Insights into the Acadian orogeny, New England Appalachians: a provenance study of the Carrabassett and Kittery formations, Maine

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ABSTRACT

The Central Maine Basin and Merrimack Trough are Silurian basins that formed adjacent to or were accreted to the Laurentian margin during the Acadian orogeny. The Early Devonian Carrabassett Formation of the Central Maine Basin and the Kittery Formation of the Merrimack Trough have major and trace element compositions indicative of a passive continental margin provenance, not unlike the older formations of the Central Maine Basin that are thought to have been derived from Laurentian sources. However, both the Carrabassett and Kittery formations have paleocurrent indicators of outboard sources. The Carrabassett Formation is one of the youngest formations of the Central Maine Basin and was deposited just prior to the Acadian orogeny. The Carrabassett and Kittery formations have major and trace element concentrations suggestive of passive margin turbidites derived from intermediate to felsic sources, inconsistent with a juvenile Avalonian provenance. The Carrabassett Formation contains detrital zircon grains that match the ages of peri-Gondwanan Ganderia. Unlike the dominance of positive bulk-rock ε_{Nd} values that are characteristic of Avalonia, Ganderia has negative ε_{Nd} values that are a better match for the negative ε_{Nd} values of the Carrabassett and Kittery formations. However, Ganderia accreted to Laurentia during the Salinic orogeny, prior to the deposition of the Carrabassett Formation, and was basement to the sediments of the Central Maine Basin upon which the Carrabassett and other formations were deposited. Wedging of Ganderia by Avalonia during the initial stages of the Acadian orogeny may have uplifted Ganderia, forming highlands outboard of the Central Maine Basin that served as the source of the Carrabassett Formation sediments.

RÉSUMÉ

Le bassin central du Maine et la cuvette de Merrimack constituent des bassins siluriens s'étant formés le long de la marge laurentienne ou s'y étant accrétés au cours de l'orogenèse acadienne. La Formation du Dévonien précoce de Carrabassett, dans le bassin central du Maine, et la Formation de Kittery, de la cuvette de Merrimack, présentent des compositions en éléments majeurs et traces signalant une provenance d'une marge continentale passive, à l'instar des formations plus âgées du bassin central du Maine qu'on pense originaires de sources laurentiennes. Les formations de Carrabassett et de Kittery comportent toutefois des indicateurs de paléocourants de sources extérieures. La Formation de Carrabassett constitue l'une des formations les plus récentes du bassin central du Maine; elle s'est mise en place juste avant l'orogenèse acadienne. Les caractéristiques géochimiques et géochronologique des formations de Carrabassett et de Kittery pourraient par conséquent permettre l'identification du terrane de collision. Les formations de Carrabassett et de Kittery possèdent des concentrations d'éléments majeurs et traces évoquant les turbidites de marge passive en provenance de sources intermédiaires à felsiques, ce qui est contradictoire avec une origine avalonienne juvénile. La Formation de Carrabassett comporte des grains détritiques de zircon correspondant aux âges du Ganderia périgondwanien. Contrairement à la prédominance de concentrations ε_{Nd} positives de roche en vrac caractéristiques d'Avalonia, Ganderia présentent des concentrations ε_{Nd} négatives qui cadrent mieux avec les concentrations ε_{Nd} négatives des formations de Carrabassett et de Kittery. Ganderia s'est toutefois accrété à Laurentia au cours de l'orogenèse salinique, avant le dépôt de la Formation de Carrabassett, et il a constitué le socle des sédiments du bassin central du Maine sur lesquels Carrabassett et d'autres formations se sont déposées. L'enfoncement d'Avalonia sous Ganderia au cours des stades initiaux de l'orogenèse acadienne pourrait avoir soulevé Ganderia, formant un massif à l'extérieur du bassin central du Maine qui a servi de source aux sédiments de la Formation de Carrabassett.

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INTRODUCTION

More studies have been conducted of and more has been written about the Acadian orogeny than any other New England orogenic event (e.g., Osberg *et al*. 1989; Roy and Skehan 1993; Rankin 1994; Bradley *et al*. 2000; Eusden *et al*. 2000; Tucker *et al*. 2001 and references therein). In spite of this volume of work, the fundamental problem of what caused the New England part of the Acadian orogeny remains.

The orogenies of the New England Appalachians resulted from the collision of several microcontinents to the Laurentian margin. In the context of this study, the most significant microcontinents are Ganderia and Avalonia. From the early to middle Paleozoic, the Laurentian margin progressively expanded due to the accretion of these microcontinents. They represent two separate peri-Gondwanan blocks that had separate but similar Neoproterozoic histories but were distinct from the Early Paleozoic (van Staal 2007). Ganderia was a Late Neoproterozoic to Early Cambrian arc terrane that rifted off Amazonia at about 505 Ma whereas Avalonia, a largely juvenile arc unconformably covered by Cambrian-Ordovician platform sediments, probably rifted from Gondwana ~30 million years later (van Staal 2007). The Salinic orogeny was caused by collision of the Ganderian margin and Laurentian at ~430–422 Ma. Many geologists think that the subsequent collision of Avalonia with composite Laurentia at ~420–400 Ma caused the Acadian orogeny (e.g., Osberg *et al*. 1989; Robinson *et al*. 1998), but lack of evidence of Acadian metamorphism in the New England part of Avalonia (Fig. 1) is a challenge to this interpretation (Walsh *et al*. 2007; Aleinikoff *et al*. 2007). Instead, the geochronology of Avalonia and inboard peri-Gondwanan terranes document a Pennsylvanian-Late Permian orogenic event (Eusden and Barreiro 1988; Spear and Harrison 1989; Tucker and Robinson 1990; Dallmeyer and Takasu 1992; Wintsch *et al*. 1992; Getty and Gromet 1992; West 1993; Lux and West 1993; Walsh *et al*. 2007).

West and north of the New England Avalonia are the peri-Gondwanan Willimantic and Pelham domes and the Massabesic Gneiss Complex (Fig. 1). In common with Avalonia, no Acadian metamophic or igneous ages have been identified in the Willimantic or the Pelham domes. Both domes contain orthogneisses with ages of ~620 Ma, a common age of peri-Gondwanan rocks, with a strong overprinting of a ~280 Ma event in the Alleghanian. As acknowledged by Robinson

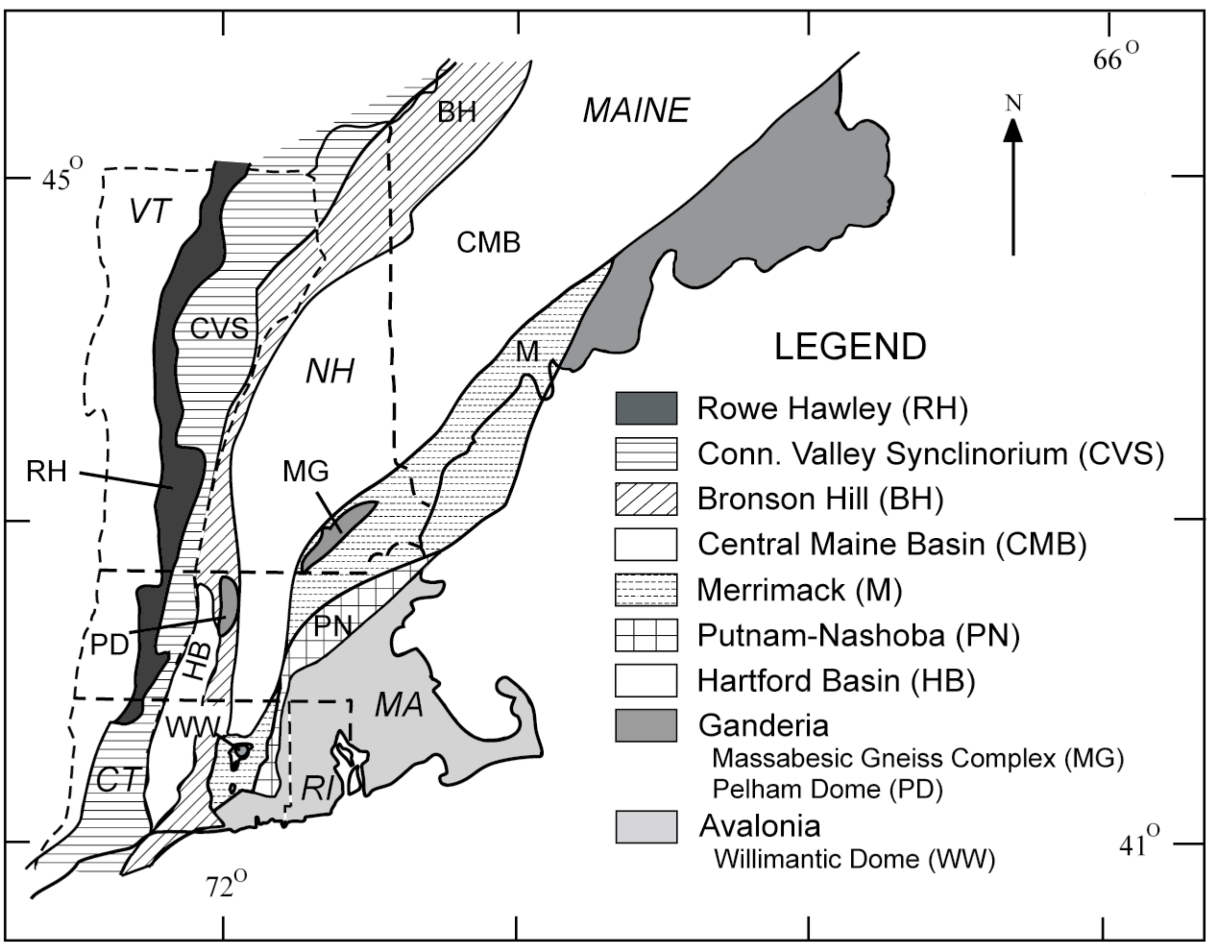

Fig. 1. Generalized geologic map showing the locations of the lithotectonic zones of New England (after Wintsch *et al*. 1992). The Carrabassett Formation is located in the Central Maine Basin (CMB).

et al. (1998), this lack of Ordovician–Devonian igneous activity and Silurian-Devonian metamorphism is inconsistent with the assignment of these domes to a peri-Gondwanan terrane that collided with Laurentia prior to the Alleghanian. For these reasons, some workers think that Avalonia did not arrive in southern New England until the Alleghanian orogeny (Zartman and Naylor 1984; Wintsch and Sutter 1986; Mosher *et al.* 1993; Wintsch *et al.* 1993; Rankin 1994; Walsh *et al.* 2007) and may have been emplaced along strike-slip faults in the Late Paleozoic (Robinson *et al.* 1998). Alternatively, Wintsch *et al.* (1992) suggested that the portion of Avalonia that collided during the Acadian was subsequently thrust further under the allochthonous rocks of the Central Maine Basin, Merrimack Trough, and Putnam-Nashoba terrane during the Alleghanian orogeny and is no longer exposed to provide evidence of Avalonian involvement with the Acadian event.

The Massabesic Gneiss complex shares the same ~620 and 280 Ma events with Avalonia of southeastern New England (Aleinikoff *et al.* 1979), and is the only peri-Gondwanan inlier that may preserve evidence of the Acadian orogeny. This gneiss contains amphibolite and an attenuated granitic dike with ~400 Ma zircon and monazite, respectively (Aleinikoff *et al.* 1995). The possibility that the Massabesic Gneiss Complex is of Ganderian affinity (Moench and Alienikoff 2003; Dorais *et al.* 2007) suggests that the complex had docked with Laurentia in the Salinic orogeny and, rather than having been the Acadian colliding terrane, it was on the receiving end of Avalonia's collision during the Acadian. Thus the question remains: What lithotectonic elements collided with Laurentia in this part of the New England Appalachians to cause the Acadian orogeny?

A Silurian to Early Devonian basin called the Central Maine Basin developed between Laurentia and the approaching terrane that docked to cause the Acadian orogeny. The earliest sediments deposited in the Central Maine Basin were derived from Laurentia whereas the uppermost formations preserve paleocurrent indicators from the east, suggesting an outboard source thought to be Avalonia (Hanson and Bradley 1989; Hanson *et al.* 1993; Bradley and Hanson 2002). Because sediments carry the major and trace element, isotopic, and detrital zircon signatures of their source rocks (O'Nions *et al.* 1983; Allegre and Rousseau 1984; Michard *et al.* 1985; McLennan *et al.* 1990; Gleason *et al.* 1994; Anderson and Sampson 1995; Bock *et al.* 1998; Wintsch *et al.* 2007), we undertook this study to determine whether or not the bulk-rock geochemical characteristics and detrital zircon geochronology of easterly derived sediments, i.e., the Carrabassett Formation of Maine, would identify the outboard terrane that collided with Laurentia. We compare these geochemical and geochronological parameters with those of the older formations of the Central Maine Basin in order to make comparisons between the source regions of sediments shed from Laurentia and outboard sources.

The Silurian Merrimack Trough lies to the east, outboard of the Central Maine Basin (Fig.1). This terrane is also an enigmatic belt that has traditionally been interpreted as peri-Gondwanan (e.g., Hibbard *et al.* 2006). Like the Carrabassett Formation of the Central Maine Basin, the Kittery Formation of the Merrimack Trough has paleocurrent indicators of an easterly source (Rickerich 1983). We also compare the bulk-rock geochemical, isotopic, and detrital zircon characteristics of the Kittery Formation with those of the Carrabassett Formation in order to evaluate provenance characteristics of the approaching Acadian colliding element.

GEOLOGIC SETTING

Central Maine Basin

The formations of the Central Maine Basin (Fig. 1) have been given different names by various workers depending on the region of study, but because we concentrated on the formations of western Maine, we use the names established by Moench and co-workers (e.g., Moench and Pankiwskyj 1988). We specifically focused on the Silurian and Devonian rocks of the Central Maine Basin which span a time frame from significantly before to just prior to and perhaps concurrent with the initial deformation of the Acadian orogeny (Bradley and Hanson 2002). From oldest to youngest, the formations of interest are the Rangeley, Perry Mountain, Smalls Falls, Madrid, and Carrabassett.

