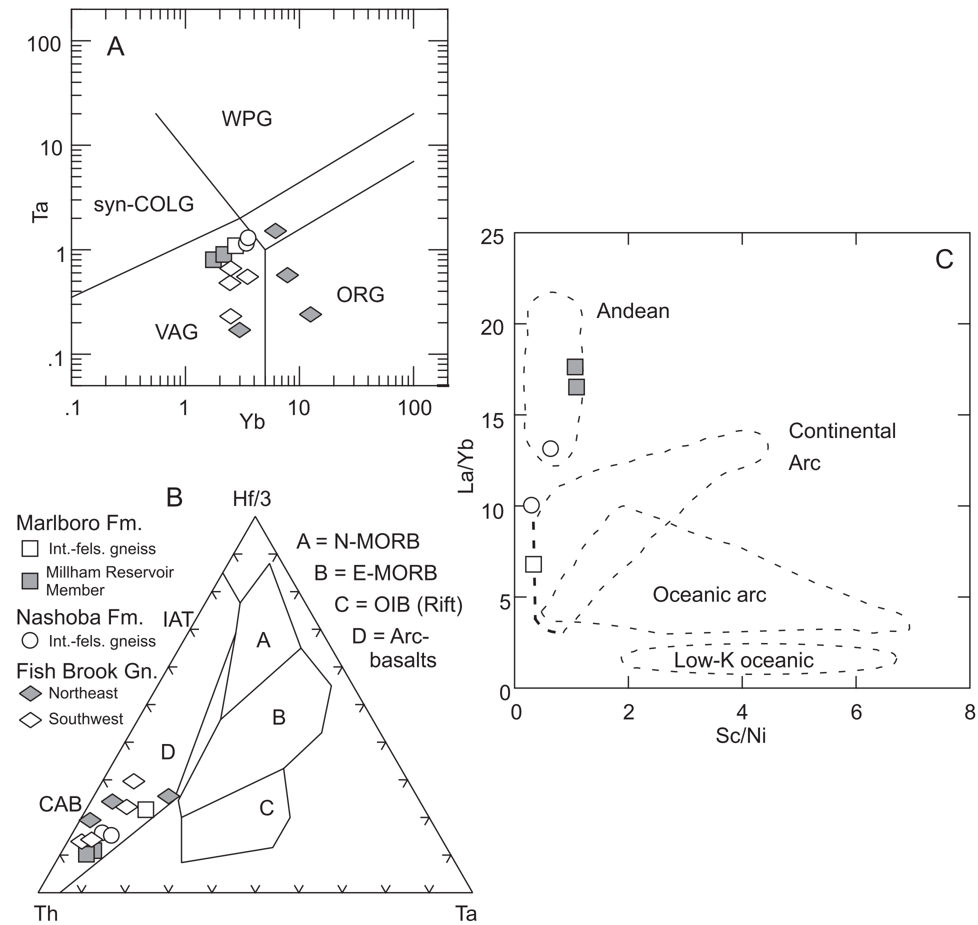

Fig. 8. Tectonic discrimination diagrams for the intermediate and felsic rocks of the Nashoba terrane. (A) Ta vs. Yb diagram for granitic rocks after Pearce and others (1984); syn-COLG = syn-collisional granite, VAG = volcanic arc granite, ORG = ocean ridge granite, WPG = within-plate granite, remaining field indicates overlap between WPG and ORG fields. (B) Th-Hf/3-Ta diagram for basalts and derivatives of Wood (1980), CAB = calc-alkaline basalt, E-MORB = enriched mid-ocean ridge basalt, IAT = island arc tholeiite, N-MORB = normal mid-ocean ridge basalt, OIB = ocean island basalt. (C) La/Yb vs. Sc/Ni diagram for volcanic arc andesites after Bailey (1981), data plotted for intermediate gneisses from the Marlboro and Nashoba Formations.

Marlboro Formation, potentially reflecting the same alkaline rift component seen in the amphibolites.

Fish Brook Gneiss.—The Fish Brook Gneiss is somewhat more evolved than the other felsic gneisses. It is dacitic to rhyolitic in composition (figs. 2 and 7B) and data plot further along the calc-alkaline trend on the AFM diagram (fig. 7A). Two geochemical populations can be distinguished within the eight samples analyzed: one from the southwestern part and one from the northeastern part of the exposed areas of Fish Brook Gneiss (fig. 1B, Appendix A). The REE patterns of the southwestern group samples (fig. 7D) are typical of volcanic arc granites with negative slopes ($[La/Yb]_N$ ~2 – 6.2) and small negative Eu anomalies, much like those of the felsic gneisses of the other formations. The northeastern group samples have flatter REE patterns ($[La/Yb]_N$ ~1 – 2) at similar LREE concentrations and moderate to large negative Eu anomalies.

Incompatible element plots show that the southwestern samples parallel the Marlboro and Nashoba Formation felsic gneisses at slightly lower concentrations, most notably in P and Ti (fig. 7C), while the northeastern samples have more prominent positive Th, and negative Sr, P, and Ti anomalies. LILE concentrations, Th/Nb, and Th/Ta are all slightly higher in the southwestern group, suggesting that the subduction and/or crustal contamination component is more pronounced than in the northeastern samples. On the granitic tectonic discrimination diagram (fig. 8A), the southwestern group of samples plot entirely within the volcanic arc granite field while three out of four samples from the northeastern group plot in the ocean ridge or within-plate granite fields.

In summary, the southwestern part of the Fish Brook Gneiss more closely resembles the intermediate and felsic gneisses of the Marlboro and Nashoba Formations, whereas the northeastern part has a somewhat more alkaline or rift-like composition. Given that evidence exists for a supra-subduction zone signature in all samples of the Fish Brook Gneiss, but only some samples show evidence of an alkaline or rift component, it is likely that the Fish Brook Gneiss represents evolved arc magmas contaminated by rift magmas or continental crust. A plot of La/Yb vs. Sc/Ni (fig. 8C) shows that intermediate and felsic gneisses of the Nashoba and Marlboro Formations have compositions typical of continental arc andesite (Bailey, 1981), suggesting that continental crust was present during the evolution of the Nashoba terrane. Therefore, the rift-like component in the Fish Brook Gneiss may indicate active rifting, or it could also be an inherited component from an older basement to the Nashoba terrane through assimilation, similar to that present in the Eocene to Miocene segments of the modern Vanuatu arc of the southwest Pacific ocean (Buys and others, 2014).

Sm-Nd ISOTOPE GEOCHEMISTRY

Four samples were collected from the Marlboro Formation for Sm-Nd analysis: two amphibolites (MFA-1 and MFA-2), one schist (MFS-1) and one felsic gneiss from the Millham Reservoir Member (MRG-4). Samples from the Nashoba Formation include two amphibolites (NFA-3 and NFA-7), one pelitic schist (NFS-1), and one paramigmatite (NFM-1). Two samples were chosen from the Fish Brook Gneiss, both granitic gneisses (FBG-3 and FBG-4). Sample locations with brief lithological descriptions are given in Appendix A and the locations are shown on figure 1B.

Methods for Sm-Nd Determination and Presentation

Whole rock samples were crushed, powdered, and dissolved for Sm-Nd isotopic geochemistry at Boston College and Boston University and then analyzed at the Boston University TIMS Facility following the methods of Harvey and Baxter (2009) and Pollington and Baxter (2010). Large hand samples were selected, then trimmed of any weathered surfaces that spanned visible compositional heterogeneities so as to yield a representative bulk rock average. These samples (several hundred grams each) were hand-crushed and ~10 gram splits were powdered from which a ~50 to 100 mg aliquot was taken for dissolution, column chemistry, and TIMS analysis. Reported $^{143}Nd/^{144}Nd$ ratios are normalized to $^{146}Nd/^{144}Nd$ of 0.7219. Full procedural blanks during the course of analysis were <30 pg, insignificant for these samples. Neodymium isotopes were ionized and measured as the oxide (NdO^+) on single rhenium filaments with a tantalum-oxide loading slurry (Harvey and Baxter, 2009). Repeat analysis of 4ng loads of an in-house Ames Nd standard solution yielded 0.5121287 ± 0.0000078 2σ over the course of analysis (n = 100; Dec 2008 to June 2010). Harvey and Baxter (2009) reported a small −0.000017 offset in $^{143}Nd/^{144}Nd$ for small Nd loads (4ng) run as NdO^+ as compared to larger loads (>100 ng) run as Nd^+ metal. Because Nd loads for samples in this study ranged from ~10 to ~70 ng, we did not apply a systematic correction. The maximum offset in model ages (resulting from a +0.000017 correction in $^{143}Nd/^{144}Nd$) would be less than -0.03 Ga, which is insignificant in our study. $^{147}Sm/^{144}Nd$ uncertainty is better than 0.1 percent based on repeat analyses of an in house mixed gravimetric Sm-Nd solution. All $\varepsilon_{Nd(initial)}$ values were calculated using an assumed crystallization age of 500 Ma; herein we refer to these as $\varepsilon_{Nd(500)}$. This date was chosen because it approximates the age of the Fish Brook Gneiss and is within the range of possible magmatic ages (500 – 540 Ma) for the Marlboro Formation. The $^{147}Sm/^{144}Nd$ ratios of the samples are such that modeling them at either 450 or 550 Ma makes no significant difference to their $^{143}Nd/^{144}Nd$ ratios (except in the case of the sedimentary rocks, which only shift by ± 0.5 ε units for ± 50 million years).

Two different methods were used to calculate mantle model ages. The first was that of DePaolo (1981) as this is the method most commonly used by other workers and therefore perhaps the most appropriate for comparison with other data. A second method, that of DePaolo and others (1991), was also used to account for the possibility that samples may have acquired different $^{147}Sm/^{144}Nd$ ratios (due to melting, metamorphism, or sedimentary winnowing, for example) since their time of primary extraction from the depleted mantle reservoir. Mantle model ages produced from these methods are referred to as $T_{DM(81)}$ and $T_{DM(91)}$ respectively.

