Timing and tectonic setting of Ordovician volcanic rocks of the Miramichi terrane in eastern Maine, USA, and southwestern New Brunswick, Canada†

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ABSTRACT

New U-Pb LA-ICP-MS ages and geochemical data from volcanic rocks in the southwestern part of the Miramichi terrane in Maine, USA, and the Eel River area, New Brunswick, Canada, indicate that calc-alkaline continental arc volcanism began in the earliest Ordovician (ca. 480 Ma) and continued into the Middle Ordovician (at least as late as ca. 463 Ma). The overlap of volcanic rock ages from the Greenfield (ca. 478–463 Ma) and Danforth, Maine (ca. 467–475 Ma), and Eel River, New Brunswick (ca. 480–468 Ma), segments of the terrane confirm previously uncertain correlations of the Olamon Stream (Greenfield), Stetson Mountain (Danforth), and Porten Road and Eel River (Eel River) formations in these areas. The youngest Middle Ordovician ages overlap those of the oldest units of the Tetagouche Group in northern New Brunswick which are attributed to crustal extension leading to opening of the Tetagouche back-arc basin.

Silicic and mafic Tetagouche Group rocks plot in within-plate fields on tectonic discrimination diagrams, distinctly different from the volcanic arc fields for the coeval silicic and mafic rocks in the two Maine segments and the Eel River segment in New Brunswick. Continental arc volcanism in the southwestern Miramichi terrane did not cease when arc extension/rifting leading to formation of the Tetagouche back-arc basin began at ca 470 Ma in New Brunswick, as proposed in a previous model that invoked a single migrating arc. Instead, southwestern Miramichi volcanism had extended from at least ca. 480 to 463 Ma—incompatible with short-lived Meductic-phase arc volcanism (ca. 476–472 Ma) proposed in that model.

RÉSUMÉ

De nouvelles datations U–Pb par LA-ICP-MS et des données géochimiques provenant de roches volcaniques de la partie sud-ouest du terrane de Miramichi dans le Maine, aux États-Unis, et dans le secteur de la rivière Eel, au Nouveau-Brunswick, Canada, révèlent que le volcanisme d'arc continental calcoalcalin a commencé au tout début de l'Ordovicien (il y a environ 480 Ma) et s'est poursuivi jusqu'à l'Ordovicien moyen (au moins jusqu'à environ 463 Ma). Le chevauchement des âges des roches volcaniques des segments de Greenfield (environ 478 à 463 Ma) et Danforth, Maine, (environ 467 à 475 Ma) et de la rivière Eel, Nouveau-Brunswick, (environ 480 à 468 Ma) du terrane confirme des corrélations auparavant incertaines entre les formations d'Olamon Stream (Greenfield), de Stetson Mountain (Danforth), de Porten Road et d'Eel River dans ces secteurs. Les âges les plus récents de l'Ordovicien moyen chevauchent ceux des unités les plus anciennes du Groupe de Tetagouche dans le nord du Nouveau-Brunswick, attribuées à une extension crustale ayant conduit à l'ouverture du bassin arrière-arc de Tetagouche.

Les roches siliceuses et mafiques du Groupe de Tetagouche se situent sur les schémas de discrimination tectonique dans des champs intraplaques nettement différents des champs d'arc volcanique des roches siliceuses et mafiques contemporaines des deux segments du Maine et du segment de la rivière Eel au Nouveau-Brunswick. Le volcanisme d'arc continental dans le terrane sud-ouest de Miramichi ne s'est pas interrompu au début de l'extension / du rifting de l'arc ayant abouti à la formation du bassin arrière-arc de Tetagouche, vers 470 Ma, au Nouveau-Brunswick, comme l'avançait un modèle précédent invoquant un arc migratoire unique. Le volcanisme dans le sud-ouest de Miramichi s'est plutôt prolongé d'au moins 480 à 463 Ma, ce qui est incompatible avec le volcanisme d'arc de la phase de courte durée de Meductic (environ 476 à 472 Ma) avancé dans ce modèle.

[*Traduit par la redaction*]

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INTRODUCTION

The Miramichi terrane is the most extensive Cambrian–Ordovician tract in Maine and New Brunswick (Fig. 1), and its volcanic rocks have been key to the timing of subduction and evolution of island arc systems in numerous tectonic models (e.g., van Staal *et al.* 2016; Ludman *et al.* 2021; Fyffe *et al.* 2023a). It is therefore surprising that so few have been dated directly; indeed, initiation of the early Meductic phase of arc evolution (van Staal *et al.* 2016) is based on a single U–Pb zircon age from the base of the eponymous Meductic Group, New Brunswick (Mohammadi *et al.* 2019), and the duration of that event is poorly constrained by sparse fossil evidence.