These formations are draped across what has been called a tectonic hinge that coincides with the eastern margin of the Bronson Hill anticlinorium (Fig. 1; Hatch *et al.* 1983). Northwest of the hinge, the sediments were deposited on a narrow shelf and lie unconformably on pre-Silurian rocks. Southeast of the hinge, the metasedimentary rocks thicken, representing the site of the Central Maine depositional basin. The hinge line appears to have been an active tectonic feature that controlled sedimentation from early Silurian to the culmination of the Acadian orogeny. The direction from which these sediments were derived is crucial to our study. An easterly or southeasterly transport direction is suggestive of Laurentian provenance. In contrast, westerly transportation directions have been interpreted as favoring a peri-Gondwanan source (Bradley and Hanson 2002).

The Rangeley Formation consists of three members, A, B, and C (Moench and Pankiwskyj 1988). Parts A and B thicken by an order of magnitude across the tectonic hinge to the southeast. Part A consists of a large sheet of marine sandstone and conglomerate, approximately 1200 m thick in the Rangeley quadrangle in Maine. The conglomerate includes boulders of the distinctive Ordovician Attean Quartz Monzonite from the Boundary Mountain anticlinorium to the northwest. Limited paleocurrent data suggest that the Perry Mountain and Smalls Falls formations were also derived from a source to the northwest (Hanson *et al.* 1993; Bradley and Hanson 2002). Interbedded quartzose sandstone and shale of the Perry Mountain Formation coarsen upward and to the northwest, also indicating a source from the northwest. Higher in the Silurian rocks of the Central Maine Basin, paleocurrent indicators indicate a non-western source area (Moench and Boudette 1970; Ludman and Griffin 1974; Ludman 1976; Bradley and

Hanson 1989, 2002). Three observations indicate transportation and perhaps derivation of the Madrid Formation from the northeast (Hanson *et al.* 1993): (1) southeasterly paleocurrent indicators, (2) decreasing ratio of facies B to facies D turbidites to the southwest, and (3) thinning of the Madrid Formation to the southwest.

The Carrabassett Formation, correlative with the Littleton Formation of New Hampshire (Moench and Pankiwskyj 1988; Hatch and Moench 1984), is the youngest, most widespread pre-Acadian formation of the Central Maine Basin. It was deposited just prior to the onset of Acadian deformation and consists of ~2000 m of Early Devonian, mud-rich turbidites that are locally metamorphosed to the chlorite zone of the greenschist facies (Hanson *et al.* 1993). Several facies are identified, from massive sandstones, undifferentiated thin to thick-bedded turbidites, chaotic facies, and thick-bedded turbidites to thin-bedded turbidites. The chaotic strata are considered to be olistrostromes. Coarse sandstone and conglomerate are absent. Paleocurrent data show a dominant flow from the southeast. Bradley and Hanson (2002) concluded that the combination of these facies and paleocurrent indicators reveals that the sediments were deposited on a submarine slope that descended to the northwest in the Central Maine depositional basin. High sedimentation rates, coupled with earthquakes from early Acadian tectonic disturbances, led to large amounts of sediment being remobilized and deposited as slumps and debris flows. As such, the Carrabassett Formation would represent deposition during the demise of the deep-water Central Maine Basin as it closed during the initial stages of Acadian collision.

Merrimack Trough

The Merrimack Trough is almost 400 km long, extending from Maine and southeastern New Hampshire through Massachusetts almost to Long Island Sound (Fig.1). In New Hampshire, it is in fault contact with the Massabesic Gneiss Complex on the northwest and with the Rye Complex on the southeast. It was originally defined by Katz (1917) to consist of the Kittery, Eliot, and Berwick formations that constitute a thick sequence of calcareous turbidites in the New Hampshire and Maine (Katz 1917; Billings 1956; Bothner *et al.* 1984; Bothner and Hussey 1999). Recently, Wintsch *et al.* (2007) concluded from detrital zircon geochronology that the Berwick Formation was Silurian and Laurentia-derived, whereas the Kittery Formation (middle Ordovician or younger), with its paleocurrent indicators of an eastern source and different detrital zircon signatures, is peri-Gondwanan. They interpreted the fault that separates the Berwick Formation from the Kittery and Eliot formations as a thrust fault that placed the Laurentia-derived Berwick on top of the peri-Gondwana-derived Kittery and Eliot. Thus it is particularly interesting to compare the provenance signature of the Carrabassett Formation with that of the Kittery Formation, as both appear to have an outboard provenance and have the potential to yield information about the Acadian colliding terrane.

SAMPLE LOCATIONS

Samples from the Carrabassett and Madrid formations were collected in Maine at stops 4, 6, 7, and 8 described in the Hanson *et al.* (1993) field guide. Rangeley Formation samples were collected in central New Hampshire at stops 1 and 2 of Lyons (1988) and stops 5, 7, and 9 of Eusden (1988). Berwick Formation samples were collected along a traverse starting at Exit 4 on Interstate 93 at Derry, New Hampshire extending eastward on Route 102 to Raymond, New Hampshire. The Eliot Formation was sampled at Stop VI-7 of Bothner (1989) at the junction of Route 155 and US4. Samples of the Kittery Formation were taken from Bothner's Stop VI-8 at Great Bay, New Hampshire, at Ogunquit, Moody Point in Wells, and at Cape Elizabeth, Maine. Approximate sample locations are shown on Figure 2.

ANALYTICAL METHODS

Detrital zircons were obtained from a ca. 5 kg sample of the Carrabassett Formation collected at Stop 4 of Hansen *et al.* (1993) at the Big Wilson Stream in Elliotsville, Maine. Zircons were extracted at Memorial University of Newfoundland using conventional mineral separation techniques (crushing, Wilfley table, and heavy liquids). Grains from the least magnetic split obtained with a Frantz isodynamic separator were hand picked in alcohol under a binocular microscope. The selected grains were mounted in an epoxy-filled grain mount and polished to obtain a flat surface. Bulk-rock XRF analyses were conducted on a Siemens SRS 303 instrument in the Department of Geological Sciences at Brigham Young University. Additional trace elements were analyzed by ICP-MS by ALS Chexex in Reno, Nevada.

In situ LA-ICP-MS analyses of areas within the selected crystals of zircon were carried out using a VG PlasmaQuad PQ-2 S+ instrument coupled to a NUWAVE UP213 nm NdYAG laser at Memorial University of Newfoundland. Additional zircons were analyzed with an Element XR coupled to a GEOLAS 193 nm eximer laser system following the methods of Košler *et al.* (2002). Raw data were corrected for electron multiplier dead time (20 ns) and processed off-line using an Excel spreadsheet program (LAMDATE) to integrate signals from each sequential set of 10 sweeps; the method follows that of Kosler *et al.* (2002). The measured $^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{235}U$ ratios were calculated and blank corrected for each analysis. The natural $^{238}U/^{235}U$ ratio of 137.88 was used to calculate the ^{235}U since it was not acquired with other isotopes due to its low natural abundance. Aspiration of the tracer solution allowed for a real-time instrument mass bias correction using known isotopic ratios of the tracer solution measured while the sample was ablated; this technique is largely independent of matrix effects that can variably influence measured isotopic ratios and hence the resulting ages (Kosler *et al.* 2002; Cox *et al.* 2003). The amount of common Pb present in the analyzed zircon grains was insignificant relative to the con-

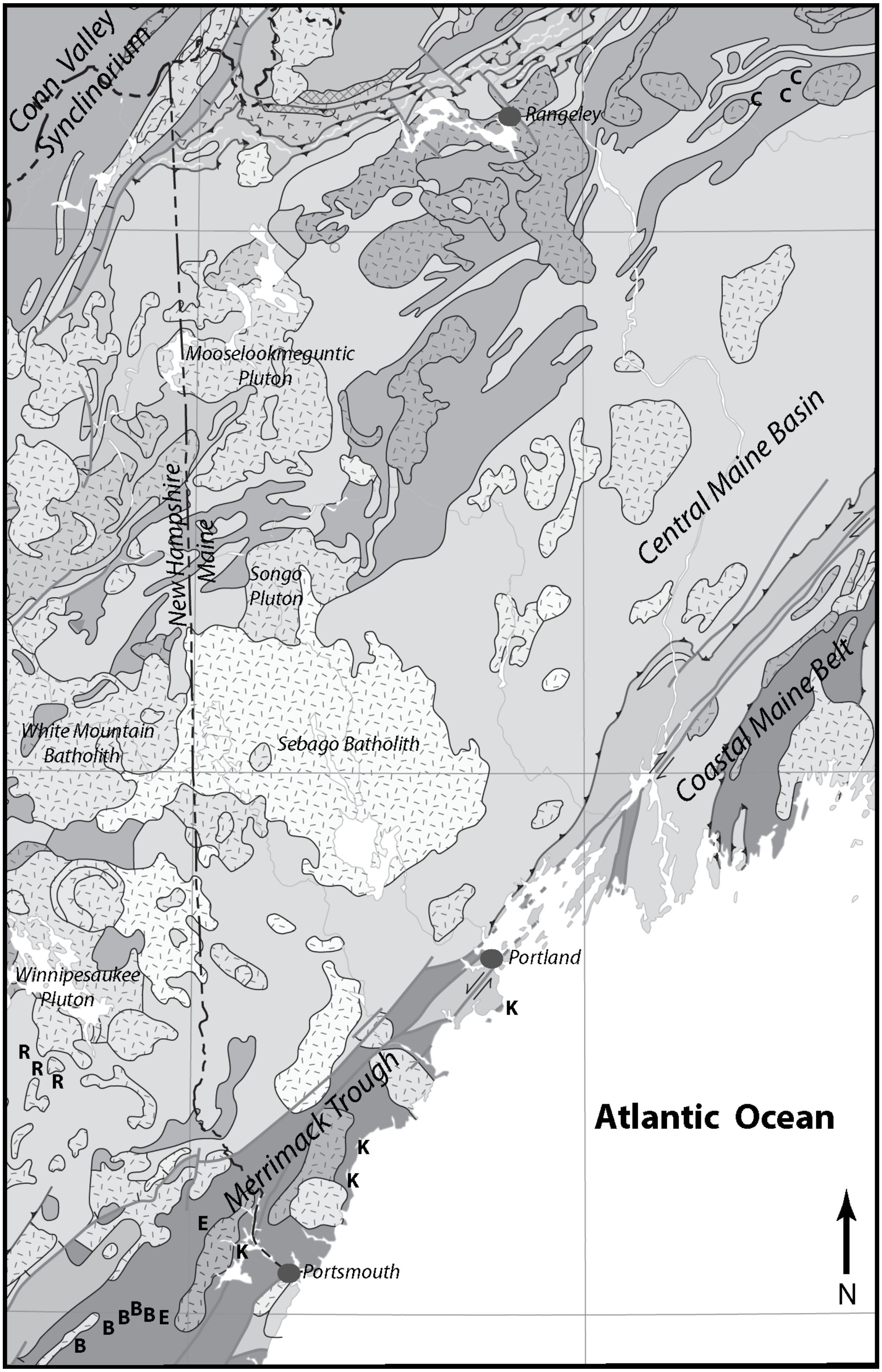

Fig. 2. Generalized geologic map of part of Maine and New Hampshire (from Hibbard *et al.* 2006) showing the approximate sample locations for the Carrabassett (C), Rangeley (R), Berwick (B), Eliot (E), and Kittery (K) formations.

tent of radiogenic Pb and therefore, no common Pb correction was applied to the data. Accuracy and reproducibility of U-Pb analysis were monitored by using zircon 91500, a natural in-house zircon standard with a known TIMS U-Pb age of 1065 ± 3 Ma (Wiedenbeck *et al.* 1995). Final ages and concordia diagrams were produced using the Isoplot/Ex macro (Ludwig 2000) in conjunction with LAMDATE Excel spreadsheet program (Kosler *et al.* 2002).

RESULTS

Bulk-rock Analyses

Bulk-rock major and trace element analyses of the Carrabassett, Rangeley, Smalls Falls, and Madrid formations of the Central Maine Basin and the Kittery, Berwick and Eliot formations of the Merrimack Trough are given in Table 1 and sample locations in Appendix A. Before discussing these results, it is appropriate to discuss how well these metasedimentary rocks represent initial compositions and the potential of element mobility during diagenesis and metamorphism. Cullers *et al.* (1997) presented a major and trace element and Nd isotopic study of the Rangeley, Perry Mountain, and Smalls Falls formations of western Maine. Their objective was to test the commonly accepted notion that the REE, Th, Sc, Co, and Cr are the most immobile elements during weathering, diagenesis, and metamorphism and as such, can be used to determine the provenance of metasedimentary rocks. They found that most major and trace element abundances relative to Al_2O_3 are statistically identical between zones of the same formation as well as between formations, suggesting no mobilization of the elements of interest in these rocks. Systematic compositional variations were attributed to varying proportions of clay minerals, feldspars, and quartz in the original protoliths. Some samples of the Perry Mountain Formation, however, are anomalous in that they have low REE contents and unrealistically old Nd $_{TDM}$ model ages, suggestive of open system behavior. Bock *et al.* (2004) also found that anomalous REE patterns and old Nd $_{TDM}$ model ages of several formations of the northern Appalachians are indicative of open system behavior. Our samples show neither anomalous REE behavior nor unrealistically old Nd $_{TDM}$ model ages; hence, we assume that the REE, Th, Sc, Co, and Cr concentrations permit determination of provenance characteristics as shown in numerous other studies (Bhatia and Crook 1986; Cox *et al.* 1995; Cullers 1994, Cullers *et al.* 1975, 1979, 1997; Wronkiewicz and Condie 1990).