Model ages determined according to DePaolo (1981) trace a given rock's isotopic evolution back along a line defined by its modern $^{147}Sm/^{144}Nd$ ratio (that is, its evolution line); the assumption is that in most cases mixing or contamination will affect the $^{143}Nd/^{144}Nd$ isotopic ratio of a magma but not significantly alter the $^{147}Sm/^{144}Nd$ ratio, while fractionation will decrease the $^{147}Sm/^{144}Nd$ ratio without affecting the $^{143}Nd/^{144}Nd$ ratio (because the mass difference between isotopes of the same element is too small for fractionation to have an effect). The evolution curve of the depleted mantle is determined by the following equation: $\varepsilon_{Nd}\ (T) = 0.25\ T^2 - 3\ T + 8.5$ for any age T (DePaolo, 1981). This method cannot be successfully applied to samples with high $^{147}Sm/^{144}Nd$ ratios [especially juvenile mafic rocks; for example, Stern (2002) set a limit at $^{147}Sm/^{144}Nd = 0.165$ above which the standard model is less reliable]. As the slope of the resulting evolution line would be similar to that of the depleted mantle evolution curve, these would result in a very large uncertainty in the location of the intersection, or no intersection at all. Such samples likely suffered from post-extraction $^{147}Sm/^{144}Nd$ fractionation; especially for samples like these, we use the model of DePaolo and others (1991).

The method of DePaolo and others (1991) posits that there is an average representative composition of continental crust for any given time in the past. Any modern rock may have had its $^{147}Sm/^{144}Nd$ altered from the average continental crustal value during the time of its formation by fractionation processes (such as partial melting). Thus, the model uses the observed modern Sm-Nd isotopic composition of a sample to calculate the sample's evolution line back to the age of crystallization (that is, an independently determined radiometric age) in order to determine the initial ε_{Nd} value. Then, to determine the depleted mantle model age, this model follows the evolution line for continental crust (with the modeled, time-dependent average $^{147}Sm/^{144}Nd$ of continental crust given by DePaolo and others, 1991) at the time of its primary extraction from the mantle back to its intercept with the evolution line of the depleted mantle. DePaolo and others (1991) use a modified equation for the depleted mantle in this model: $\varepsilon_{Nd}\ (T) = 8.6 - 1.91\ T$ where T is the age in Ga. In theory, this method should correct for any significant alteration of the $^{147}Sm/^{144}Nd$ ratio during rock formation, yielding a more accurate T_{DM} for the continental parent material. Note that this method *cannot* account for processes (such as incorporation of juvenile melt with a different ε_{Nd}) that would also change the ε_{Nd} at the time of crystallization. In this case, samples would represent mixes of different material and T_{DM} information is consequently obscured.

Amphibolites

The high $\varepsilon_{Nd(500)}$ values for Marlboro and Nashoba Formation amphibolite samples MFA-1, NFA-3 and NFA-7 (table 2) are consistent with a depleted mantle source that had little or no contamination by evolved material. The higher $^{147}Sm/^{144}Nd$ ratio of Marlboro Formation amphibolite sample MFA-2, and lower $\varepsilon_{Nd(500)}$ value (+4.07) as compared with MFA-1, is consistent with derivation from a mix of depleted mantle melt and a more isotopically evolved contaminant than in MFA-1. Its $T_{DM(91)}$ age of 0.86 Ga suggests incorporation of early Neoproterozoic or older material.

Intermediate and Felsic Gneisses

The intermediate $\varepsilon_{Nd(500)}$ values of the Millham Reservoir Member (MRG-4) and Fish Brook Gneiss samples (FBG-3 and FBG-4) are consistent with derivation either from a moderately evolved, significantly older source or from a mix of juvenile (for example, magmatic arc) and evolved sources. Given the arc-like geochemical compositions of MRG-4 and FBG-4 and possibly FBG-3, the latter is the most probable explanation. The juvenile source is likely the same depleted mantle from which the Marlboro Formation amphibolites were derived and the evolved source may be the basement of the Nashoba terrane. The depleted mantle models both give middle to late Mesoproterozoic (~1.1-1.5 Ga) model ages for these samples (figs. 9A and 9B, table 2). These ages also most likely indicate a mix of juvenile ~500 Ma and evolved material older than middle to late Mesoproterozoic. The evolved source may be the basement of the Nashoba terrane. If true, and if the basement is dominantly igneous in origin, then its isotopic signature is likely Paleoproterozoic or older, because mantle-derived rocks of even early Mesoproterozoic age would not have sufficiently low $^{143}Nd/^{144}Nd$ ratios or sufficiently high concentrations of Nd to shift juvenile mantle melts at 500 Ma to ε_{Nd} values near zero. If the basement contains significant amounts of metasedimentary rock, however, then it could have a much higher concentration of Nd. In that case incorporation of crust as young as early Mesoproterozoic may have been sufficient to produce the observed $\varepsilon_{Nd(500)}$ values.

Metasedimentary Rocks

The negative $\varepsilon_{Nd(500)}$ values of the Marlboro Formation schist (MFS-1) and the two metasedimentary samples from the Nashoba Formation (NFS-1, NFM-1) (table 2, fig. 9) indicate significant contributions from an evolved continental source while the low $^{147}Sm/^{144}Nd$ ratios suggest derivation from a dominantly felsic source. Neither the amphibolites nor the felsic rocks of the Marlboro Formation have sufficiently evolved isotopic compositions to produce the $\varepsilon_{Nd(500)}$ value of the Marlboro Formation schist, suggesting at least some additional sediment source, such as unexposed basement of the Nashoba terrane or an external evolved continental source. All three metasedimentary samples plot in an approximate group with depleted mantle model ages in the late Paleoproterozoic, which reflects the average minimum age of the source regions. Based on U-Pb LA-ICPMS detrital zircon ages, the source areas for the Nashoba terrane did include Paleoproterozoic and even Archean material (Loan, ms, 2011; Loan and others, 2011).

DISCUSSION

Geochemistry of the Nashoba Terrane

The metaigneous rocks of the Marlboro and Nashoba Formations consist of tholeiitic, calc-alkaline, and a few alkaline basalts as well as calc-alkaline andesites, with compositions indicative of formation in island arcs, continental arcs, ocean ridges and back-arc basins. Thus, these rocks have geochemical characteristics consistent with their formation in an arc/back-arc complex. Amphibolite samples from the Nashoba

TABLE 2
Sm-Nd data

Sample	Rock Type	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (500 Ma)	ε_{Nd} (500Ma)	$T_{DM(81)}$ (Ga)	$T_{DM(91)}$ (Ga)
MFA-1	Marlboro Fm., amphibolite	0.512922±08	0.168956±37	0.512368	+7.29	***	0.54‡
MFA-2	Marlboro Fm., amphibolite	0.512820±12	0.188597±114	0.512203	+4.07	***	0.86
NFA-3	Nashoba Fm., amphibolite	0.513067±08	0.209756±37	0.51238	+7.54	***	0.51‡
NFA-7	Nashoba Fm., amphibolite	0.512967±05	0.193718±12	0.512333	+6.61	***	0.61‡
MRG-4	Millham Reservoir gneiss	0.512385±00	0.131013±14	0.511958	–0.72	1.209	1.28
FBG-3	Fish Brook Gneiss (NE)	0.512568±08	0.157260±34	0.512054	+1.16	1.277†	1.12
FBG-4	Fish Brook Gneiss (SW)	0.512468±09	0.156415±186	0.511957	–0.75	1.521†	1.3
MFS-1	Marlboro Fm., bio-musc schist	0.511951±06	0.116830±14	0.511569	–8.31	1.714	1.84
NFS-1	Nashoba Fm., bio-grt-sill schist	0.512069±71	0.121254±56	0.511672	–6.29	1.601	1.7
NFM-1	Nashoba Fm., paramigmatite	0.511956±08	0.114496±20	0.511581	–8.07	1.666	1.82

*** Samples for which $^{147}Sm/^{144}Nd$ ratio is too high for a model age to be calculated via the method of DePaolo (1981). † The $^{147}Sm/^{144}Nd$ ratio of these samples is high enough to introduce some error but not so high as to preclude significance. ‡ Samples for which the model of DePaolo and others (1991) does not apply because their high ε_{Nd} values indicate they are juvenile and therefore not likely to have interacted with continental crust: the model ages reflect this as they are only slightly higher than the assumed crystallization ages.

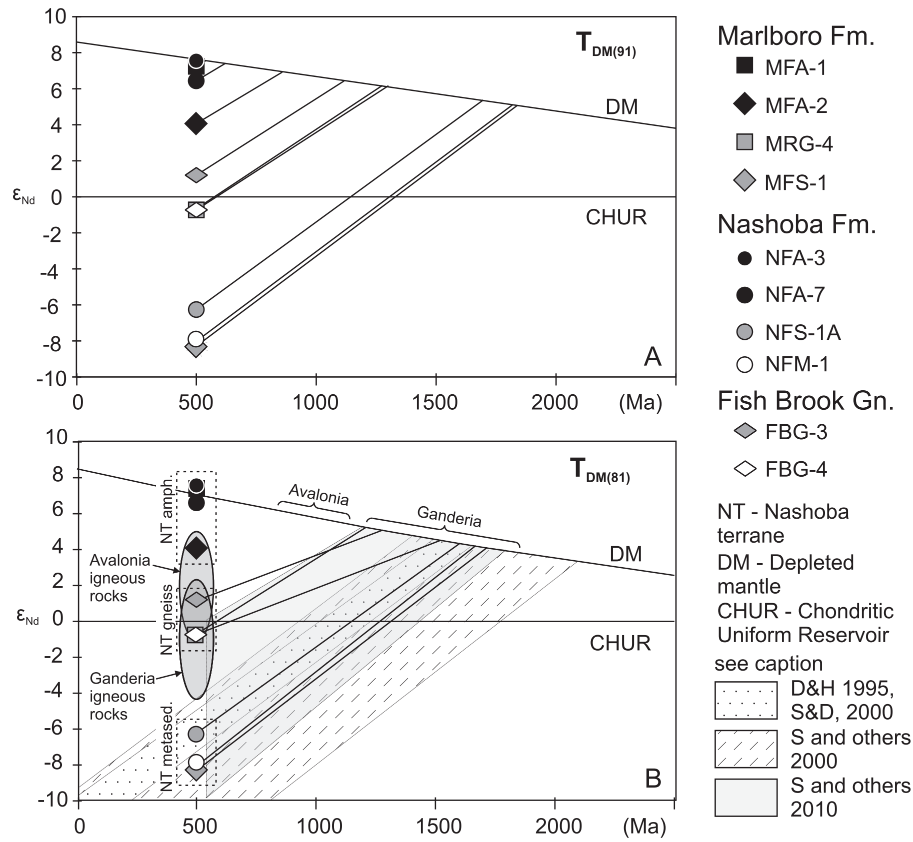

Fig. 9. (A) Plot of ε_{Nd} vs. time for samples from this study. The sub-parallel lines indicate the evolution lines of samples back to their mantle model ages calculated, along with the depleted mantle (DM) line, according to the method of DePaolo and others (1991). (B) Plot of ε_{Nd} vs. time for samples from this study, with evolution curves and DM line calculated according to the method of DePaolo (1981). Note that in this model the DM line is curved rather than linear. Brackets indicate typical ranges for mantle model ages for Avalonian and Ganderian rocks. Also indicated: typical ranges of ε_{Nd} values for intermediate and felsic igneous rocks from Avalonia and Ganderia (ellipses; based on data compiled in Barr and others, 1998, and Hibbard and others, 2007b), and data from Ganderian sedimentary and metasedimentary rocks. Dotted: data from metasedimentary rocks of the Gander group in Newfoundland (D'Lemos and Holdsworth, 1995; Schofield and D'Lemos, 2000). Gray: data for Saint John Group of the Avalonian Caledonia terrane, from Satkoski and others (2010). Dashed: data for two metasiltstones from the Brookville terrane in southern New Brunswick, from Samson and others (2000).

Formation contain a greater range of compositions than the Marlboro Formation, including strongly LREE depleted, MORB-like basalt and hints of alkaline rift-like signatures. The REE data suggest that the Nashoba Formation had greater subduction zone and continental input, but higher Th enrichment over Nb in the Marlboro Formation may indicate the reverse to be the case.

The southwestern group of samples from the Fish Brook Gneiss is similar to the intermediate composition and felsic gneisses of the Marlboro and Nashoba Formations. In general these appear to be typical of continental arc andesite and rhyolite, formed through interaction between juvenile arc magmas and evolved continental material. However, the northeastern group of Fish Brook Gneiss samples differs in REE and Yb-Ta compositions and appears to have a more significant crustal melt component.

The Sm-Nd isotopic characteristics of the mafic and intermediate composition rocks are consistent with a trace element geochemistry and formation in an arc/back-arc tectonic setting. Three of four amphibolites in the Marlboro and Nashoba Formations show juvenile mantle compositions and were likely derived directly from the mantle. The fourth amphibolite, from the Marlboro Formation, shows evidence of incorporation of more evolved material, such as that coming from a continental basement to the Nashoba terrane. However, the generally flat HREE patterns in both the Marlboro and Nashoba Formation amphibolite samples indicate that garnet was not stable during the equilibration of these magmas. Therefore any crust present could not have been of significant thickness.

Based on high $^{147}Sm/^{144}Nd$ ratios and moderate $\varepsilon_{Nd(500)}$ values, the intermediate and felsic rocks can best be explained as having a mixture of juvenile and evolved sources. If instead these rocks were the partial melts of strictly crustal rocks with moderate $\varepsilon_{Nd(500)}$ values, they would have lower $^{147}Sm/^{144}Nd$ ratios due to preferential incorporation of Nd over Sm into melts. The model ages suggest input from a Mesoproterozoic or older basement to the Nashoba terrane. The metasedimentary rocks of the Marlboro and Nashoba Formations have significantly evolved compositions, indicating input of material of Paleoproterozoic or older age.

Model for Tectonic Setting of the Nashoba Terrane

The basaltic magmas of the Marlboro Formation that show juvenile mantle signatures erupted as arc and back-arc tholeiites on a thinned or attenuated continental crust, with minimal incorporation of continental material (fig. 10A). Transitional to calc-alkaline basalts of the Marlboro Formation indicate that fractional crystallization and wallrock assimilation took place (fig. 10B), implying that magma ascent was hindered by a thickened volcanic pile. Andesitic and dacitic magmas of the Marlboro Formation and the more felsic magmas of the Fish Brook Gneiss indicate additional fractionation and/or assimilation, that suggests they encountered an even thicker crust. In summary, the Marlboro and Nashoba Formations, and Fish Brook Gneiss have geochemical characteristics that are best explained by a primitive volcanic arc setting emplaced on rifted or otherwise attenuated continental crust, followed by fractionation and/or assimilation in a thickened crust.

The greater volume of metasedimentary rocks, higher proportion of MORB-like basalts, and presence of a few alkaline basalts in the Nashoba Formation suggest a setting with a higher back-arc component than that of the Marlboro Formation. However, there are also amphibolites in the Nashoba Formation that have negative Eu anomalies and higher $[La/Yb]_N$ ratios than any of the amphibolites in the Marlboro Formation, indicating an overall strong arc component. Most likely, the Nashoba Formation developed in a widening arc/back-arc system as the distance between the arc and back-arc volcanic centers increased (figs. 10B and 10C). This would allow less mixing between arc and back-arc magmas, explaining the distinct and separate arc-like and MORB-like REE patterns in the amphibolites of the Nashoba Formation. The wide range of compositions in the Boxford Member of the Nashoba Formation including, arc, back-arc and rift lavas suggest that it formed in close proximity to the arc. However, the decreasing abundance of volcanic rocks and the increasing amount of sedimentary rocks in the remainder of the Nashoba Formation indicate that it likely formed further from the arc in a widening and extending back-arc basin. Later tectonism significantly reduced the width of this basin and resulted in the modest breadth of the modern Nashoba terrane.

Terrane Affinity: Ganderia or Avalonia?

One goal of this study was to use Sm-Nd geochemistry to test whether the Nashoba terrane has Ganderian or Avalonian affinity. The high positive $\varepsilon_{Nd(500)}$ values of the

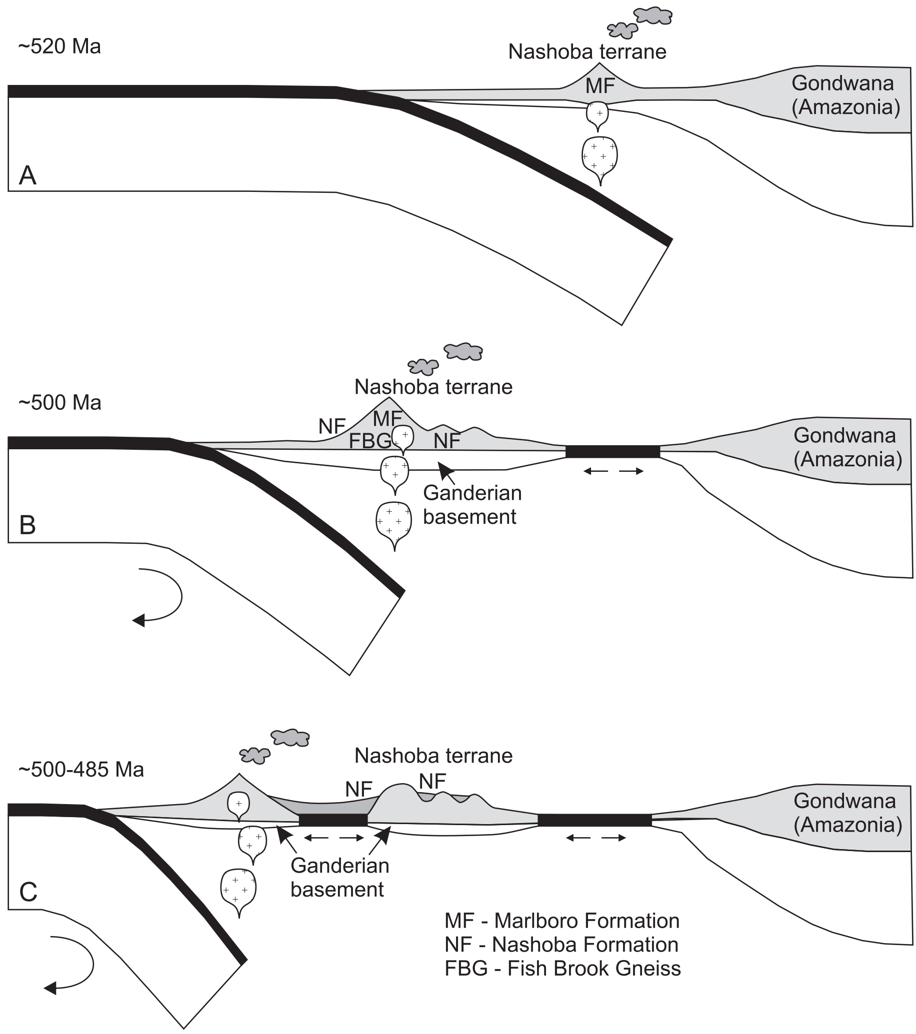

Fig. 10. Simplified tectonic model for the formation of the of the Nashoba terrane in the Cambrian. (A) Eruption of the earliest basaltic magmas through thinned continental crust on or near the Gondwanan (Amazonian) margin. (B) Magmas become more evolved (Marlboro and Nashoba Formations and Fish Brook Gneiss) as crust thickens, Ganderia separates from Gondwana. (C) Arc extends as activity moves to the NW; back-arc sedimentation occurs.

amphibolites reflect input of juvenile magmas around 500 Ma and are consistent with either Ganderia or Avalonia (Hibbard and others, 2007a). The near-zero $\varepsilon_{Nd(500)}$ values of the intermediate composition and felsic rocks are within the range where the values of the most evolved Avalonian and most juvenile Ganderian felsic igneous rocks overlap (fig. 9B). It is possible that these values are a result of mixing between juvenile material (for example, the amphibolites with high $\varepsilon_{Nd(500)}$) and more evolved material (lower $\varepsilon_{Nd(500)}$ values than their actual measured values), in which case it is more likely that the evolved material has Ganderian crustal affinity. Regardless, the Mesoproterozoic $T_{DM(81)}$ model ages are older than typical Avalonian igneous rocks ($\sim$0.8 – 1.1 Ga; Nance and Murphy 1996; Murphy and others, 2000, 2004, 2008; Murphy and Nance, 2002; Hibbard and others, 2007a) and are consistent with the typical range for

Ganderian igneous rocks (~1.2 – 1.8 Ga; Samson and others, 2000; Schofield and D'Lemos, 2000; Rogers and others, 2006; Hibbard and others, 2007a; Pollock and others, 2012; Dorais and others, 2012).