Log values of SiO_2/Al_2O_3 versus Fe_2O_3/K_2O (Fig. 3) show that the samples (including analyses of Lathrop *et al.* 1996 and Cullers *et al.* 1997) plot as shale and wacke with a few samples scattering in the Fe-sandstone field (Herron 1988). The Rangeley Formation is dominated by shale protoliths whereas the other formations are wacke-dominated. Ague (1991, 1997) found evidence of SiO_2 loss in the Littleton Formation with increasing metamorphic grade so the lower log (SiO_2/Al_2O_3) values of the Rangeley Formation compared to the Carrabassett may be influenced by SiO_2 loss during metamorphism.

Because compatible elements have higher concentrations

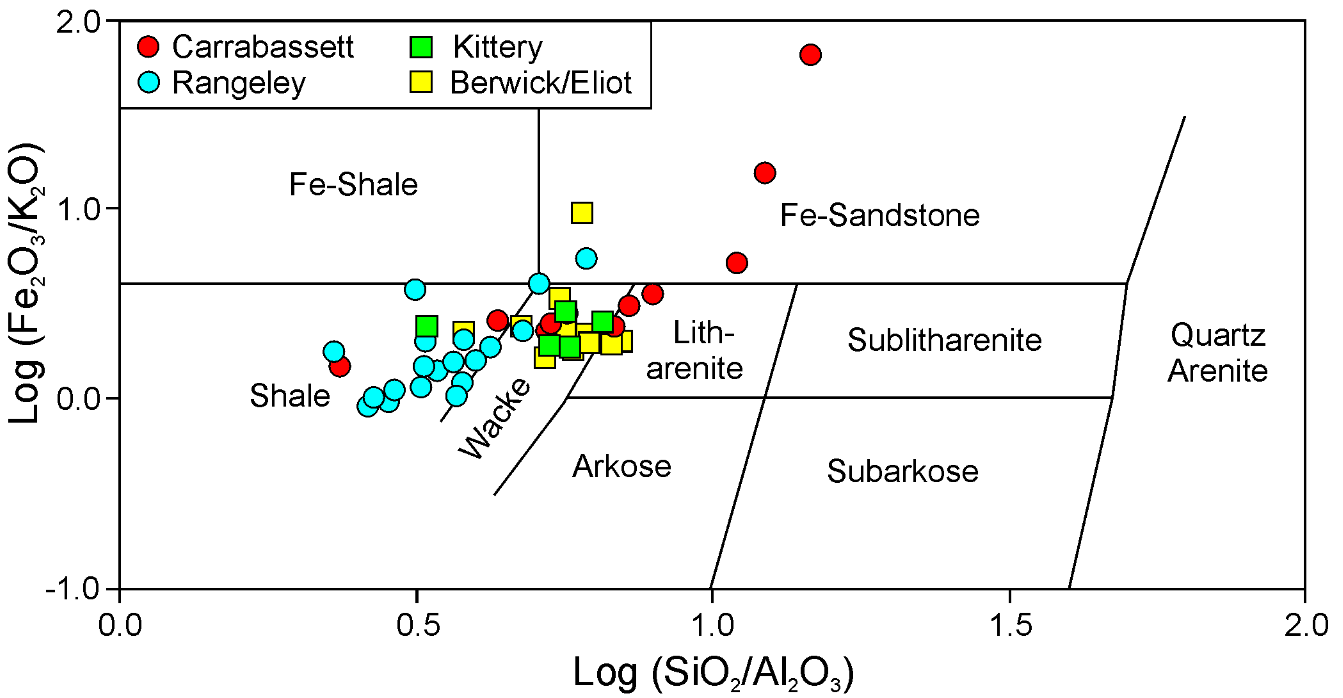

Fig. 3. **Log (SiO_2/Al_2O_3) versus log (Fe_2O_3/K_2O) classification diagram (after Herron 1988). Carrabassett Formation plot in fields from shale to Fe-sandstone. Most of the samples from the Kittery Formation and Berwick/Eliot formations plot as wacke. Our Rangeley Formation samples do not include the basal conglomeratic member and are primarily shale.**

Table 1. Bulk-rock Analyses of samples from the Central Maine and Merrimack Trough.

Sample	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	CIA	Rb	Cs	Sr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Zr	Hf	Y	Nb	Ta	Th	U	Pb	Sc	Cr	Co	Ni	Cu	Zn	Ga
Carrabassett Formation																																														
H-2	83.90	0.54	5.75	6.40	0.11	0.77	0.21	1.22	0.10	0.11	1.11	100.22	69.7	7	76	118	19	36.0	76.0	9.1	32.0	5.7	1.2	5.3	0.7	3.9	0.8	2.3	0.4	2.3	0.4	442.0	11	26.0	9		15		14	0	58	11.0	24	3	53	6
H-3	72.01	0.94	13.40	6.10	0.06	1.19	0.27	1.22	2.62	0.13	2.41	100.35	71.5	117	28	89	429	14.5	27.5	3.7	12.5	2.5	0.5	2.5	0.4	2.4	0.5	1.6	0.3	1.7	0.2	315.0	4	32.0	17		10		10	15	90	7.5	41	14	90	17
H-5	83.20	0.59	7.51	4.45	0.03	0.79	0.10	1.18	0.90	0.09	1.27	100.11	70.8	42	28	52	164	12.5	27.5	3.1	11.0	2.1	0.5	2.1	0.3	1.7	0.4	1.1	0.1	1.1	0.1	259.0	3	22.0	10		13		17	0	55	3.5	21	11	57	8
H-6	76.89	0.66	9.72	5.71	0.07	1.38	0.11	1.07	1.64	0.10	1.76	99.11	72.2	77	19	43	287	8.5	19.0	2.3	7.0	1.5	0.4	1.7	0.3	1.7	0.4	1.1	0.1	1.2	0.1	249.0	3	22.0	12		9		16	9	73	8.5	34	36	77	11
H-7	75.90	0.73	10.46	5.69	0.07	1.36	0.11	1.06	1.89	0.12	1.87	99.26	72.4	85	22	46	324	11.0	21.5	2.6	9.5	2.1	0.6	2.6	0.5	3.4	0.8	2.3	0.4	2.4	0.4	267.0	7	23.0	13		8		14	11	77	16.5	33	32	74	12
H-8	71.35	0.87	12.64	5.83	0.06	1.84	0.16	1.64	2.16	0.14	2.35	99.04	70.4	105	29	84	365	12.5	28.5	3.2	11.0	2.5	0.5	2.7	0.5	2.6	0.6	1.7	0.3	1.6	0.3	302.0	3	33.0	16		9		10	15	97	4.0	43	13	76	16
H-9	67.06	0.91	15.30	7.21	0.10	2.10	0.69	1.78	2.99	0.13	2.30	100.56	67.3	163	39	173	430	19.0	38.5	4.4	16.0	3.0	0.7	2.9	0.4	2.5	0.5	1.5	0.2	1.5	0.2	229.0	3	32.0	16		6		27	18	126	12.0	69	33	106	20
H-10	70.58	1.01	13.34	5.91	0.08	1.68	0.35	1.51	2.73	0.15	2.01	99.35	68.7	127	75	110	424	36.5	74.5	8.6	31.0	5.9	1.4	6.6	1.0	6.3	1.3	3.7	0.6	3.8	0.6	306.0	8	39.0	17		7		17	15	104	17.5	49	7	86	17
H-11	81.02	0.55	6.58	7.22	0.15	1.01	0.22	0.77	0.49	0.15	1.51	99.67	75.0	27	78	75	76	37.5	78.0	8.8	33.5	6.7	2.0	7.7	0.9	4.9	0.9	2.6	0.4	2.6	0.4	371.0	10	29.0	10		11		27	0	64	8.5	28	14	74	7
Rangeley Formation																																														
R-2-1	71.60	0.81	11.95	7.01	0.20	1.94	1.31	2.07	1.68	0.33	1.69	100.59	61.1	86	2.5	111	237	44.0	88.0	9.8	40.0	8.3	1.5	8.5	1.0	6.6	1.3	3.9	0.5	3.4	0.5	301.0	7	35.0	14		11	2.0	14	13	73	44.0	37	37	99	17
R-2-2	73.40	0.81	11.75	6.83	0.11	1.90	0.34	0.67	2.52	0.08	1.88	100.29	72.5	107	2.3	99	689	35.5	73.0	8.8	33.0	6.0	1.2	5.4	0.6	3.8	0.8	2.9	0.4	2.5	0.4	263.0	5	22.0	13		10	1.7	21	12	65	29.0	37	37	86	19
R-3-1	71.30	0.86	13.05	6.80	0.10	2.13	0.56	1.12	2.66	0.07	1.69	100.34	69.5	113	3.1	135	730	39.0	80.5	9.0	37.0	6.6	1.5	6.3	0.7	4.7	0.9	2.7	0.4	2.8	0.3	265.0	5	27.0	16		11	2.6	21	13	68	43.0	33	33	98	20
R-3-2	72.20	0.81	12.60	7.08	0.13	2.13	0.54	0.95	2.33	0.05	1.64	100.46	71.3	111	3	99	657	38.0	79.5	9.0	36.0	5.0	1.4	5.0	0.6	4.3	0.8	2.4	0.4	3.1	0.4	252.0	5	24.0	15		10	1.4	16	12	71	40.0	40	40	101	20
R-5-1	71.30	0.87	13.13	6.31	0.06	1.37	0.94	1.77	2.61	0.08	2.17	100.61	63.8	160	7.4	211	408	28.5	63.5	6.5	25.0	5.2	1.3	4.2	0.6	3.9	0.9	2.5	0.4	2.5	0.3	291.0	7	25.0	18		16	2.5	28	16	66	29.0	27	27	90	21
R-5-2	59.00	0.96	18.74	8.97	0.08	2.13	0.29	0.81	4.41	0.11	3.70	99.20	73.9	210	9.8	91	656	58.5	118.5	13.5	51.0	9.3	1.5	8.5	0.8	6.3	1.3	3.7	0.6	3.9	0.5	189.0	4	41.0	22		18	4.2	35	20	92	10.0	25	25	116	31
R-6-1	73.40	0.79	10.88	6.14	0.18	1.68	1.63	2.74	1.83	0.07	1.00	100.34	53.5	103	3.1	179	351	39.0	79.0	9.1	13.0	6.0	1.5	5.5	0.7	4.2	0.9	2.7	0.4	2.6	0.4	355.0	7	24.0	15		11	1.8	21	15	70	23.0	38	20	101	16
R-6-2	74.20	0.77	10.35	6.66	0.15	1.82	1.32	2.15	1.78	0.03	1.06	100.29	56.8	97	3	173	376	37.5	76.0	8.9	12.0	5.5	1.4	5.3	0.7	4.3	0.9	2.6	0.4	2.8	0.4	290.0	6	26.0	14		10	2.0	20	13	66	46.0	41	27	106	14
R-6-3	71.20	0.68	11.64	5.28	0.26	1.53	3.68	1.91	1.50	0.64	2.07	100.39	50.4	75	2.3	189	308	36.0	69.0	8.5	12.0	6.5	1.0	6.3	0.7	4.8	0.9	2.7	0.4	2.7	0.4	273.0	6	30.0	14		8	2.2	14	10	59	30.0	30	149	75	17
Madrid Formation																																														
H-12	71.03	0.66	11.50	4.54	0.06	2.52	3.12	2.01	2.23	0.13	2.05	99.85	50.2	95	69	202	389	33.0	68.5	7.8	28.0	5.6	1.3	6.1	0.9	4.7	1.0	3.0	0.5	2.8	0.4	234.0	6	28.0	13		8		15	13	142	13.5	61	13	59	14
H-13	71.26	0.79	12.44	4.85	0.05	2.62	1.97	2.95	2.25	0.14	0.57	99.89	53.4	88	43	190	403	21.5	42.5	5.1	18.5	3.4	1.1	3.9	0.6	3.4	0.8	2.5	0.4	2.8	0.4	282.0	7	23.0	13		11		16	14	151	13.0	53	11	65	15
H-14	55.11	0.66	12.60	4.66	0.17	7.06	9.15	1.36	2.93	0.10	5.84	99.64	36.4	121	76	380	497	37.0	75.5	9.1	31.0	6.1	1.3	6.1	0.9	4.6	1.0	3.1	0.4	2.8	0.4	206.0	6	27.0	13		8		12	11	60	12.0	28	8	66	18
H-15	71.34	0.69	11.85	4.50	0.07	2.38	3.16	2.56	2.05	0.13	1.89	100.61	49.3	82	67	223	369	32.5	67.0	8.1	29.0	5.6	1.1	5.6	0.8	4.5	0.9	2.7	0.4	2.5	0.4	237.0	6	28.0	13		12		15	14	121	13.0	47	13	60	15
H-16	55.92	0.93	18.85	8.64	0.10	4.99	0.63	1.37	6.13	0.18	2.35	100.08	65.3	194	44	85	898	22.5	43.5	5.1	18.5	3.4	0.7	3.7	0.5	3.0	0.6	1.8	0.3	1.8	0.3	174.0	2	36.0	16		2		16	23	192	12.5	112	55	115	26
H-19	66.44	0.54	9.73	3.15	0.13	1.71	8.62	1.65	1.29	0.14	6.77	100.17	33.0	61	51	382	286	25.5	51.0	6.0	21.0	4.5	1.1	4.8	0.7	3.9	0.9	2.4	0.3	2.3	0.3	166.0	5	25.0	10		11		17	9	74	8.5	27	4	40	12
H-20	68.02	0.61	12.52	5.01	0.06	2.84	3.67	2.49	2.23	0.12	2.42	99.99	48.7	97	54	225	393	28.5	54.0	6.7	23.5	4.7	1.0	4.9	0.7	3.8	0.8	2.3	0.3	2.1	0.3	166.0	4	23.0	12		7		14	13	87	12.0	49	10	66	16
Eliot Formation																																														
E-1	66.03	0.68	9.28	3.76	0.07	2.58	5.60	1.88	1.98	0.15	8.61	100.62	37.6	74	2	225	288	33.5	72.0	9.2	35.0	7.1	1.6	6.1	1.1	5.5	1.3	3.5	0.6	3.2	0.5	430.0	14	31.0	10	0.5	10	3.0	10	12		11.5	65	15	55	11
E-2	66.03	0.76	9.41	3.82	0.07	2.59	5.52	1.66	2.24	0.18	8.37	100.65	38.2	83	2.2	224	313	39.5	85.0	10.8	41.0	7.9	1.6	6.6	1.2	6.0	1.4	3.9	0.6	3.8	0.6	516.0	17	33.0	12	0.5	13	3.5	15	14		11.5	70	25	60	12
E-3	55.68	0.75	14.54	6.75	0.07	4.47	4.33	1.48	3.16	0.15	8.10	99.48	51.4	130	3.9	203	473	32.0	66.0	8.3	30.5	6.1	1.3	4.9	0.9	4.5	1.1	2.9	0.4	2.7	0.4	157.0	5	24.5	11	0.5	11	3.0	20	17		24.0	125	35	110	20
E-4	62.00	0.63	11.53	4.77	0.07	3.02	5.42	1.66	2.84	0.12	8.41	100.47	42.4	107	3.2	224	387	28.5	61.0	7.8	29.0	5.8	1.2	4.7	0.9	4.0	0.9	2.4	0.4	2.3	0.3	183.5	6	22.0	10	0.5	9	2.5	20	15		16.0	85	25	45	15
Kittery Formation																																														
K-1	70.06	0.64	11.61	4.49	0.06	3.08	3.05	2.06	2.54	0.12	3.04	100.75	49.8	112	4.1	189	405	27.0	58.0	7.4	27.5	5.5	1.2	4.7	0.8	4.3	1.0	2.7	0.4	2.4	0.3	157.5	5	24.5	10	0.5	8	2.5	70	12		14.5	90	25	110	16
K-4	45.44	3.00	15.82	13.07	0.20	5.67	8.60	3.61	1.42	0.61	3.14	100.58	40.6	43	1.1	543	282	34.0	69.0	8.7	35.5	7.3	2.3	6.5	1.1	4.9	1.1	2.6	0.3	2.0	0.3	201.0	6	24.0	45	3.5	3	1.5	5	19		36.0	55	160	120	24
K-6	56.31	0.86	16.96	7.37	0.11	4.83	6.07	1.99	3.16	0.15	1.61	99.42	48.9	168	8.6	314	329	37.5	78.5	10.0	36.5	7.0	1.3	5.9	1.0	5.2	1.2	3.1	0.5	3.2	0.4	163.0	5	27.0	13	1.0	13	3.5	15	19		25.0	145	5	80	24
K-9	64.75	0.66	11.95	5.06	0.06	3.29	3.15	1.27	2.81	0.14	6.29	99.43	52.4	117	5.2	133	403	31.5	67.5	8.9	33.0	6.4	1.4	5.7	1.0	5.3	1.2	3.1	0.5	2.8	0.4	164.0	6	28.5	11	0.5	10	3.0	5	13		16.0	85	20	55	16
K-11	68.56	0.66	9.89	3.98	0.08	2.51	5.16	2.20	1.75	0.13	5.74	100.66	39.9	65	2.2	180	245	28.0	60.0	7.7	29.0	5.7	1.2	5.3	0.9	4.9	1.2	2.9	0.5	2.9	0.4	264.0	9	28.0	10	0.5	8	2.0	20	14		12.5	75	15	50	12
K-12	69.14	0.67	11.70	4.65	0.06	3.11	2.83	2.15	1.82	0.15	4.29	100.57	52.3	61	1.9	138	399	34.0	71.0	9.1	33.0	6.7	1.3	5.6	1.0	4.9	1.1	2.9	0.4	2.7	0.4	221.0	7	26.0	11	0.5	9	2.0	10	13		14.5	90	30	65	15
Berwick Formation																																														
B-1	69.81	0.68	10.74	4.12	0.12	2.54	7.15	1.50	2.06	0.12	1.02	99.86	37.8	74	8.9	319	420	33.5	70.5	8.9	33.0	6.6	1.4	5.6	1.0	5.1	1.1	3.2	0.5	3.0	0.5	316.0	10	29.0	11	0.5	10	3.0	30	13		13.0	70	20	50	13
B-2	70.00	0.71	11.38	4.40	0.07	2.95	4.60	1.97	2.22	0.15	2.05	100.50	44.8	95	4.5	205	355	34.5	73.0	9.3	35.0	7.0	1.4	5.9	1.1	5.5	1.3	3.4	0.5	3.4	0.5	297.0	10	30.0	13	1.0	11	4.0	15	14		15.0	80	20	60	15
B-3	71.19	0.87	11.81	4.58	0.07	3.13	3.28	2.01	2.12	0.17	1.18	100.41	50.5	94	4.4	215	370	45.5	88.0	11.9	43.5	8.6	1.8	7.2	1.3	6.5	1.5	3.8	0.6	3.7	0.6	428.0	14	35.0	14	0.5	15	3.0	20	12		14.0	75	15	60	15
B-4	60.50	0.88	14.62	6.61	0.10	4.30	8.11	1.99	2.09	0.17	1.02	100.39	41.9	96	7.7	254	399	29.0	68.5	8.4	31.0	6.3	1.5	5.8	1.0	5.1	1.2	3.2	0.5	2.9	0.4	197.0	7	28.5	12	0.5	11	2.5	30			21.0	80	30	95	19
B-5	70.47	0.59	11.63	4.22	0.10	2.91	7.73	1.16	0.50	0.14	0.98	100.43	41.3	56	8.5	244	114	27.5	57.5	7.4	27.0	5.6	1.3	4.9	0.9	4.7	1.1	2.9	0.5	2.6	0.4	171.0	6	26.5	11	1.0	8	2.5	25	13		14.0	80	35	70	14
B-6	68.69	0.67	12.24	4.53	0.12	3.39	6.39	0.64	1.56	0.16	1.20	99.59	46.0	89	13	202	263	37.0	74.0	9.5	35.0	6.7	1.5	6.1	1.1	5.3	1.2	3.2	0.5	2.9	0.4	210.0	7	30.5	11	0.5	10	3.0	15	13		15.0	85	45	55	16
B-8	67.36	0.80	14.30	5.85	0.09	2.65	2.93	2.18	2.62	0.14	1.00	99.92	54.9	132	16	177	484	25.5	80.0	6.2	22.5	4.6	1.3	3.7	0.7	3.9	0.9	2.7	0.4	2.7	0.4	242.0	8	23.0	12	0.5	11	2.5	45	18		18.5	65	30	95	19
B-9	68.12	0.67	11.75	4.49	0.08	3.08	6.14	1.83	2.49	0.14	0.58	99.37	41.1	82	4.4	232	403	33.5	69.5	8.8	32.5	6.6	1.4	5.6	1.0	5.1	1.1	3.1	0.4	2.9	0.4	233.0	8	28.0	10	0.5	10	3.0	15	12		15.0	85	20	60	15