The strongly negative $\varepsilon_{Nd(500)}$ values and Paleoproterozoic model ages (using either $T_{DM(81)}$ or $T_{DM(91)}$ model) of the three metasedimentary rocks sampled are characteristic of Ganderian sedimentary rocks (Samson and others, 2000; Schofield and D'Lemos, 2000; Rogers and others, 2006; Pollock and others, 2012) and could not have been derived from typical Avalonian crust (Barr and others, 1998; Hibbard and others, 2007b). These samples are the most definitive evidence for Ganderian basement. However, Satkoski and others (2010) showed that sedimentary rocks of the Caledonia terrane in New Brunswick, interpreted to be part of Avalonia, (for example, Barr and Kerr, 1997; Hibbard and others, 2006) have broadly similar Sm-Nd isotopic characteristics (fig. 9B) and detrital zircon ages between 540 and 490 Ma, which overlap the range of radiometric ages of the Nashoba terrane. Thus, the isotopic characteristics of the metasedimentary rocks in the Nashoba terrane are typical of Ganderian terranes, but not completely outside the range for all terranes currently interpreted as Avalonian. However, in addition to the isotopic data, other evidence exists for a Ganderian affinity. During the time of the abundant magmatism in the Nashoba terrane (~540 – 500 Ma) there was a lack of magmatic activity in Avalonia, which was a stable platform at this time (for example, Landing and Murphy, 1991; Hibbard and others, 2007a; Pollock and others, 2012; van Staal and Barr, 2012). Furthermore, detrital zircon age distributions of metasedimentary rocks of the Nashoba terrane match those from Ganderian terranes in eastern Canada, (for instance, a major peak at ~540 Ma; van Staal and others, 2009; Loan and others, 2011; Loan, ms, 2011; Pollock and others, 2012). However, they contrast significantly with the distributions seen in Avalonian rocks (for instance, a major peak at ~ 610 Ma and very few Cambrian zircons are typical of Avalonia, but not of the Nashoba terrane; Fyffe and others, 2009; Loan, ms, 2011; Pollock and others 2012). Thus, we interpret the Nashoba terrane as being underlain by Ganderian sialic crust and part of the larger Ganderian terrane of the northern Appalachians.

Regional Comparisons

Penobscot arc.—The Ganderian affinity and ~500 to 540 Ma age range for the arc rocks of the Marlboro Formation and Fish Brook Gneiss indicate a temporal relationship with Penobscot arc activity in the northern Appalachians (for example, Hibbard and others, 2007a; van Staal and others, 2009; Fyffe and others, 2011; van Staal and Barr, 2012). That volcanic arc formed along the Iapetus ocean-facing, leading edge of the Amazonian margin of Gondwana at *ca.* 515 to 485 Ma (for example, Fyffe and others, 2011; Pollock and others, 2012; van Staal and Barr, 2012) and temporally overlapped with the more inboard rifting of Ganderia from Gondwana at ~505 Ma (Murphy and others, 2006; Schulz and others, 2008; van Staal and others, 2009; Fyffe and others, 2009; Zagorevski and others, 2010; Pollock and others, 2012; van Staal and Barr, 2012). Penobscot magmatic arc activity is well documented on the eastern side of Ganderia in the Annidale and New River terranes of southeastern New Brunswick (fig. 1A) (Johnson and others, 2009, 2012; Fyffe and others, 2011; van Staal and Barr, 2012), as well as in the Bourinot volcanic belt in the Bras d'Or terrane in Nova Scotia (fig. 1A: White and others, 1994; Barr and others, 1998), the Victoria Lake Supergroup in central Newfoundland (fig. 1A; Zagorevski and others, 2007a, 2007b, 2010) and the Bay du Nord Group in the Hermitage Flexure, along the south coast of Newfoundland (fig. 1A; Valverde-Vaquero and others, 2006a; Zagorevski and others, 2010). In all these areas, extensional, NW migrating (current coordinates), arc/back-arc systems formed during Penobscot arc activity that likely produced several arcs and intervening back-arc basins (Valverde-Vaquero and others, 2006b; Zagorevski and others, 2007a, 2010; van Staal and others, 2009; Fyffe and others, 2009, 2011). These Penobscot arcs formed on extended and rifted blocks of Ganderian crust, such as those exposed in the Brookville and New River terranes in southeastern New Brunswick (fig. 1A; Johnson and others, 2009, 2012; Fyffe and others, 2011; Pollock and others, 2012; van Staal and Barr, 2012) and the Bras d'Or terrane in Cape Breton Island (fig. 1A; Barr and others, 1998; van Staal and Barr, 2012). This basement is composed largely of Neoproterozoic arc-related volcanic and plutonic rocks (Hibbard and others, 2007a; Pollock and others 2012; van Staal and Barr, 2012), although older sedimentary rocks are present in these terranes in the Green Head Group of the Brookville terrane and George River metamorphic suite of the Bras d'Or terrane (fig. 1A; for example, van Staal and Barr, 2012). The Penobscot arc rocks show the influence of the Ganderian crustal basement in both their isotopically evolved ε_{Nd} signatures and their detrital zircon suites in a similar fashion to that seen in the Nashoba terrane (Fyffe and others, 2009, 2011; Kay and others 2011; Pollock and others, 2012; Kay, ms, 2012). For example, in the New River and Annidale terranes of southern New Brunswick (fig. 1A) Penobscot volcanic rocks were deposited on Neoproterozic sialic crust and range in age from ~514 to 482 Ma (Johnson and others, 2009, 2012; Fyffe and others, 2011). These volcanic arc rocks have compositions ranging from basalt through basaltic andesite to felsite with tholeiitic, transitional and calc-alkaline chemistries (Johnson and others, 2012). The mafic rocks include those with both enriched and depleted LREE patterns as well as depleted and non-depleted Nb signatures (Johnson and others, 2009, 2012; Fyffe and others, 2011), characteristic of rocks erupted in arc/back-arc settings, and are thus similar to those in the Nashoba terrane. It is not clear that the Nashoba terrane is, or once was, continuous with the Annidale terrane in southern New Brunswick, or whether they represent separate arcs that were active at this time, perhaps not unlike the SW Pacific ocean today (van Staal and others, 1998). However, it is clear that volcanic rocks in the Nashoba terrane do represent a continuation into southeastern New England of Penobscot-aged arc/back-arc volcanism.

Ellsworth terrane.—In eastern Maine, the Ellsworth terrane lies along the trailing (SE) edge of Ganderia (fig. 1A). It consists of a mid-Cambrian (509±1 to 504±3 Ma; Ruitenberg and others, 1993; Schulz and others, 2008) greenschist facies bimodal volcanic suite with interlayered sedimentary rocks in the Ellsworth and Castine sequences (van Staal, 2007; Schulz and others, 2008; Fyffe and others, 2009), and these temporally overlap the volcanic rocks in the Nashoba terrane. In New Brunswick, somewhat similar but slightly older rocks occur in the New River terrane and include the oldest dated Penobscot arc rocks: a rhyolite breccia in the upper part of the Mosquito Lake Road Formation (514± 2 Ma; Johnson and McLeod, 1996; Johnson, 2001; McLeod and others, 2003; Fyffe and others, 2011; Johnson and others, 2012). The Mosquito Lake Road Formation includes andesite and rhyolite with arc chemistries. The volcanic rocks in the Ellsworth terrane in Maine, however, differ in having a strong bimodal distribution and mafic rocks with concave down REE patterns. This has led to their interpretation as forming in an extensional marine basin (Schulz and others, 2008; Fyffe and others 2011) in one of two tectonic settings. Fyffe and others (2009, 2011) and Hibbard and others (2007a) interpret these rocks to have formed in a back-arc basin during the extensional phase of Penobscot volcanism following the initiation of the original arc magmatism. In that case, the Ellsworth terrane volcanic rocks could be equivalent to the back-arc volcanic rocks in the Marlboro or particularly the Nashoba Formation. However, Schulz and others (2008) interpreted the Ellsworth terrane volcanic rocks in Maine as the initial rifted boundary that formed during rifting of Ganderia from Gondwana. If this were true, the Ellsworth terrane in Maine would have formed farther inboard of the Gondwanan continental margin than the Nashoba terrane arc/back-arc rocks and is not correlative. In this scenario, if the

Ellsworth terrane volcanic rocks ever extended to southern New England, they would have lain east of the Nashoba terrane and thus have been lost through later subduction erosion and/or strike-slip faulting.

Younger Tectonic Activity

In Atlantic Canada, Penobscot arc volcanism was followed by a period of non-magmatic activity as the expansive arc/back-arc system tectonically consolidated and was closed during the Penobscot orogeny (~486–478 Ma) (Zagorevski and others, 2007b, 2010; Johnson and others, 2012; van Staal and Barr, 2012). However, shortly following this consolidation a new period of arc volcanism, the Popelogan-Victoria arc, (fig. 1A; ~475–455 Ma) developed above an east-dipping subduction zone, in part, on the remnants of the Penobscot arc (van Staal, 1994; van Staal and others, 1998; Zagorevski and others, 2010; van Staal and Barr, 2012; van Staal and others, 2016). Volcanic rocks of this age (472–465 Ma) are also present in the Falmouth-Brunswick sequence and Casco Bay Group in southwestern Maine (West and others, 2004; Hussey and others, 2010). As with its predecessor (the Penobscot arc), the Popelogan-Victoria arc was extensional and migrated to the NW, opening the extensive Tetagouche-Exploits back-arc basin from ~473 to 455 Ma (van Staal, 1994; van Staal and others, 1998, 2016; van Staal and Barr, 2012). A passive margin, Ganderia's trailing margin, formed the eastern side of this basin (van Staal and Barr, 2012). This basin closed during the Silurian Salinic orogeny and Ganderia fully accreted to the leading edge of Laurentia by ~423 Ma (for example, van Staal and others, 1998; Valverde-Vaquero and others, 2006a; Fyffe and others, 2011, van Staal and Barr, 2012; van Staal and others, 2016). Thus far, no evidence for this younger (Ordovician) volcanism exists in the Nashoba terrane, where no early Paleozoic metaigneous rocks have been dated as younger than ~ 500 Ma. However, U-Pb LA-ICPMS analysis of detrital zircon from a paragneiss of the Nashoba Formation yielded a small youngest age population of ~461 ±19 Ma (Loan, ms, 2011; Loan and others, 2011). While LA-ICPMS analyses can produce anomalously young ages because of uncorrected Pb loss (for example, Bowring and others, 2006), this age suggests it might be possible that the Nashoba terrane experienced additional sedimentation and/or volcanism during the time of the Ordovician Popelogan-Victoria arc/back-arc cycle.

CONCLUSIONS

Geochemical and $^{147}Sm/^{144}Nd$ isotopic data from the Nashoba terrane show that the Cambrian metabasaltic and more felsic metaigneous rocks of the Marlboro and Nashoba Formations and Fish Brook Gneiss have tholeiitic, transitional, calc-alkaline and even alkaline chemistries and indicate that this terrane formed as an arc/back-arc complex on thinned or attenuated continental crust. The isotopic data point toward the presence of an isotopically evolved, Mesoproterozoic or older continental basement that had at least some input from a Paleoproterozoic source, indicating this basement is Ganderian. Thus, the Nashoba terrane is part of the Ganderian microcontinent, signifying that Ganderia extends farther SE into SE New England than previously established. The Nashoba terrane is not part of the Avalonian microcontinent or a separate oceanic arc/back-arc complex. The age and geochemical composition of the magmatism in the Nashoba terrane can be correlated with that of the Penobscot arc/back-arc that formed in the early Paleozoic along the leading margin of Ganderia and seen farther north in the Appalachians, particularly in the Annidale and New River terranes of southern New Brunswick. This correlation implies that Cambrian-early Ordovician arc/back-arc activity occurred farther to the SE than previously recognized and thus extends the range of this activity from Newfoundland to southeastern New England. Recognition of this correlation provides a context for the Nashoba terrane within the framework of the northern Appalachian orogen.

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APPENDIX A

TABLE A1

Sm-Nd sample descriptions and locations

Sample Number	Sample Description	UTM (m E – m N)	Location Description
MARLBORO FORMATION			
MFA-1	plagioclase-hornblende amphibolite	19T 0286518 4690566	South side of Rt. 20, ~1.5 km west of I-495, Marlborough, MA approximately in the middle of the Marlboro Formation.
MFA-2	plagioclase-hornblende amphibolite	19T 028582 468957	Hayes Memorial Drive, ~0.75 km south of Rt. 20, Marlborough, MA, near the eastern boundary of the Marlboro Formation.
MFS-1	plagioclase-biotite-muscovite-schist	19T 0290148 4691454	Main St., Marlborough, MA, across from City Hall, – type locality of Marlboro Formation of Emerson (1917).
MRG-4	augite-hornblende-quartz-biotite-plagioclase gneiss	19T 0285875 4692590	Intersection of Robin Hill St. and Jacobs Rd., Marlborough, MA – on north side of the Millham Resevoir Member, <200 m from the Assabet River fault.
NASHOBA FORMATION			
NFA-3	plagioclase-hornblende amphibolite	19T 031355 471216	Middlesex Turnpike, ~250 m north of Nutting Lake, Billerica, MA, Boxford Member, near the eastern boundry of the Nashoba Formation.
NFA-7	plagioclase-hornblende amphibolite	19T 028221 469532	~200 m south of Ross Dam spillway, off Linden St., Berlin, MA.
NFM-1	finely-layered paramigmatite with plagioclase-quartz microcline leucosomes and sillimanite-muscovite-biotite melanosomes	19T 0290589 4706881	Adjacent to parking lot, 60 Codman Hill Rd., Boxborough, MA. (large bulk sample processed for homogenization).
NFS-1	sillimanite-garnet-muscovite-schist with quartzofeldspathic layers	19T 0280619 4690986	East side of Green St., ~500 m north of I-290, Northborough, MA near the western boundary of the Nashoba Formation.
FISH BROOK GNEISS			
FBG-3	granitic gneiss	19T 033304 472356	~300m north of Forest St., in the Boxford State Forest, North Andover, MA – northeastern body of the Fish Brook Gneiss.
FBG-4	granitic gneiss	19T 0313811 4710606	East side of Rt. 3, ~0.7 km south of Orchard Rd. overpass, Billerica, MA – southwestern body of the Fish Brook Gneiss.

APPENDIX A *(continued)*

Sm-Nd Sample Descriptions

Marlboro Formation.—Four samples were collected from the Marlboro Formation: two amphibolites (MFA-1 and MFA-2), one schist (MFS-1) and one granulite from the Millham Reservoir Member (MRG-4).

MFA-1 is a fine-grained weakly foliated plagioclase-hornblende amphibolite composed of approximately 55% hornblende and 40% labradorite ($An_{50\text{-}55}$) (An contents determined petrographically) with trace amounts of apatite. Although in hand sample MFA-1 appears to have 1–5 cm hornblende porphyroblasts, petrographic analysis shows that these are in fact aggregates of 0.1–2 mm crystals. MFA-1 is located approximately in the middle of the Marlboro Formation, immediately west of the town of Marlborough, Massachusetts (fig. 1B).

MFA-2 is a fine- to medium-grained weakly foliated plagioclase-hornblende amphibolite composed of approximately 55% hornblende and 35% andesine (An_{47}) with minor amounts of quartz, epidote, biotite and chlorite. The biotite forms only along fractures; the epidote and chlorite most likely represent a retrograde assemblage. MFA-2 was collected approximately 1 km southwest of MFA-1, near the eastern boundary of the Marlboro Formation.

MFS-1 is a fine-grained well foliated plagioclase-biotite-muscovite schist composed of approximately 55% muscovite, 35% quartz, 5% biotite, and 5% oligoclase with minor amounts of garnet and secondary chlorite. MFS-1 was collected in the center of the city of Marlborough at the type locality of the Marlboro Formation as defined by Emerson (1917).

MRG-4 is a medium-grained augite-hornblende-quartz-biotite-plagioclase foliated gneiss composed of approximately 40% andesine ($An_{35\text{-}45}$), 20% biotite, 10% quartz, 8% hornblende, 5% augite and minor amounts of apatite, titanite, and clinozoisite-epidote. Additionally, about 10% is made up of ~2mm size grains of enstatite-hypersthene that appear to be relict phenocrysts. By contrast, the augite crystals have been largely dismembered by shearing. MRG-4 was collected on the northern side of the Millham Reservoir Granulite, less than 200m from the Assabet River fault zone (fig. 1B).

Nashoba Formation.—Samples from the Nashoba Formation include two amphibolites (NFA-3 and NFA-7), one pelitic schist (NFS-1) and one paramigmatite (NFM-1).

NFA-3 is a fine-grained well foliated augite-plagioclase-hornblende amphibolite from the Boxford Member, near the eastern boundary of the Nashoba Formation (fig. 1B). It is composed of approximately 50% hornblende, 30% labradorite (An_{54}), 12% augite, 5% titanite and minor amounts of clinozoisite. The augite is typically limited to plagioclase rich layers and much of the titanite occurs as overgrowths on opaques, most likely ilmenite.

NFA-7 is a medium-grained plagioclase-hornblende amphibolite with minor quartz from near the western boundary of the Nashoba Formation (fig. 1B). It is composed of approximately 50% hornblende, 40% plagioclase, 5% ilmenite, and minor amounts of quartz and apatite.

NFS-1 is a graphitic garnet-sillimanite-muscovite schist with quartzofeldspathic layers from near the western boundary of the Nashoba Formation. It is composed of 35% sericite, 25% quartz, 10% sillimanite, 10% muscovite, 10% biotite, 5% garnet, and 2% graphite with minor apatite.

NFM-1 is a finely layered paramigmatite with plagioclase-quartz-microcline leucosomes and sillimanite-muscovite-biotite melanosomes from near the western boundary of the Nashoba Formation (fig. 1B). It is composed of approximately 25% quartz, 20% biotite, 20% muscovite, 20% microcline feldspar, 8% labradorite, 5% prismatic sillimanite and minor amounts of zircon. To compensate for the heterogeneity of the paramigmatite, approximately 500 cm^3 of sample was processed and homogenized for Sm/Nd analysis.

Fish Brook Gneiss.—Two samples of granitic gneiss were chosen from the Fish Brook Gneiss. FBG-3 (northeastern body; fig. 1B) is composed of approximately 60% oligoclase (An_{26}), 15% quartz, 15% orthoclase, and 8% biotite with minor amounts of muscovite, chlorite and epidote. FBG-4 (southwestern body) is composed of approximately 40% plagioclase, 25% orthoclase, 20% quartz, 13% biotite and 2% garnet.