while incompatible elements have lower abundance in mafic compared to felsic rocks, Cullers *et al.* (1997) used these ratios to determine the general characteristics of source regions of sediments. Figure 4 illustrates the range of trace element ratios for sediments derived from silicic and mafic sources (Cullers *et al.* 1997). La/Sc values (Fig. 4a) for the Carrabassett Formation and the Merrimack Trough formations are as low as 0.8 and show good overlap, extending to values as high as 3.6. The lower values fall within the overlap in compositions derived from mafic and silicic sources, suggesting that these formations were derived from intermediate to silicic sources. The Rangeley Formation plots within the silicic provenance range, extending to slightly higher ratios than the Carrabassett and Merrimack sediments. Likewise with Th/Sc values (Fig. 4b): all formations show some samples with intermediate compositions between mafic and silicic sources, but the Rangeley extends to slightly more silicic values. All formations have Th/Co values (Fig. 4c) in the lower range of values for silicic sources. The Cr/Th diagram (Fig. 4d) differs somewhat from the others in that the Merrimack Trough formations are dominated by intermediate values whereas the Carrabassett and Rangeley samples are silicic. On average, the Rangeley Formation has the lowest Cr/Th values, indicating a more consistent silicic source. Even though the Kittery and Carrabassett formations have outboard paleocurrent indicators, there is no distinction in trace element ratios of these formations except that the Kittery has slightly higher Cr/Th values (Fig. 4d) than most of the Carrabassett samples.

Chrondrite-normalized REE diagrams for Carrabassett, Rangeley, Kittery, Eliot, and Berwick formations are plotted in Fig. 5. All the analyses are quite similar and only show subtle differences in slope and in overall REE abundances. The Carrabassett Formation shows the largest range in REE abundances, with LREE between 36 and 158 times chondrite values and $(La/Lu)_N$ values between 2.9 and 13 (Table 2; Fig. 5a). The Rangeley Formation has the highest REE abundances and steepest slopes, with LREE ranging between 120 to 247 times chondrite values (Fig. 5b) and an average $(La/Lu)_N$ value of 10.26. All the Merrimack Trough formations are similar in overall REE abundances and slopes. $(La/Lu)_N$ values are 7.0–9.6 for the Berwick Formation, 6.8–9.9 for the Eliot, and 7.3–9.7 for the Kittery (Fig. 5c, 5d, and 5e). Cullers *et al.* (1997) found that $(La/Lu)_N$ values for sediments derived from silicic rocks range between 3.0 and 27 and mafic rocks between 1.1 and 7.0. The $(La/Lu)_N$ values for our sampled formations, regardless of provenance, lie at the lower range of silicic values, again suggesting mixed or intermediate composition source regions.

Average REE concentrations of the Rangeley and Kittery formations are shown in Fig. 5f. Because the Carrabassett Formation shows a wide range of values, average compositions for samples with LREE > 100 and < 100 times chondrite values are plotted. Also plotted are average values for turbidites from fore-arc, Andean-type arc and passive-margin settings (Taylor and McLennon 1985). The > 100 times chondrite Carrabassett Formation average and the Rangeley and Kittery averages are most similar to passive margin turbidites. The < 100 times chondrite Carrabassett average is more similar to fore-arc turbidites. However, none of the compatible/incompatible element ratios in the Carrabassett Formation (Fig. 4) suggest a mafic component as might be expected in a fore-arc setting. Additionally, all the Carrabassett, Rangeley, and Merrimack samples plot along the trailing edge turbidite field defined by McLennan *et al.* (1993) in the Zr/Sc versus Th/Sc diagram (Fig. 6).

Nd and Sr Isotopic Compositions

Isotopic compositions of Nd and Sr for the metasedimentary rocks of the Central Maine Basin were published by Lathrop *et al.* (1996) and are plotted in Fig. 7 with our analyses of the Merrimack Trough formations (Table 2). Lathrop *et al.* (1996) included one sample of the Carrabassett Formation and two of the Littleton Formation which is thought to be the Carrabassett equivalent in New Hampshire (Moench and Pankiwskyj 1988; Hatch and Moench 1984). All samples plot below bulk-Earth values at ε_{Nd} values between -5 and -10 and Sr_i values ranging from 0.7100 to 0.7170. No significant isotopic difference exists between the Carrabassett/Littleton Formation and the Rangeley Formation which has Laurentian provenance. All

Table 2. Merrimack Trough Nd and Sr Isotopic Compositions.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	E_{Nd} (0 Ma)	E_{Nd} (420 Ma)	T_{DM}	Rb (ppm)
B-1	6.30	31.41	0.1212	0.512058	-11.3	-7.3	1.62	74
B-3	7.96	40.88	0.1177	0.512015	-12.2	-7.9	1.63	94
B-6	6.63	31.83	0.1260	0.512008	-12.3	-8.5	1.80	89
B-9	6.07	30.12	0.1218	0.512069	-11.1	-7.1	1.61	82
E-1	6.36	32.58	0.1181	0.511977	-12.9	-8.7	1.70	74
E-3	5.07	25.85	0.1185	0.511999	-12.5	-8.3	1.67	130
K-6	7.26	37.29	0.1177	0.511981	-12.8	-8.6	1.68	168
K-9	6.16	30.49	0.1221	0.511969	-13.1	-9.1	1.79	117
K-11	5.47	27.03	0.1224	0.512000	-12.4	-8.5	1.74	65