REFERENCES

Abu-Moustafa, A., and Skehan, J. W., 1976, Petrography and geochemistry of the Nashoba Formation, east-central Massachusetts, *in* Lyons, P. C., and Brownlow, A. H., editors, Studies in New England Geology: Geological Society of America Memoirs, v. 146, p. 31–70, https://doi.org/10.1130/MEM146-p31

Bailey, J. C., 1981, Geochemical criteria for a refined tectonic discrimination of orogenic andesites: Chemical Geology, v. 32, n. 1–2, p. 139–154, https://doi.org/10.1016/0009-2541(81)90135-2

Barr, S. M., and Kerr, A., 1997, Late Precambrian plutons in the Avalon terrane of New Brunswick, Nova Scotia and Newfoundland, *in* Sinha, A. K., Whalen, J. B., and Hogan, J. P., editors, The nature of

magmatism in the Appalachian orogeny: Geological Society of America Memoirs, v. 191, pp. 45–74, https://doi.org/10.1130/0-8137-1191-6.45
Barr, S. M., Raeside, R. P., and White, C. E., 1998, Geological correlations between Cape Breton Island and Newfoundland, Northern Appalachian orogen: Canadian Journal of Earth Sciences, v. 35, n. 11, p. 1252–1270, https://doi.org/10.1139/e98-016
Bell, K. G., and Alvord, D. C., 1976, Pre-Silurian stratigraphy of Northeastern Massachusetts, *in* Page, L. R., editor, Contributions to the stratigraphy of New England: Geological Society of America Memoirs, v. 148, p. 179–216, https://doi.org/10.1130/MEM148-p179
Bowring, S. A., Schoene, B., Crowley, J. L., Ramezani, J., and Condon, D. J., 2006, High-Precision U-Pb zircon geochronology and the stratigraphic record: Progress and promise, *in* Olszewski, T., editor, Geochronology: Emerging Opportunities: Philadelphia, Pennsylvania, The Paleontological Society, Paleontological Society Short Course, Paleontological Society Papers, v. 11, p. 23–43.
Buchanan, J. W., II, Kuiper, Y. D., and Buchwaldt, R., 2015, New advances on the deformation and anatectic history of the Nashoba terrane, New England Appalachians: Geological Society of America Abstracts with Programs, v. 47, n. 7, p. 862.
Buys, J., Spandler, C., Holm, R. J., and Richards, S. W., 2014, Remnants of ancient Australia in Vanuatu: Implications for crustal evolution in island arcs and tectonic development of the southwest Pacific: Geology, v. 42, n. 11, p. 939–942, https://doi.org/10.1130/G36155.1
Cabanis, B., and Lecolle, M., 1989, Le diagramme La/10-Y/15-Nb/8; un outil pour la discrimination des series volcaniques et la mise en evidence des processus de melange et/ou de contamination crustale: Comptes Rendus de l'Academie des Sciences, Serie 2, Mecanique, Physique, Chimie, Sciences de l'Univers, Sciences de la Terre, v. 309, n. 20, p. 2023–2029.
Castle, R. O., 1964, Geology of the Andover Granite and surrounding rocks, Massachusetts: United States Geological Survey Open-File Report 64-33, 550 p.
——— 1965, Gneissic rocks in the South Groveland quadrangle, Essex County, Massachusetts: United States Geological Survey Professional Paper 525-C, p. C81-C86.
D'Lemos, R. S., and Holdsworth, R. E., 1995, Samarium-Neodymium isotopic characteristics of the northeastern Gander zone, Newfoundland Appalachians, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, Current perspectives in the Appalachian-Caledonian orogen: Geological Society of Canada Special Paper 41, p. 239–252.
DePaolo, D. J., 1981, Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic: Nature, v. 291, p. 193–196, https://doi.org/10.1038/291193a0
DePaolo, D. J., Linn, A. M., and Schubert, G., 1991, The continental crustal age distribution: Methods of determining mantle separation ages from Sm-Nd isotopic data and application to the Southwestern United States: Journal of Geophysical Research, v. 96, n. B2, p. 2071–2088, https://doi.org/10.1029/90JB02219
DiNitto, R. G., Hepburn, J. C., Durfee Cardoza, K., and Hill, M., 1984, The Marlboro Formation in its type area and associated rocks just west of the Bloody Bluff fault zone, Marlborough area, Massachusetts, *in* Hanson, L., editor, Geology of the coastal lowlands, Boston, Massachusetts to Kennebunk, Maine: Salem, Massachusetts, New England Intercollegiate Geological Conference, 76th Annual Meeting, p. 271–291.
Dorias, M. J., Wintsch, R. P., Kunk, M. J., Aleinikoff, J., Burton, W., Underdown, C., and Kerwin, C. M., 2012, P-T-t conditions, Nd and Pb isotopic compositions and detrital zircon geochronology of the Massabesic Gneiss complex, New Hampshire: Isotopic and metamorphic evidence for the identification of Gander basement, central New England: American Journal of Science, v. 312, n. 10, p. 1049–1097, https://doi.org/10.2475/10.2012.01
Durfee, K. A., ms, 1983, Petrography and Geochemistry of the Sandy Pond Amphibolite Member of the Marlboro Formation, Marlborough, MA: Chestnut Hill, Massachusetts, Boston College, Department of Geology and Geophysics, Undergraduate Honors thesis, 35 p.
Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: United States Geological Survey Bulletin 597, 289 p.
Fyffe, L. R., Barr, S. M., Johnson, S. C., McLeod, M. J., McNicoll, V. J., Valverde-Vaquero, P., van Staal, C. R., and White, C. E., 2009, Detrital zircon ages from Neoproterozoic and Early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: Implications for the tectonic evolution of Ganderia: Atlantic Geology, v. 45, p. 110–144, https://doi.org/10.4138/atlgeol.2009.006
Fyffe, L. R., Johnson, S. C., and van Staal, C. R., 2011, A review of Proterozoic to early Paleozoic lithotectonic terranes in the northeastern Appalachian orogen of New Brunswick, Canada, and their tectonic evolution during Penobscot, Taconic, Salinic, and Acadian orogenesis: Atlantic Geology, v. 47, p. 211–248, https://doi.org/10.4138/atlgeol.2011.010
Goldsmith, R., 1991a, Stratigraphy of the Milford-Dedham zone, eastern Massachusetts: An Avalon terrane, *in* Hatch, N. L., Jr., editor, The Bedrock Geology of Massachusetts: United States Geological Survey Professional Paper 1366 E-J, p. E1-E62.
——— 1991b Stratigraphy of the Nashoba Zone, eastern Massachusetts: An enigmatic terrane, *in* Hatch, N. L., Jr., editor, The Bedrock Geology of Massachusetts: United States Geological Survey Professional Paper 1366 E-J, p. F1-F22.
——— 1991c, Structural and metamorphic history of eastern Massachusetts, *in* Hatch, N. L., Jr., editor, The Bedrock Geology of Massachusetts: United States Geological Survey Professional Paper 1366 E-J, p. H1-H63.
Harvey, J., and Baxter, E. F., 2009, An improved method for TIMS high precision neodymium isotope analysis of very small aliquots (1-10 ng): Chemical Geology, v. 258, n. 3–4, p. 251–257, https://doi.org/10.1016/j.chemgeo.2008.10.024
Hastie, A. R., Kerr, A. C., Pearce, J. A., and Mitchell, S. F., 2007, Classification of altered volcanic island arc

rocks using immobile trace elements: Development of the Th-Co discrimination diagram: Journal of Petrology, v. 48, n. 12, p. 2341–2357, https://doi.org/10.1093/petrology/egm062

Hatcher, R. D., Jr., 2010, The Appalachian orogen: A brief summary, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoirs, v. 206, p. 1–19, https://doi.org/10.1130/2010.1206(01)

Hepburn, J. C., and DiNitto, R. G., 1978, Preliminary bedrock geologic map of the Marlborough quadrangle, Middlesex and Worcester counties, Massachusetts: United States Geological Survey Open-File Report 78-222, 29 p.

Hepburn, J. C., Dunning, G. R., and Hon, R., 1995, Geochronology and regional tectonic implications of Silurian deformation in the Nashoba Terrane, Southeastern New England, U.S.A., *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, Current perspectives in the Appalachian-Caledonian orogen: Geological Association of Canada Special Paper 41, p. 349–366.

Hermes, O. D., and Zartman, R. E., 1992, Late Proterozoic and Silurian alkaline plutons within the southeastern New England Avalon Zone: The Journal of Geology, v. 100, n. 4, p. 477–486, https://doi.org/10.1086/629599

Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian orogen, Canada-United States of America: Geological Survey of Canada map 2096A, scale 1:1,500,000.

Hibbard, J. P., van Staal, C. R., and Miller, B. V., 2007a, Links among Carolinia, Avalonia, and Ganderia in the Appalachian peri-Gondwanan realm, *in* Sears, J. W., Harms, T. A., and Evenchick, C. A., editors, Whence the mountains? Inquiries into the evolution of orogenic systems: A volume in honor of Raymond A. Price: Geological Society of America Special Papers, v. 433, p. 291–311, https://doi.org/10.1130/2007.2433(14)

Hibbard, J. P., van Staal, C. R., and Rankin, D. W., 2007b, A comparative analysis of pre-Silurian crustal building blocks of the Northern and Southern Appalachian orogen: American Journal of Science, v. 307, n. 1, p. 23–45, https://doi.org/10.2475/01.2007.02

——— 2010, Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician-Permian, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoirs, v. 206, p. 51–69, https://doi.org/10.1130/2010.1206(03)

Hill, M. D., Hepburn, J. C., Collins, R. D., and Hon, R., 1984, Igneous rocks of the Nashoba block, eastern Massachusetts, *in* Hanson, L. S., editor, Geology of the coastal lowlands; Boston, MA to Kennebunk, ME: Salem, Massachusetts, New England Intercollegiate Geological Conference, 76th Annual Meeting, p. 61–80.