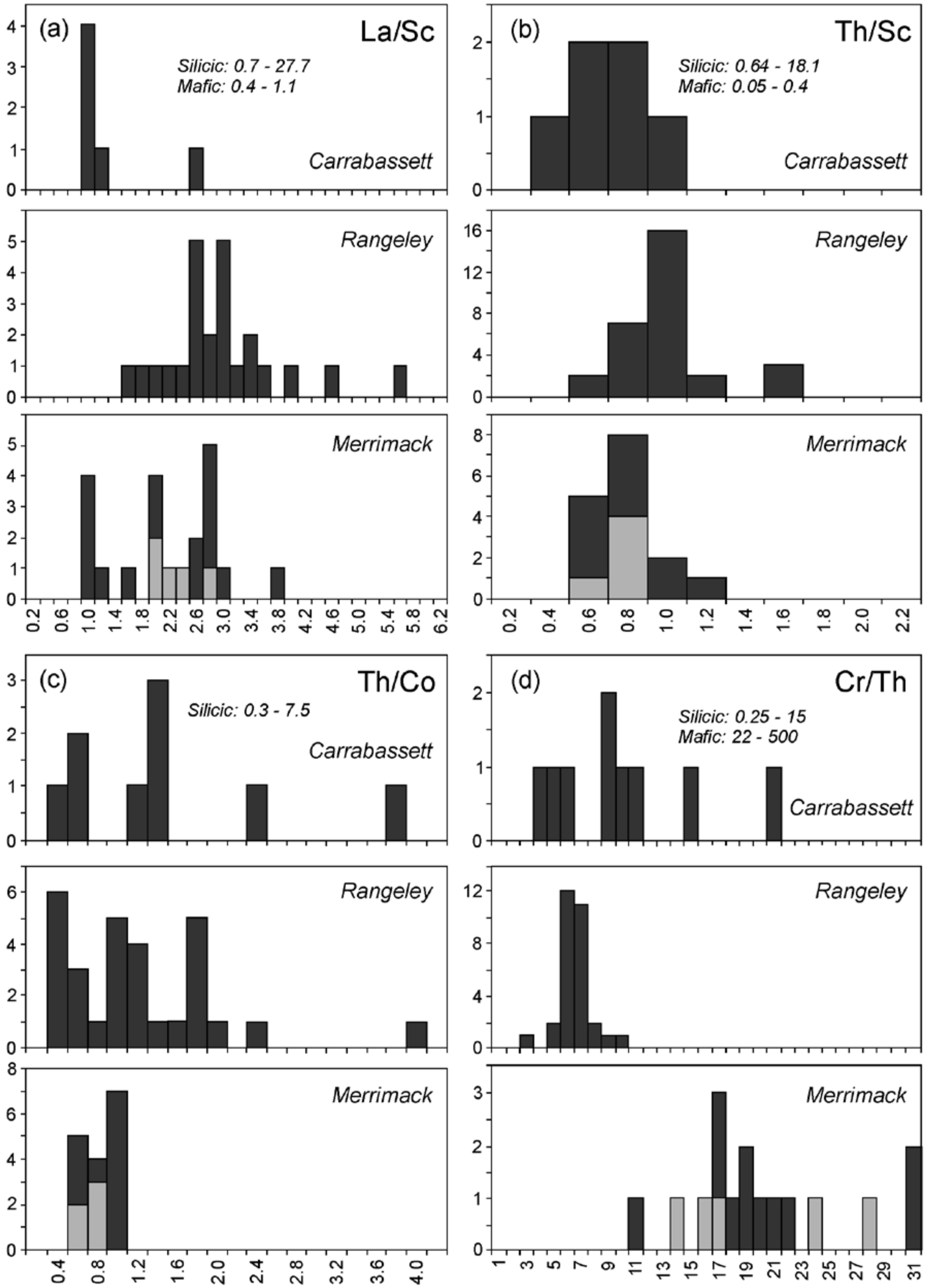

Fig. 4. Histograms of incompatible/compatible element ratios (La/Ca, Fig 4a; Th/Sc, Fig. 4b; Th/Co, Fig. 4c) and compatible/incompatible element ratio (Cr/Th, Fig. 4d). In each histogram, the Carrabassett, Rangeley, and Merrimack Trough formations (Kittery Formation shown in light grey) show similar ratios, plotting at the more mafic end of the silicic range of ratios, suggesting intermediate compositions for the source regions. Silicic and mafic source rock ratios are after Cullers *et al*. (1997).

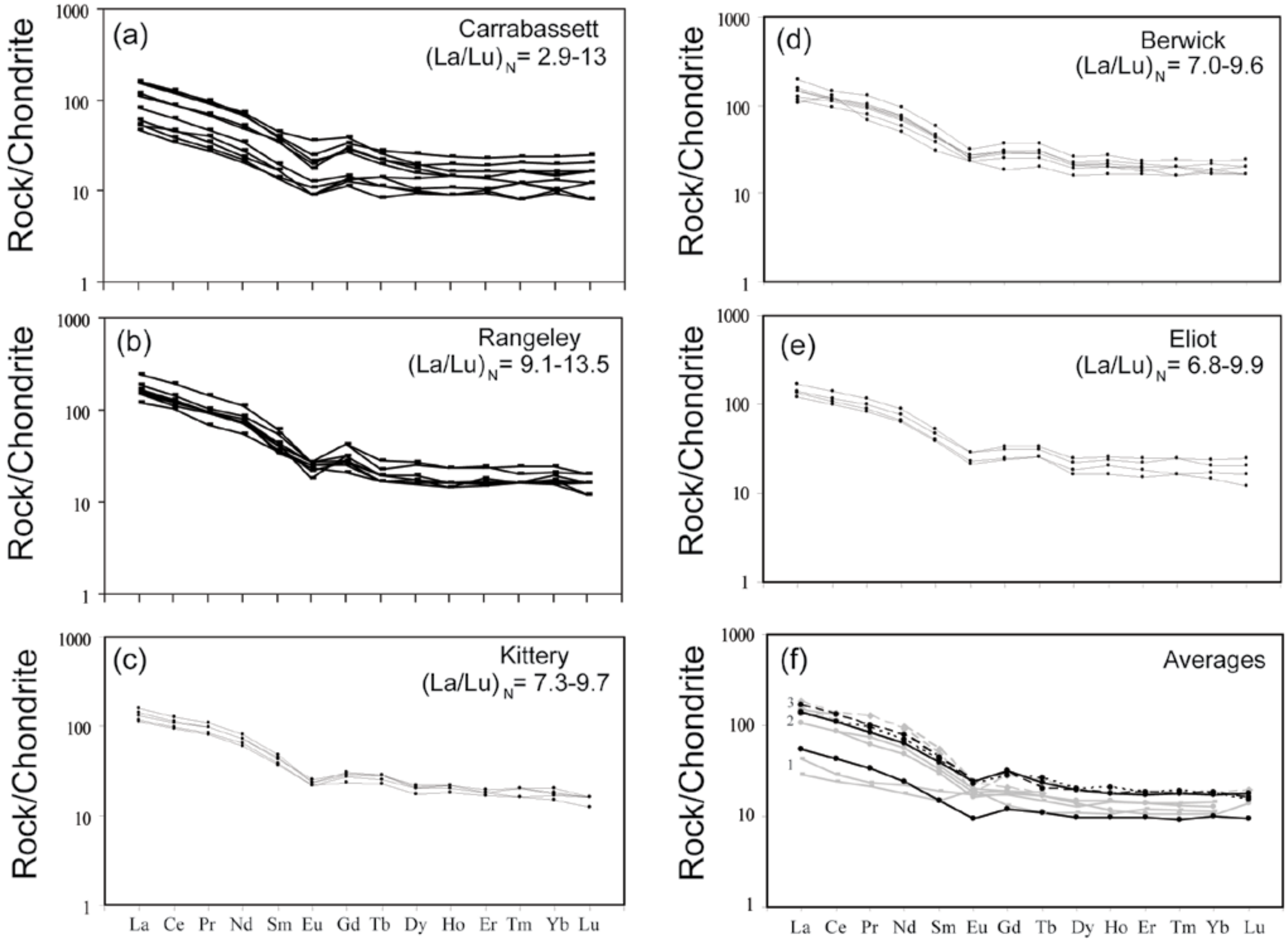

Fig. 5. Chondrite-normalized REE patterns for the Carrabassett, Rangeley and Merrimack Trough formations and averages for each formation. The Carrabassett Formation shows a range of REE enrichment, but the samples with LREE values ~100 times chondrite values are similar to those of the Rangeley and Merrimack Trough formations. Also plotted are REE patterns of average turbidites from fore-arc (1), Andean margin (2), and passive margin (3) settings (Fig. 5c with averages from Taylor and McLennan 1985). The > 100 times Carrabassett average (solid line) and the Rangeley (dashed line) and Kittery (dotted line) averages are most similar to passive margin turbidites. The < 100 times chondritic Carrabassett Formation samples (solid line) are similar to fore-arc turbidites.

Merrimack Trough samples, including those from the Kittery Formation, plot in the Central Maine Basin field, identical to the Carrabassett and Rangeley formation samples. Thus, regardless of whether the Carrabassett and Kittery formations have paleocurrent indicators of an offshore source, their isotopic signatures are no different from the Rangeley Formation metasedimentary rocks that were derived from Laurentia.

Carrabassett/Littleton Formation Nd model ages average 1.7 Ma (Lathrop *et al.* 1996) as do the averages of the formations from the Merrimack Trough (Table 2). Rangeley Formation and other Laurentia-derived formations have Nd model ages that average 1.61 Ma (Lathrop *et al.* 1996). These ages are similar to the non-altered samples of Cullers *et al.* (1997) and Bock *et al.* (2004), suggesting that the samples of Lathrop *et al.* (1996) represent original provenance signatures.

McLennan *et al.* (1993) combined Nd isotopic data with Th/Sc ratios to distinguish active arc and trailing edge turbidites (Fig. 8). Active arc turbidites define the non-quartzose field, comprising sediments that are dominated by mafic sources. The majority of these sediments plot at positive ε_{Nd} and low Th/Sc values. In contrast, turbidites derived from trailing edge settings are quartzose with negative ε_{Nd} values. The Merrimack Trough formations plot in the quartzose field with no distinction between the Kittery Formation and the Eliot/Berwick analyses. Although we lack Nd isotopic data on our Carrabassett Formation samples, they have the same Th/Sc values as the Merrimack metasedimentary rocks and Lathrop *et al.* (1996) reported the same range in ε_{Nd} values for the Littleton as the Merrimack; thus the Carrabassett Formation would plot among the Merrimack samples which are derived from a non-juvenile, quartzose source.

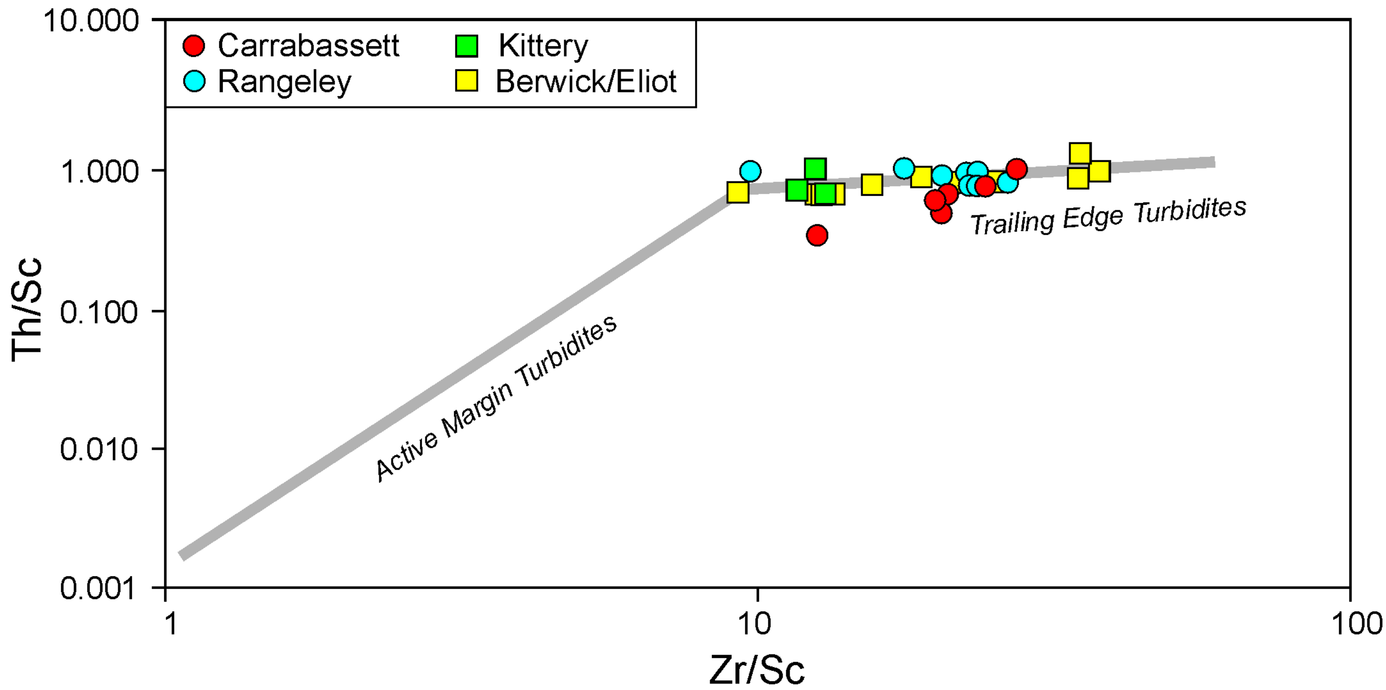

Fig. 6. Zr/Sc versus Th/Sc diagram (after McLennan *et al.* 1993). Carrabassett, Rangeley, Kittery and Berwick/Eliot formations all plot as trailing edge turbidites.

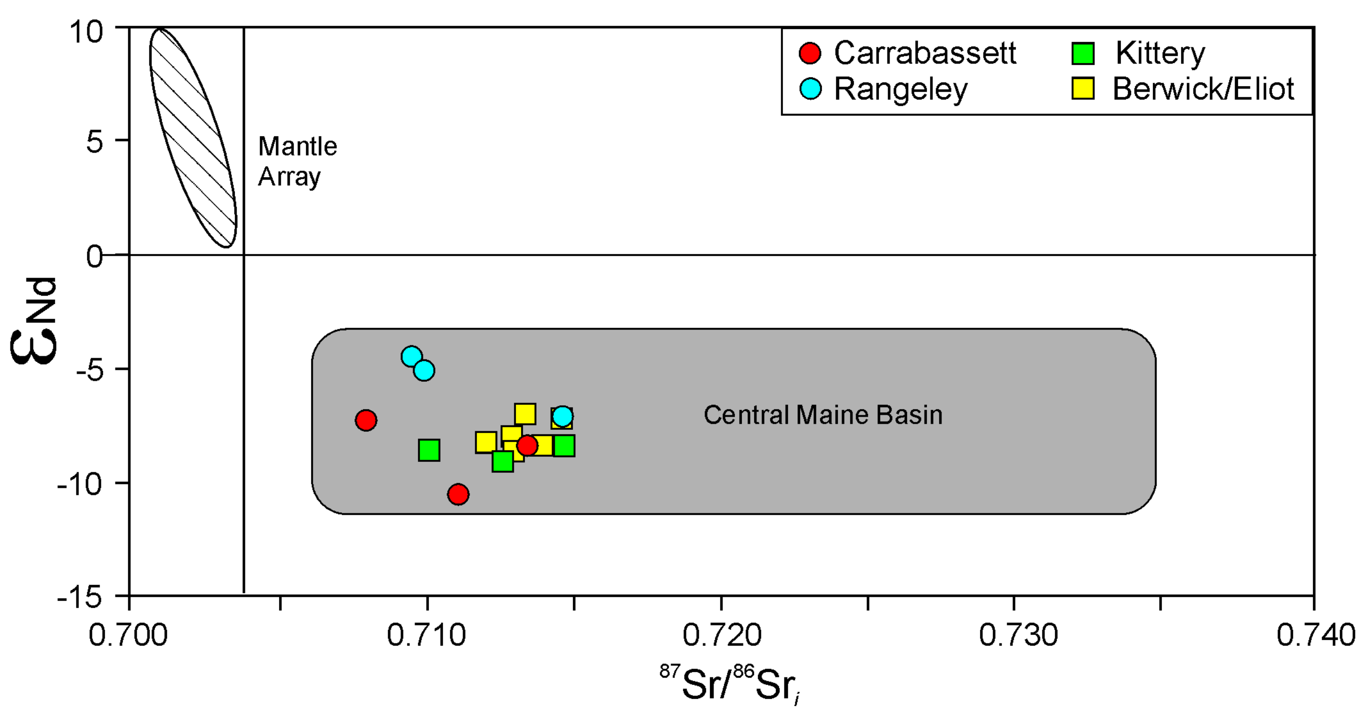

Fig. 7. Initial Sr versus ε_{Nd} (420 Ma) values showing data from the Carrabassett/Littleton Formation and other Central Maine Basin metasedimentary rocks (grey field; data from Lathrop *et al.* 1996). Although paleocurrent data indicate provenance from the east, the Carrabassett Formation has isotopic values identical to Laurentia-derived sediments, suggesting an older mature crustal component in the Carrabassett Formation. Similarly, the Kittery and Berwick/Eliot formations have identical bulk-rock isotopic values.