Hussey, A. M., II, Bothner, W. A., and Aleinikoff, J., 2010, The tectono-stratigraphic framework and evolution of southwestern Maine and southeastern New Hampshire, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodina to Pangea: The lithotectonic record of the Appalachian Region: Geological Society of America Memoirs, v. 206, p. 205–230, https://doi.org/10.1130/2010.1206(10)

Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, n. 5, p. 523–548, https://doi.org/10.1139/e71-055

Johnson, S. C., 2001, Contrasting geology in the Pocologan River and Long Reach areas: Implicatons for the New River belt and correlations in southern New Brunswick and Maine: Atlantic Geology, v. 37, n. 1, p. 61–79, https://doi.org/10.4138/1972

Johnson, S. C., and McLeod, M. J., 1996, The New River belt: A unique segment along the western margin of the Avalon composite terrane, southern New Brunswick, *in* Nance, R. D., and Thompson, M. D., editors, Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic: Geological Society of America Special Papers, v. 304, p. 149–164, https://doi.org/10.1130/0-8137-2304-3.149

Johnson, S. C., McLeod, M. J., Fyffe, L. R., and Dunning, G. R., 2009, Stratigraphy, geochemistry, and geochronology of the Annidale and New River belts, and the development of the Penobscot arc in southern New Brunswick, *in* Martin, G. L., editor, Mineral Resource Report 2009-2: New Brunswick Division of Natural Resources; Minerals, Policy, and Planning Division, p. 141–218.

Johnson, S. C., Fyffe, L. R., McLeod, M. J., and Dunning, G. R., 2012, U-Pb ages, geochemistry, and tectonomagmatic history of the Cambro-Ordovician Annidale Group: A remnant of the Penobscot arc system in southern New Brunswick?: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 166–188, https://doi.org/10.1139/E11-031

Kay, A., ms, 2012, Sm-Nd isotope, major element, and trace element geochemistry of the Nashoba terrane, eastern Massachusetts: Chestnut Hill, Massachusetts, Boston College, M.S. thesis, 130 p.

Kay, A., Hepburn, J. C., and Kuiper, Y., 2011, Trace element and Sm-Nd isotopic geochemical characteristics of the Nashoba terrrane, eastern Massachusetts: Geological Society of America, Abstracts with Programs, v. 43, n. 1, p. 150.

Kopera, J. P., Hepburn, J. C., and DiNitto, R. G., 2006, Bedrock geologic map of the Marlborough Quadrangle, Massachusetts: Office of the Massachusetts State Geologist, GM-06-01, scale 1:24,000, map and text.

Landing, E., and Murphy, J. B., 1991, Uppermost Precambrian(?)-Lower Cambrian of mainland Nova Scotia: Faunas, depositional environments, and stratigraphic revision: Journal of Paleontology, v. 65, n. 3, p. 382–396, https://doi.org/10.1017/S0022336000030365

Loan, M. L., ms, 2011, New constraints on the age and deposition of the metasedimentary rocks in the Nashoba terrane, SE New England: Chestnut Hill, Massachusetts, Boston College, M.S. thesis, 125 p.

Loan, M., Hepburn, J. C., Kuiper, Y., and Tubrett, M. N., 2011, Age constraints on the deposition and provenance of meta-sedimentary units of the Nashoba terrane: Geological Society of America Abstracts with Programs, v. 43, n. 1, p. 160.

McLeod, M. J., Johnson, S. C., and Krogh, T. E., 2003, Archived U-Pb (zircon) dates from southern New Brunswick: Atlantic Geology, v. 39, n. 3, p. 209–225, https://doi.org/10.4138/1182

Murphy, J. B., and Nance, R. D., 2002, Sm-Nd isotopic systematics as tectonic tracers: An example from West Avalonia in the Canadian Appalachians: Earth-Science Reviews, v. 59, n. 1–4, p. 77–100, https://doi.org/10.1016/S0012-8252(02)00070-3

Murphy, J. B., Strachan, R. A., Nance, R. D., Parker, K. D., and Fowler, M. B., 2000, Proto-Avalonia: A 1.0-1.2 Ga tectonothermal event and constraints for the evolution of Rodinia: Geology, v. 28, n. 12, p. 1071–1074, https://doi.org/10.1130/0091-7613(2000)28<1071:PAGTEA>2.0.CO;2

Murphy, J. B., Pisarevsky, S. A., Nance, R. D., and Keppie, J. D., 2004, Neoproterozoic - Early Paleozoic evolution of peri-Gondwanan terranes: Implications for Laurentia-Gondwana connections: International Journal of Earth Science (Geologische Rundschau), v. 93, n. 5, p. 659–682, https://doi.org/10.1007/s00531-004-0412-9

Murphy, J. B., Gutierrez-Alonso, G., Nance, R. D., Fernandez-Suarez, J., Keppie, J. D., Quesada, C., Strachan, R. A., and Dostal, J., 2006, Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture?: Geology, v. 34, n. 5, p. 325–328, https://doi.org/10.1130/G22068.1

Murphy, J. B., Dostal, J., and Keppie, J. D., 2008, Neoproterozoic–Early Devonian magmatism in the Antigonish Highlands, Avalon terrane, Nova Scotia: Tracking the evolution of the mantle and crustal sources during the evolution of the Rheic Ocean: Tectonophysics, v. 461, n. 1–4, p. 181–201, https://doi.org/10.1016/j.tecto.2008.02.003

Nance, R. D., and Murphy, J. B., 1996, Basement isotopic signatures and Neoproterozoic paleogeography of Avalonian-Cadomian and related terranes in the Circum-North Atlantic, *in* Nance, R. D., and Thompson, M. D., editors, Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic: Geological Society of America Special Papers, v. 304, p. 333–346, https://doi.org/10.1130/0-8137-2304-3.333

O'Brien, S. J., Wardle, R. J., and King, A. F., 1983, The Avalon zone: A Pan-African terrane in the Appalachian orogen of Canada: Geological Journal, v. 18, n. 3, p. 195–222, https://doi.org/10.1002/gj.3350180302

Oakes-Coyne, L., Hepburn, J. C., and Hon, R., 1996, Geochemistry of the meta-volcanic rocks of the Putnam-Nashoba terrane, southeastern New England: Geological Society of America Abstracts with Programs, v. 28, n. 3, p. 87.

Pearce, J. A., 2008, Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust: Lithos, v. 100, n. 1–4, p. 14–48, https://doi.org/10.1016/j.lithos.2007.06.016

Pearce, J. A., Harris, B. W., and Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, n. 4, p. 956–983, https://doi.org/10.1093/petrology/25.4.956

Pollington, A. D., and Baxter, E. F., 2010, High resolution Sm-Nd garnet geochronology reveals the uneven pace of tectonometamorphic processes: Earth and Planetary Science Letters, v. 293, n. 1–2, p. 63–71, https://doi.org/10.1016/j.epsl.2010.02.019

Pollock, J. C., Hibbard, J. P., and Sylvester, P. J., 2009, Early Ordovician rifting of Avalonia and birth of the Rheic Ocean: U-Pb detrital zircon constraints from Newfoundland: Journal of the Geological Society, London, v. 166, p. 501–515, https://doi.org/10.1144/0016-76492008-088

Pollock, J. C., Hibbard, J. P., and van Staal, C. R., 2012, A paleogeographical review of the peri-Gondwanan realm of the Appalachian orogen: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 259–288, https://doi.org/10.1139/e11-049

Raposa, M., ms, 1985, A Geochemical and petrological study of the Boxford Member of the Nashoba Formation, Eastern Massachusetts: Chestnut Hill, Massachusetts, Boston College, Department of Geology and Geophysics, Undergraduate Honors thesis, 37 p.

Rast, N., and Skehan, J. W., 1983, The evolution of the Avalonian plate: Tectonophysics, v. 100, n. 1–3, p. 257–286, https://doi.org/10.1016/0040-1951(83)90191-9

Robinson, P., and Goldsmith, R., 1991, Stratigraphy of the Merrimack Belt, Central Massachusetts, *in* Hatch, N. L., Jr., editor, The Bedrock Geology of Massachusetts: United States Geological Survey Professional Paper 1366 E-J, p. G1–G37.

Rogers, N., van Staal, C. R., McNicoll, V., Pollock, J., Zagorevski, A., and Whalen, J., 2006, Neoproterozoic and Cambrian arc magmatism of the Victoria Lake Supergroup: A remnant of Ganderian basement in central Newfoundland?: Precambrian Research, v. 147, n. 3–4, p. 320–341, https://doi.org/10.1016/j.precamres.2006.01.025

Ruitenberg, A. A., McLeod, M. J., and Krogh, T. E., 1993, Comparative metallogeny of Ordovician volcanic and sedimentary rocks in the Annidale-Shannon (New Brunswick) and Harborside-Blue Hill (Maine) areas: Implications of new U-Pb age dates: Exploration and Mining Geology, v. 2, n. 4, p. 355–365.

Samson, S. D., Barr, S. M., and White, C. E., 2000, Nd isotopic characteristics of terranes within the Avalon Zone, southern New Brunswick: Canadian Journal of Earth Sciences, v. 37, n. 7, p. 1039–1052, https://doi.org/10.1139/e00-015

Satkoski, A. M., Barr, S. M., and Samson, S. D., 2010, Provenance of Late Neoproterozoic and Cambrian sediments in Avalonia: Constraints from detrital zircon ages and Sm-Nd isotopic compositions in southern New Brunswick, Canada: Journal of Geology, v. 118, n. 2, p. 187–200, https://doi.org/10.1086/649818

Schofield, D. I., and D'Lemos, R. S., 2000, Granite petrogenesis in the Gander Zone, NE Newfoundland: Mixing of melts from multiple sources and the role of lithospheric delamination: Canadian Journal of Earth Sciences, v. 37, n. 4, p. 535–547, https://doi.org/10.1139/e99-116

Schulz, K. J., Stewart, D. B., Tucker, R. D., Pollock, J. C., and Ayuso, R. A., 2008, The Ellsworth terrane, coastal Maine: Geochronology, geochemistry, and Nd-Pb isotopic composition – Implications for the rifting of

Ganderia: Geological Society of America Bulletin, v. 120, n. 9–10, p. 1134–1158, https://doi.org/10.1130/B26336.1

Shervais, J. W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 59, n. 1, p. 101–118, https://doi.org/10.1016/0012-821X(82)90120-0

Skehan, J. W., and Abu-Moustafa, A. A., 1976, Stratigraphic analysis of rocks exposed in the Wachusett-Marlborough tunnel, east-central Massachusetts, *in* Page, L. R., editor, Contributions to the stratigraphy of New England: Geological Society of America Memoirs, v. 148, p. 217–240, https://doi.org/10.1130/MEM148-p217

Skehan, J. W., and Rast, N., 1990, Pre-Mesozoic evolution of Avalon terranes of southern New England, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., editors, Geology of the composite Avalon terrane of Southern New England: Geological Society of America, Special Papers, v. 245, p. 13–54, https://doi.org/10.1130/SPE245-p13

Sorota, K., ms, 2013, Age and origin of the Merrimack terrane, southeastern New England: A detrital zircon U-Pb geochronology study: Chestnut Hill, Massachusetts, Boston College, M.S. thesis, 155 p.

Sorota, K., Hepburn, J. C., Kuiper, Y., and Turbrett, M., 2011, Age and origin of the Merrimack terrane, southeastern New England: A detrital zircon U-Pb study: Geological Society of America Abstracts with Programs, v. 43, n. 5, p. 42.

Stern, R. J., 2002. Crustal evolution in the East African orogen: A neodymium isotopic perspective: Journal of African Earth Sciences, v. 34, n. 3–4, p. 109–117, https://doi.org/10.1016/S0899-5362(02)00012-X

Stroud, M. M., Markwort, R. J., and Hepburn, J. C., 2009, Refining temporal constraints on metamorphism in the Nashoba terrane, southeastern New England, through monazite dating: Lithosphere, v. 1, n. 6, p. 337–342, https://doi.org/10.1130/L50.1

Sun, S., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, *in* Saunders, A. D., and Norry, M. J., editors, Magmatism in the ocean basins: Geological Society, London, Special Publications, v. 42, p. 313–345, https://doi.org/10.1144/gsl.sp.1989.042.01.19

Turner, L., ms, 1996, Geochemical trace element analysis of the Fish Brook Gneiss of the Nashoba terrane: Chestnut Hill, Massachusetts, Boston College, Department of Geology and Geophysics, Undergraduate Honors thesis, 54 p.

Valverde-Vaquero, P., Dunning, G. R., and O'Brien, S. J., 2006a, Polycyclic evolution of the Late Neoproterozoic basement in the Hermitage Flexure region (southwest Newfoundland Appalachians): New evidence from the Cinq-Cerf gneiss: Precambrian Research, v. 148, n. 1–2, p. 1–18, https://doi.org/10.1016/j.precamres.2006.03.001

Valverde-Vaquero, P., van Staal, C. R., McNicoll, V., and Dunning, G. R., 2006b, Mid-Late Ordovician magmatism and metamorphism along the Gander margin in central Newfoundland: Journal of the Geological Society, London, v. 163, p. 347–362, https://doi.org/10.1144/0016-764904-130

van Staal, C. R, 1994, Brunswick subduction complex in the Canadian Appalachians: Record of the Late Ordovician to Late Silurian collision between Laurentia and the Gander margin of Avalon: Tectonics, v. 13, n. 4, p. 946–962, https://doi.org/10.1029/93TC03604

van Staal, C. R, 2007, Pre-Carboniferous metallogeny of the Canadian Appalachians, *in* Goodfellow, W. D., editor, Mineral Deposits of Canada: A synthesis of major deposit types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 793–818.

van Staal C. R., and Barr, S. M., 2012, Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin, *in* Percival, J. A., Cook F. A., and Clowes, R. M., editors, Tectonic styles in Canada: The Lithoprobe perspective: Geological Association of Canada, Special Paper 49, p. 41–95.

van Staal, C. R., and Hatcher, R. D., Jr., 2010, Global setting of Ordovician orogenesis, *in* Finney, S. C., and Berry, W. B. N., editors, The Ordovician earth system: Geological Society of America Special Papers, v. 466, p. 1–11, https://doi.org/10.1130/2010.2466(01)

van Staal, C. R., Dewey, J. F., MacNiocall, C., and McKerrow, W. S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: History of a complex, west and southwest Pacific-type segment of Iapetus, *in* Blundell, D. J., and Scott, A. C., editors, Lyell: The Past is the key to the present: Geological Society, London, Special Publications, v. 143, p. 199–242, https://doi.org/10.1144/gsl.sp.1998.143.01.17

van Staal, C. R., Whalen, J. B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J. B., Keppie, J. D., and Hynes, A. J., editors, Ancient orogens and modern analogues: Geological Society, London, Special Publications, v. 327, p. 271–316, https://doi.org/10.1144/sp327.13

van Staal, C. R., Barr, S. M., and Murphy, J. B., 2012, Provenance and tectonic evolution of Ganderia: Constraints on the evolution of the Iapetus and Rheic oceans: Geology, v. 40, n. 1, p. 987–990, https://doi.org/10.1130/G33302.1

van Staal, C. R., Wilson, R. A., Kamo, S. L., McClelland, W. C., and McNicoll, V., 2016, Evolution of the Early and Middle Ordovician Popelogan arc in New Brunswick, Canada, and adjacent Maine, USA: Record of arc-trench migration and multiple phases of rifting: Geological Society of America Bulletin, v. 128, n. 1–2, p. 122–146, https://doi.org/10.1130/B31253.1

Walsh, G. J., Aleinikoff, J. N., and Dorais, M. J., 2009, Tectonic history of the Avalon and Nashoba terranes along the western flank of the Milford antiform, Massachusetts: Geological Society of America Abstracts with Programs, v. 41, n. 3, p. 98.

——— 2011a, Bedrock geologic map of the Grafton quadrangle, Worcester County, Massachusetts: U.S. Geological Survey Scientific Investigations Map 3171, scale 1:24,000.

Walsh, G. J., Aleinikoff, J. N., Wintsch, R. P., and Ayuso, R. A., 2011b, Origin of the Quinebaug-Marlboro belt in southeastern New England: Geological Society of America Abstracts with Programs, v. 43, n. 1, p. 158.

Walsh, G. J., Aleinikoff, J. N., Wintsch, R. P., and Ayuso, R. A., McAlleer, R. J., and Mershschat, A. J., 2015, Unravelling the prolonged history of the Ganderian margin of southeastern New England: Geological Society of America Abstracts with Programs, v. 47, n. 1, p. 42.

West, D. P., Coish, R. A., and Tomascak, P. B., 2004, Tectonic setting and regional correlation of Ordovician metavolcanic rocks of the Casco Bay Group, Maine: Evidence from trace element and isotope geochemistry: Geological Magazine, v. 141, n. 2, p. 125–140, https://doi.org/10.1017/S0016756803008562

White, C. E., Barr, S. M., Bevier, M. L., and Kamo, S., 1994, A revised interpretation of the Cambrian and Ordovician rocks in the Bourinot belt in central Cape Breton Island, Nova Scotia: Atlantic Geology, v. 30, n. 2, p. 123–142, https://doi.org/10.4138/2125

Williams, H., and Hatcher, R. D., Jr., 1983, Appalachian suspect terranes, *in* Hatcher, R. D., Jr., Williams, H., and Zietz, I., editors, Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoirs, v. 158, p. 33–53, https://doi.org/10.1130/MEM158-p33

Winchester, J. A., and Floyd, P. A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–343, https://doi.org/10.1016/0009-2541(77)90057-2

Wintsch, R. P., Aleinikoff, J. N., Walsh, G. J., Bothner, W. A., Hussey, A. M., II, and Fanning, C. M., 2007, SHRIMP U-Pb evidence for a late Silurian age of metasedimentary rocks in the Merrimack and Putnam-Nashoba terranes, eastern New England: American Journal of Science, v. 307, n. 1, p. 119–167, https://doi.org/10.2475/01.2007.05

Wones, D. R., and Goldsmith, R., 1991, Intrusive rocks of Eastern Massachusetts, *in* Hatch, N. L., Jr., editor, The bedrock geology of Massachusetts: United States Geological Survey Professional Paper 1366 E-J, p. I1–I61.

Wood, D. A., 1980, The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, n. 1, p. 11–30, https://doi.org/10.1016/0012-821X(80)90116-8

Zagorevski, A., van Staal, C. R., and McNicoll, V. J., 2007a, Distinct Taconic, Salinic and Acadian deformation along the Iapetus suture zone, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 44, n. 11, p. 1567–1585, https://doi.org/10.1139/E07-037

Zagorevski, A., van Staal, C. R., McNicoll, V., and Rogers, N., 2007b, Upper Cambrian to Upper Ordovician peri-Gondwanan island arc activity in the Victoria Lake Supergroup, Central Newfoundland: Tectonic development of the northern Ganderian margin: American Journal of Science, v. 307, n. 2, p. 339–370, https://doi.org/10.2475/02.2007.02

Zagorevski, A., van Staal, C. R., Rogers, N., McNicoll, V. J., and Pollock, J. C., 2010, Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians, *in* Tollo, R. P., Batholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodinia to Pangea: The lithotectonic record of the Appalachian region: Geological Society of America Memoirs, v. 206, p. 367–396, https://doi.org/10.1130/2010.1206(16)

Zen, E., editor, Goldsmith, R., Ratcliffe, N. M., Robinson, P., and Stanley, R. S., compilers, 1983, Bedrock geologic map of Massachusetts: United States Geological Survey Special Geologic Map, 3 sheets, scale 1:250,000.