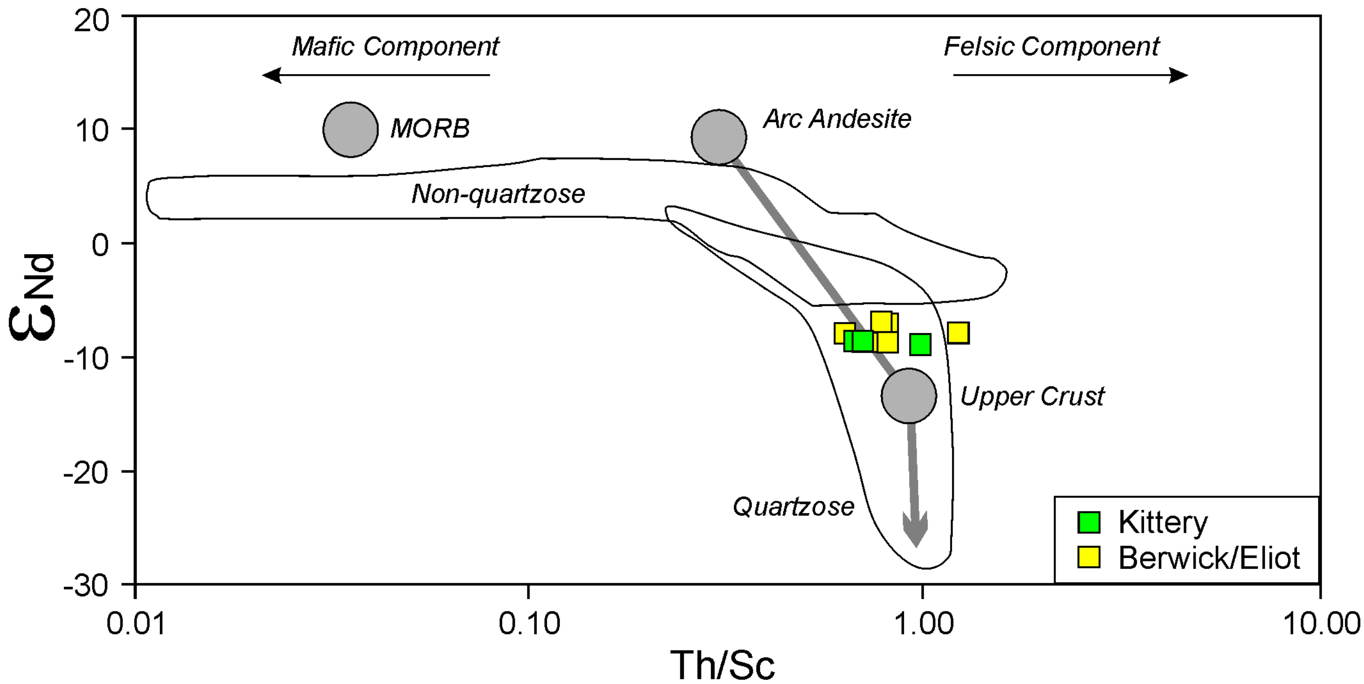

Fig. 8. Th/Sc versus ε_{Nd} diagram (after McLennan *et al*. 1993), with ε_{Nd} calculated at 413 Ma. The Berwick/Eliot and Kittery formation samples plot in the quartzose, upper crustal provenance field. Although no isotopic data for our Carrabassett Formation samples are available, our samples have the same Th/Sc ratios, and the Carrabassett samples of Lathrop *et al.* (1996) have the same ε_{Nd} values, as the Berwick/Eliot and Kittery samples.

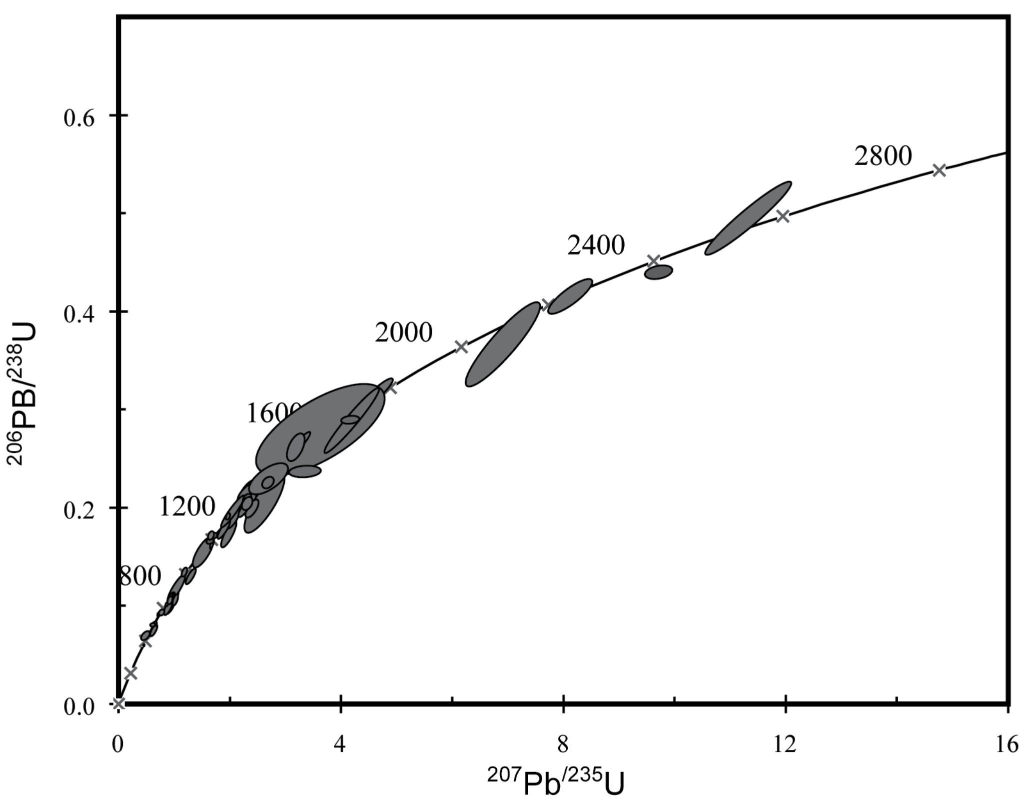

Fig. 9. $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ concordia diagram for the Carrabassett Formation.

Detrital Zircon Geochronology

A plot of $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ for detrital zircons from the Carrabassett Formation is shown in Fig. 9. Plotted data are within ± 10% of concordancy and the data point error ellipses are 1σ. The complete data set is given in Table 3. A relative probability and histogram diagram is plotted in Fig. 10a. A potential Acadian zircon fraction is present with an age of 412 ± 23 Ma. Zircon grains with Taconic-like ages are present also, with ages of 445 ± 29 and 482 ± 12 Ma. A dominant peak is centered at ~600 Ma. The most prominent peak on the diagram ranges from 900 to 1440 Ma, centered at 1200 Ma. Individual grains have older ages of ~1500–1600, 1800, 2080, 2200, and 2600 Ma. The paucity of ~600 Ma and 1490–1610 zircons in Laurentia presents an obvious difference between Laurentia and the Carrabassett Formation (Sampson *et al*. 2005). Likewise, two grains centered around 2280 Ma in the Carrabassett Formation contrast with the absence of grains of that age in Avalonia (Samson *et al*. 2005).

Comparisons of Carrabassett Formation detrital zircons with available zircon ages from Ganderia are presented in Fig. 10b. Ganderia ages are for inherited zircons derived from plutonic rocks and boulders thought to represent the unexposed basement (Roddick and Bevier 1995; van Staal *et al*. 1996), from orthogneisses of the Lyme Dome, Connecticut (Walsh *et al*. 2007), and from metasedimentary rocks east of the Dog Bay Line, Newfoundland (Pollock *et al*. 2007). Good matches are evident between the Carrabassett and Ganderia supracrustal rocks with strong similarities at ~600 Ma and the common peak centered at ~1200 Ma.

Table 3. LA-ICPMS Detrital Zircon Data for the Carrabassett Formation, Maine.

Analyses	$^{207}Pb/^{235}U$	± 1σ	$^{206}Pb/^{238}U$	± 1σ	Rho	$^{207}Pb/^{235}U$ (Ma)	± 1σ	$^{206}Pb/^{238}U$ (Ma)	± 1σ	$^{207}Pb/^{206}Pb$	± 1σ	$^{207}Pb/^{206}Pb$ (Ma)	± 1σ	% conc.
de07A08	0.8252	0.0178	0.0977	0.0016	0.38	610.9	9.9	601.1	9.3	0.0614	0.0013	654.9	45.6	92
de07A09	1.6447	0.0319	0.1604	0.0046	0.73	987.5	12.3	959.1	25.4	0.0733	0.0018	1021.2	45.9	94
de07A15	3.3177	0.2401	0.2340	0.0051	0.15	1485.2	56.5	1355.3	26.5	0.1041	0.0061	1498.9	107.6	90
de07A20	1.9294	0.0333	0.1882	0.0027	0.42	1091.3	11.5	1111.7	14.8	0.0767	0.0011	1113.3	29.3	100
de07A23	1.6611	0.0519	0.1685	0.0026	0.24	993.8	19.8	1003.6	14.1	0.0732	0.0022	1020.8	61.0	98
de07A24	2.2732	0.0631	0.2066	0.0040	0.35	1204.0	19.6	1210.6	21.2	0.0825	0.0013	1257.5	31.6	96
de07A27	4.1297	0.1255	0.2870	0.0037	0.21	1660.2	24.8	1626.5	18.4	0.1069	0.0025	1646.9	42.7	99
de07A28	0.9483	0.0157	0.1082	0.0012	0.33	677.2	8.2	662.6	7.0	0.0663	0.0009	714.5	29.3	93
de07A33	2.2759	0.0832	0.2010	0.0053	0.36	1204.8	25.8	1180.8	28.6	0.0846	0.0032	1307.3	73.9	90
de07A34	0.7311	0.0387	0.0896	0.0026	0.27	557.2	22.7	552.9	15.4	0.0626	0.0017	595.8	58.8	93
de07A35	0.8828	0.0414	0.1018	0.0035	0.36	642.5	22.3	625.1	20.2	0.0623	0.0031	683.0	104.5	92
de07A51	3.1574	0.1283	0.2591	0.0115	0.55	1446.8	31.3	1485.3	58.8	0.0906	0.0052	1438.0	110.1	103
de07A52	0.6643	0.0143	0.0872	0.0012	0.33	517.2	8.7	538.8	7.2	0.0570	0.0012	591.1	45.4	91
de07A57	2.6483	0.0849	0.2226	0.0049	0.34	1314.2	23.6	1295.4	25.8	0.0893	0.0025	1409.8	52.9	92
de07A58	1.5951	0.0505	0.1629	0.0025	0.24	968.3	19.8	972.9	13.8	0.0739	0.0021	1039.6	57.4	94
de07A59	9.6986	0.2020	0.4384	0.0056	0.31	2406.6	19.2	2343.4	25.1	0.1659	0.0019	2516.2	19.5	93
de07A61	1.6287	0.0482	0.1687	0.0034	0.34	981.4	18.6	1005.0	18.6	0.0723	0.0026	994.0	72.6	101
oc02a08	2.6505	0.1441	0.2165	0.0126	0.7947	1314.8	40.1	1263.5	66.9	0.0814	0.0012	1230.3	29.6	103
oc02a09	2.2853	0.1415	0.2130	0.0107	0.6878	1207.7	43.7	1244.7	57.0	0.0775	0.0015	1135.2	39.5	110
oc02a13	1.9623	0.1002	0.1871	0.0084	0.7302	1102.7	34.3	1105.7	45.4	0.0749	0.0011	1066.5	30.4	104
oc02a16	3.3807	0.2466	0.2656	0.0119	0.7048	1499.9	57.2	1518.6	60.6	0.0950	0.0014	1527.7	27.7	99
oc02a17	1.9400	0.1105	0.1702	0.0111	0.8114	1095.0	38.2	1013.1	61.3	0.0746	0.0014	1056.9	37.6	96
oc02a18	2.3298	0.1854	0.2114	0.0102	0.5965	1221.4	56.5	1236.1	54.4	0.0827	0.0019	1262.4	44.8	98
oc02a19	2.4207	0.1340	0.2116	0.0118	0.8149	1248.8	39.8	1237.4	62.9	0.0787	0.0011	1165.4	28.5	106
oc02a20	2.0020	0.1027	0.1862	0.0087	0.6576	1116.2	34.7	1100.9	47.0	0.0741	0.0015	1044.7	41.8	105
oc02a24	2.5732	0.1123	0.2149	0.0079	0.7052	1293.1	31.9	1254.9	41.7	0.0828	0.0014	1263.4	32.4	99
oc02a25	6.8820	0.5480	0.3642	0.0350	0.9065	2096.3	70.6	2002.2	165.2	0.1298	0.0013	2094.8	18.0	96
oc02a32	0.4436	0.0608	0.0660	0.0039	0.5269	372.8	42.8	412.2	23.9	0.0545	0.0016	390.4	65.8	106
oc02a33	0.5877	0.0489	0.0715	0.0048	0.7225	469.4	31.3	445.3	28.8	0.0558	0.0011	445.8	42.6	100
oc02a34	0.9561	0.0655	0.1043	0.0062	0.7499	681.3	34.0	639.8	36.4	0.0621	0.0011	678.7	38.1	94
oc02a37	0.9984	0.1332	0.1143	0.0118	0.8701	703.0	67.7	697.6	68.3	0.0621	0.0010	677.4	33.3	103
oc02a39	0.8848	0.0621	0.0961	0.0061	0.674	643.6	33.5	591.2	36.0	0.0603	0.0014	615.6	49.9	96
oc02a46	0.8416	0.0651	0.0950	0.0062	0.7173	620.0	35.9	584.8	36.6	0.0581	0.0013	533.1	48.8	110
oc02a47	2.5768	0.2926	0.2017	0.0247	0.8104	1294.1	83.1	1184.7	132.6	0.0853	0.0020	1322.2	45.8	90
oc02a48	1.4787	0.1459	0.1513	0.0128	0.7572	921.7	59.8	908.2	71.7	0.0671	0.0015	840.4	48.1	108
oc02a54	2.3666	0.0973	0.1963	0.0078	0.6711	1232.6	29.3	1155.3	41.8	0.0810	0.0013	1221.6	31.4	95
oc02a62	8.0972	0.3297	0.4137	0.0145	0.8406	2241.9	36.8	2231.6	66.3	0.1390	0.0012	2214.8	15.3	101
oc02b03	4.6092	0.2345	0.3143	0.0125	0.9084	1750.9	42.5	1761.6	61.3	0.1079	0.0008	1764.9	13.2	100
oc02b04	3.5973	0.9486	0.2772	0.0381	0.6823	1548.9	209.5	1577.2	192.5	0.1044	0.0020	1704.4	35.9	93
oc02b06	2.6590	0.2839	0.2268	0.0132	0.6439	1317.2	78.8	1317.6	69.3	0.0874	0.0015	1369.5	32.6	96
oc02b12	2.2238	0.0936	0.1959	0.0072	0.8044	1188.6	29.5	1153.3	39.0	0.0799	0.0008	1194.1	19.9	97
oc02b14	4.1626	0.4077	0.2866	0.0271	0.963	1666.7	80.2	1624.4	135.5	0.1035	0.0007	1688.7	13.3	96
oc03a05	0.9035	0.0408	0.1058	0.0034	0.7269	653.6	21.8	648.4	19.6	0.0629	0.0007	703.3	23.0	92
oc03a07	1.8559	0.0943	0.1749	0.0079	0.8471	1065.5	33.5	1039.3	43.2	0.0765	0.0008	1106.9	20.5	94
oc03a08	3.2204	0.1598	0.2627	0.0103	0.916	1462.1	38.5	1503.9	52.4	0.0927	0.0006	1481.5	12.3	102
oc03a11	11.3083	0.6306	0.4939	0.0307	0.9545	2548.9	52.0	2587.4	132.7	0.1671	0.0009	2528.5	9.0	102
oc03b04	0.6002	0.0289	0.0777	0.0020	0.4382	477.4	18.3	482.6	12.0	0.0561	0.0010	458.1	39.2	105
oc03b05	1.1466	0.0504	0.1312	0.0037	0.5195	775.6	23.9	794.8	21.2	0.0648	0.0012	766.5	39.5	104
oc03b08	2.0178	0.1708	0.1936	0.0135	0.9342	1121.5	57.5	1141.1	72.9	0.0798	0.0007	1191.1	18.4	96

DISCUSSION

Bulk-Rock Geochemistry

The above results show that there are no significant bulk-rock geochemical differences between Laurentia-derived sediments as typified by our Rangeley Formation samples and the easterly derived Carrabassett and Kittery formations. The Carrabassett Formation, with an outboard source, has similar trace element ratios as the Rangeley Formation. Likewise, the Kittery Formation, which also has outboard paleocurrent indicators, is no different than the Berwick and Eliot formations of the Merrimack Trough nor is it significantly different from the Laurentia-derived Rangeley Formation. Thus all the formations appear to have been derived from source regions that were neither dominated by mafic rocks such as found in primitive arcs nor exclusively by silicic rocks. Rather, it is plausible that the sediments were produced from large areas that homogenized to an average intermediate composition. The intermediate composition is also supported by REE abundances. The Rangeley, Berwick, Eliot, and Kittery formations and the > 100 times chondritic portion of the Carrabassett Formation all have REE abundances most similar to passive margin turbidites (Fig. 5), an inference supported by the Zr/Sc verus Th/Sc diagram (Fig. 6).

Isotopic data (Fig. 7) show no differences between Central Maine Basin metasedimentary rocks, including the Rangeley Formation, and either the Carrabassett Formation or the Merrimack Trough formations. All the metasedimentary samples fall in a relatively narrow range of ε_{Nd} values between -6 and -10. This range differs considerably from Avalonian granites commonly used to define the basement of Avalonia (Nance and Murphy 1994; Nance *et al.* 2002; Murphy and Nance 2002) in that most of the granites have positive ε_{Nd} values. Many workers have therefore concluded that Avalonia consists primarily of juvenile crust which is isotopically distinct from older materials derived from Laurentia. In contrast, Ganderian plutons tend to have negative ε_{Nd} values of the same range as the

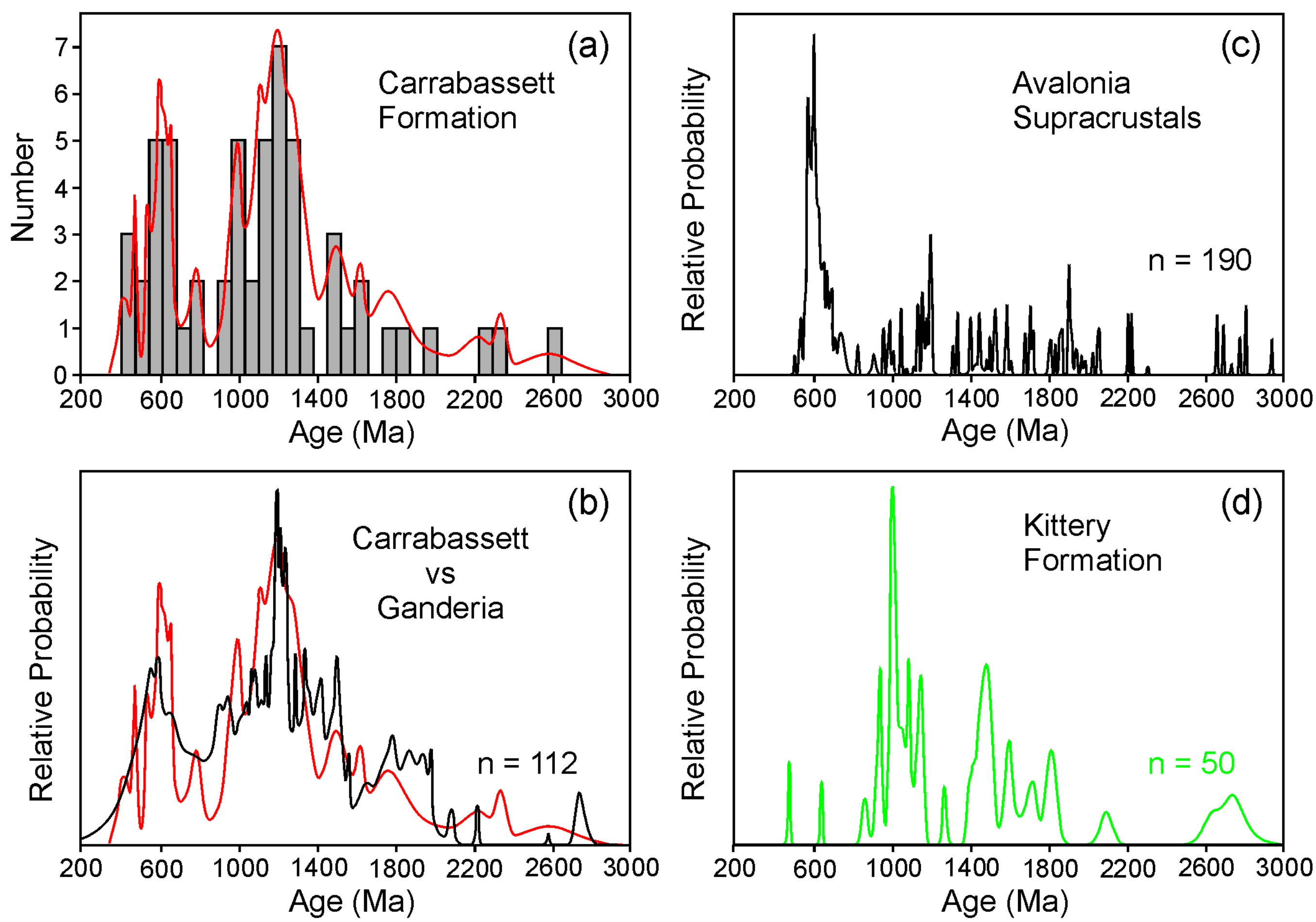

Fig. 10. (a) Histogram and relative probability plot of zircon ages, Carrabassett Formation. (b) Comparison of Carrabassett Formation (red) and Ganderian (black) relative probability plots. Ganderian ages are from Roddick and Bevier (1995), van Staal *et al.* (1996), Walsh *et al.* (2007), and Pollock *et al.* (2007). (c) Relative probability plot of zircon ages from Avalonian metasedimentary rocks (Keppie *et al.* 1998; Barr *et al.* 2003; Murphy *et al.* 2004). (d) Relative probability plot of zircon ages from the Kittery Formation (Wintsch *et al.* 2007).

Carrabassett and Kittery metasedimentary rocks (Roddick and Bevier 1995; van Staal *et al*. 1996). The Nd model ages of the Carrabassett Formation (Lathrop *et al*. 1996) and the Kittery Formation average 1.70 Ma and 1.74 Ma, respectively. These ages are far older than the age of Avalonia, which is dominated by juvenile arc rocks of ~600 Ma and Neoproterozoic model ages (Nance and Murphy 1994; Nance *et al*. 2002; Murphy and Nance 2002), but are similar to Ganderian model ages (Whalen *et al*. 1996, 1997; Schofield and D'Lemos 2000). Thus it appears that both the Carrabassett and Kittery formations potentially match Ganderian but not Avalonian basement.

The picture is complicated when one considers the Neoproterozoic through Cambrian supracrustal rocks associated with Avalonia. A recent study by Satkoski *et al*. (2007) showed that some of the sedimentary cover rocks of the Avalonian Caledonia terrane of New Brunswick have positive ε_{Nd} values and are interpreted as being derived from Avalonian sources. However, other metasedimentary units have negative ε_{Nd} values and were interpreted as originating from a large, isotopically mature source (Samson *et al*. 2000; Murphy 2002; Satkoski *et al*. 2007). These Avalonian supracrustal rocks are interpreted as being derived from older, Gondwanan sources and deposited on Avalonian basement (Satkoski *et al*. 2007). Therefore, based on bulk-rock ε_{Nd} values alone, we cannot exclude the possibility that the Carrabassett Formation could be dominated by recycled Avalonian supracrustal rocks rather than juvenile Avalonian basement. However, the abundance of Avalonian supracrustal rocks with mature crustal signatures appears to be relatively small and the odds of the Carrabassett Formation exclusively representing recycling of such supracrustal rocks seems low. Additionally, the available detrital zircon ages of these supracrustal rocks are considerably different than those of the Carrabassett Formation (compare Fig. 10a with 10c).

It appears that no bulk-rock characteristics, either trace element or isotopic, can clearly distinguish the Laurentia-derived Rangeley from peri-Gondwanan Carrabassett or Kittery formations. As it has been shown that Quaternary sediments sampling large continental masses have remarkably uniform ε_{Nd} values of ~-11 and T_{DM} of 1.9 Ga (Goldstein *et al*. 1984, 1997; Goldstein and Jacobsen 1988), we interpret this lack of unique bulk-rock compositions of sediments derived from Laurentia (Rangeley Formation) and Gondwana (Carrabassett/Kittery formations) as signifying that the formations represent sediments derived from large regions of mature continental crust which homogenized their bulk-rock characteristics. These characteristics differ from the juvenile Avalonian crust, but not necessarily from Avalonian supracrustal rocks.

Geochronology

Although there are similarities between the ages of detrital zircon grains in the Carrabassett Formation and those of Laurentia, a noticeable difference is the paucity of ~600 and 1490 to 1610 Ma zircons in the Laurentian populations, which points to a non-Laurentian component for the Carrabassett Formation sedimentary rocks. The Carrabassett Formation ages cluster at ~1200 Ma, perhaps representing a Grenvillian component derived from Laurentia, but as demonstrated by van Staal *et al*. (1996), such ages are also common in peri-Gondwanan Ganderia. Thus, based on detrital zircon geochronology, a Ganderian source is plausible. Figure 10b compares relative probability plots for Carrabassett Formation zircons with those of Ganderia (Roddick and Bevier 1995; van Staal *et al*. 1996; Pollock *et al*. 2007; Walsh *et al*. 2007). There are strong similarities at 500–700 Ma, 1000–1400 Ma, and ~1750 Ma. These similarities, along with the similar Nd isotopic values and model ages, and a passive margin depositional setting for Ganderia (Williams 1979; van der Pluijm and van Staal 1988) that is also characteristic of the Carrabassett Formation (Fig. 5f and Fig. 6), indicate that Ganderia may have been the source for the easterly derived sediments that became the Carrabassett Formation.

In contrast, the detrital zircon ages from Avalonian metasedimentary rocks (Keppie *et al*. 1998; Barr *et al*. 2003; Murphy *et al*. 2004) shown in Fig. 10c have some similarities to the Carrabassett Formation ages, but are of vastly different proportions. The Kittery Formation of the Merrimack Trough has a relative probability plot that is also different from the Carrabassett Formation, even though Wintsch *et al*. (2007) considered the Kittery Formation to be derived from Gondwana. The Kittery Formation has a prominent peak at ~1000 Ma whereas the most prominent peak in the Carrabassett Formation is at ~1200 Ma. Additionally, the Carrabassett Formation has a well-defined peak at ~600 Ma; the Kittery Formation yielded only one zircon of that age. Therefore, even though the Kittery Formation has an outboard source that may be Gondwanan (Wintsch *et al*. 2007), the detritial zircon ages indicate that this source was different from that of the Carrabassett Formation. This difference may not be a surprise given the up to 70 Ma age difference between the two formations.

Provenance and tectonic setting of the Carrabassett Formation

The criteria for assigning Ganderian provenance to the Carrabassett Formation are summarized in Fig. 11. Although some bulk-rock characteristics match other terranes, one or more mismatches suggest that these terranes were not Carrabassett Formation sources. Paleocurrent indicators suggest an outboard source, suggestive of either Ganderia or Avalonia. Bulk-rock major and trace element concentrations, the bulk-rock Nd isotopic compositions, and the Nd model ages do not discriminate between Ganderian, Avalonian supracrustal, or Laurentian sources because all three of those sources represent mature, continental crust. These parameters do however, eliminate the juvenile arc portion of Avalonia, and since this is the dominant component of Avalonia, these mismatches minimize the possibility of an Avalonian provenance. The detrital zircon ages eliminate Laurentia and the younger juvenile Avalonia as sources. While the Avalonian supracrustal rocks are permissible source rocks for the Carrabassett sediments based on bulk-rock characteristics, the detrital zircon ages of the supracrustal rocks (Barr *et al*. 2003; Samson *et al*. 2005) differ from those of the Carrabassett Formation. In contrast, the detrital zircon ages of the Carrabassett Formation are a good match for Ganderian ages. Thus the only potential source that matches all measured characteristics of the Carrabassett Formation is Ganderia.

A Ganderian provenance is in apparent contrast to tectonic scenarios which indicate that Ganderia was already accreted to Laurentia (~430 Ma, van Staal *et al*. 2004, 2006), apparently serving as basement upon which the sediments of the Central Maine Basin, including the Carrabassett Formation, were deposited. However, the eastern margin of Ganderia may have been exposed in the early Devonian if crustal-scale wedging of Ganderia by Avalonia as proposed for eastern Newfoundland (van der Velden *et al*. 2004) also occurred in northern New England. The likelihood of this scenario is increased by the identification of similar wedging along the Ganderia-Avalonia boundary in southern New England (Aleinikoff *et al*. 2007; Walsh *et al*. 2007).

We envision the wedging of Ganderian crust by the Avalonian indenter to have initiated with the Salinic orogeny in the early to middle Silurian. The closure around Ganderia would have lead to interference among the lithospheric mantles of Laurentia, Ganderia, and Avalonia, apparently resulting in delamination of the lithospheric mantle of Ganderia. During early stages of delamination the mantle likely created a keel, causing subsidence of the basin. To the east, where Ganderian and Avalonian crusts interacted, wedging caused slices of Ganderia to override Avalonia (Wintsch *et al*. 1992). The consequent crustal thickening created relief (Fig. 12). Erosion and transportation yielded sediments with westward paleocurrent directions (Bradley and Hanson 1989, 2002) and geochemical signatures and a detrital zircon suite consistent with a Ganderian passive margin source. Potential specific Ganderian source regions include the Miramichi, a known Ganderian highland at that time (Pickerill and Fyffe 1999), and the Liberty-Orrington and St. Croix sequences (van Staal *et al*. 1996; Tucker *et al*. 2001; Reusch *et al*. 2006).

Provenance and tectonic setting of the Kittery Formation

Wintsch *et al*. (2007) noted that the Kittery Formation contains primarily Mesoproterozoic detrital zircons; only two of their analyses ware younger. Paleocurrent directions from the east and the absence of a significant Ordovician age population in the formation led Wintsch and coworkers to suggest that the formation was derived from peri-Gondwanan sources and deposited in the Fredericton Sea, farther east of the Miramichi arch (Tucker *et al*. 2001). A Fredericton Sea origin for the Kittery sediments could explain the differences in the relative probability plots of the Carrabassett and Kittery formations shown in Fig. 10.

CONCLUSIONS

The Carrabassett Formation of western Maine is the youngest, most widespread pre-Acadian formation of the Central Maine Basin. The sediments were deposited in a northwest-migrating trench slope during the initial stages of the Acadian orogeny and represent a pulse of sediment derived from Ganderia to the east. The detrital zircons in the Carrabassett Formation are most compatible with chronological fingerprints of Ganderia, specifically the dominant population of ages of ~600 Ma and 900–1440 Ma. Both the Carrabassett

	Paleocurrent Indicators	Bulk-rock Major/Trace Elements	Bulk-rock Nd Isotopes	Nd Model Ages	Detrital Zircons
Ganderia	X	X	X	X	X
Juvenile Avalonia	X	—	—	—	—
Avalonia Supracrustals	X	X	X	X	—
Laurentia	—	X	X	X	—

Fig. 11. Matrix diagram showing matches between the bulk-rock major and trace element characteristics, bulk-rock Nd isotopic values, Nd model ages, and detrital zircon ages of the Carrabassett Formation and Ganderia. Carrabassett Formation paleocurrent indicators reflect an outboard source. Although some of these parameters also match other terranes, one or more mismatches complicate either Avalonia or Laurentia as sources.

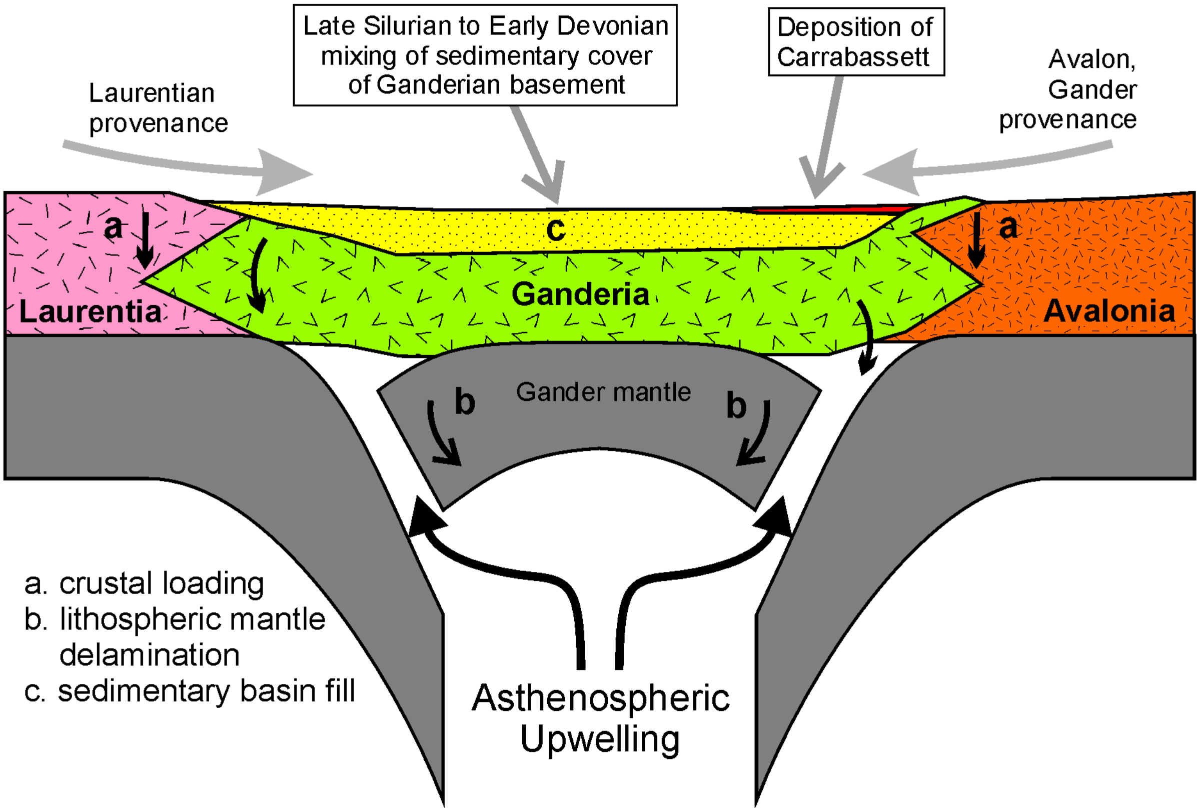

Fig. 12. A schematic diagram showing tectonic wedging of the Ganderian and Avalonian plates to produce the highlands on the Ganderia terrane. The Carrabassett Formation probably represents turbidites shed from these highlands.

Formation and Ganderia have zircons with ages of ~600 Ma and between 2000–2400 Ma, ages that are rare to absent in Laurentia and Avalonia, respectively. REE abundances and Zr/Sc versus Th/Sc ratios suggest trailing edge turbidites for the Carrabassett and Kittery formations, reflecting the passive margin setting of Ganderia.

Carrabassett Formation bulk-rock $\varepsilon_{Nd\,(413\,Ma)}$ values are negative (-8 to -10), unlike the positive values for juvenile Avalonian crust. Similar negative values for Laurentia-derived sediments in the Central Maine Basin (Rangeley Formation) and peri-Gondwana-derived Merrimack Trough sediments indicate the inability of bulk-rock ε_{Nd} values to discriminate Laurentian and Gondwanan sources when sediments were derived form large regions of mature crust. Unless the sedimentary source is restricted to and dominated by juvenile arc detritus such as Avalonian crust, mixing of sediment yields an intermediate crustal composition, as does bulk-rock incompatible/compatible element ratios.

Even though Ganderia was basement to the sediments of the Central Maine Basin, tectonic wedging of Avalonia into Ganderia is inferred to have uplifted Ganderia outboard of the Central Maine Basin, permitting shedding of Ganderia-derived sediments to the west as the first outboard pulse of sediment. We infer that the collision of Avalonia with the Taconic- and Salinic-modified Laurentian margin did indeed cause the Acadian orogeny in New England, but because the leading edge of Avalonia wedged mid-crustal Ganderia, the portion of Avalonia that experienced Acadian metamorphism lies beneath Ganderian rocks in eastern New England.

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Editorial responsibility: Sandra M. Barr

Appendix A. Sample locations for bulk-rock analyses based on best estimates from Google Earth.

Sample	Latitude	Longitude
Carrabassett Formation		
H-2	45°22'08.69"N	69°26'12.00"W
H-3	45°22'08.69"N	69°26'12.00"W
H-5	45°18'14.05"N	69°26'09.13"W
H-6	45°18'14.05"N	69°26'09.13"W
H-7	45°18'14.05"N	69°26'09.13"W
H-8	45°18'14.05"N	69°26'09.13"W
H-9	45°16'16.01"N	69°28'56.98"W
H-10	45°16'16.01"N	69°28'56.98"W
H-11	45°22'08.69"N	69°26'12.00"W
Rangeley Formation		
R-2-1	43°27'42.29"N	71°40'19.05"W
R-2-2	43°27'42.29"N	71°40'19.05"W
R-3-1	43°27'42.29"N	71°40'19.05"W
R-3-2	43°27'42.29"N	71°40'19.05"W
R-5-1	43°23'00.61"N	71°26'29.31"W
R-5-2	43°23'00.61"N	71°26'29.31"W
R-6-1	43°23'00.61"N	71°26'29.31"W
R-6-2	43°23'00.61"N	71°26'29.31"W
R-6-3	43°23'00.61"N	71°26'29.31"W
Madrid Formation		
H-12	45°04'07.44"N	69°54'21.80"W
H-13	45°04'06.96"N	69°54'20.99"W
H-14	45°04'06.92"N	69°54'20.43"W
H-15	45°04'05.74"N	69°54'18.10"W
H-16	45°04'05.11"N	69°54'15.63"W
H-19	44°57'27.64"N	69°52'13.27"W
H-20	44°57'27.64"N	69°52'13.27"W

Sample	Latitude	Longitude
Eliot Formation		
E-1	42°52'12.25"N	70°58'41.32"W
E-2	42°52'12.25"N	70°58'41.32"W
E-3	42°52'12.25"N	70°58'41.32"W
E-4	42°52'12.25"N	70°58'41.32"W
Kittery Formation		
K-1	43°05'28.42"N	70°51'55.75"W
K-4	43°14'40.28"N	70°35'27.76"W
K-6	43°14'40.28"N	70°35'27.76"W
K-9	43°17'14.97"N	70°34'12.78"W
K-11	43°33'30.57"N	70°12'18.45"W
K-12	43°33'30.57"N	70°12'18.45"W
Berwick Formation		
B-1	42°52'12.25"N	71°20'37.44"W
B-2	42°52'10.60"N	71°20'37.07"W
B-3	42°52'10.60"N	71°20'37.07"W
B-4	42°52'10.60"N	71°20'37.07"W
B-5	42°53'59.80"N	71°18'18.43"W
B-6	42°53'59.80"N	71°18'18.43"W
B-8	42°58'54.34"N	71°13'17.24"W
B-9	43°00'01.50"N	71°10'33.21"W