Models describing the tectonic role of Miramichi volcanic rocks have been based almost entirely on information from New Brunswick (e.g., van Staal *et al.* 2016; Fyffe *et al.* 2023a) because data have only recently become available for the southwestward extension of the terrane in eastern Maine (Ludman *et al.* 2021; Ludman 2023). Prior to this project, only four ages had been reported for the entire southwestern two-thirds of the Miramichi terrane, three from east-central Maine and one from southwestern New Brunswick.

The goal of this study was to remedy that scarcity in order to resolve questions about the correlation of volcanic rocks among the southwesternmost Eel River, Danforth, and Greenfield segments of the terrane; the initiation and duration of volcanism; and its role in regional tectonic evolution. This paper presents the first ages of Ordovician volcanic rocks from the Danforth segment of the Miramichi terrane and additional ages from the Greenfield and Eel River segments in Maine and New Brunswick, respectively (Fig. 1).

TECTONIC CONTEXT

The lithotectonic framework of the northern Appalachians (Fig. 2a) reflects the closure of the Iapetus and Rheic oceans and progressive accretion to ancestral North America (Laurentia) of microcontinental crustal fragments that had rifted from the Gondwanan margin in the late Neoproterozoic to Early Cambrian (e.g., Ganderia and Avalonia; van Staal and Barr 2012; Fig. 2b). Each accretionary episode was accompanied by an orogenic event (Table 1) and current relationships were set by the Late Devonian. The late Paleozoic Alleghanian orogeny, the climactic event in the central and southern Appalachians, had little impact on the study area.

Following the seminal works of Williams (1995) and Hibbard *et al.* (2006), modelers of northern Appalachian orogen tectonics considered the Munsungun–Winterville terrane to be the leading edge of Ganderia, including two of the authors of this paper (e.g., Fyffe *et al.* 2011; van Staal *et al.* 2016; Keppie *et al.* 2021; Ludman and Whittaker 2023); however, Wang and Pollock. (2023) and Ludman *et al.* (2024) demonstrated that it is more likely peri-Laurentian and that the suture between Laurentia and Ganderia lies between the Munsungun–Winterville and Weeksboro–Lunksoos Lake terranes, as shown in Fig. 1.

The Miramichi terrane lies in the centre of the Ganderian microcontinent and its arc, rifted arc, and back-arc volcanic rocks record the subduction of Iapetan oceanic lithosphere leading to accretion of Ganderia to Laurentia. Researchers in Maine and New Brunswick agree that Miramichi volcanism occurred in a continental arc above an east-dipping subduction zone (Sayres 1986; Winchester *et al.* 1992; Fyffe *et al.* 2011; van Staal *et al.* 2016; Ludman *et al.* 2021; Fyffe *et al.* 2023a).

GEOLOGIC SETTING

Late-stage high-angle faults typically separate the Miramichi terrane from adjacent younger rocks, except for unconformable relationships in parts of northern New Brunswick (Wilson 2017). In addition, faults and large plutonic complexes divide the Miramichi terrane, from northeast to southwest, into the Tetagouche and Eel River segments in New Brunswick and the Danforth and Greenfield segments in Maine, (Figs. 1, 3; Fyffe *et al.* 2011; Ludman and Whittaker 2023). The resulting isolation of these segments makes it difficult to trace major structural features along the length of the terrane, correlate stratigraphic units, and assess their tectonic significance.

The four segments share a common pre-volcanic foundation comprising an Upper Cambrian to Lower Ordovician, largely quartzofeldspathic basal clastic unit overlain by anoxic shales and siltstones (Fig. 4). Overlying volcanic units are also similar in the three southwestern segments, where Lower to early Middle Ordovician calc-alkaline basalt-andesite-rhyolite suites indicate subduction-related volcanic arc activity. In contrast, Middle Ordovician tholeiitic rocks in the northernmost Tetagouche segment record a later episode of rifting that created a back-arc basin with oceanic lithosphere preserved in the Elmtree inlier (Fig. 1). The Tetagouche segment is also unique in that contacts between pre-volcanic and volcanic units are, at least locally, unconformable rather than conformable as reported in the three other segments (van Staal *et al.* 2003). Simplified geological maps of the volcanic and pre-volcanic strata in the Greenfield (a) and Danforth (b) segments are shown in Figure 5.

Differences among the three southwestern segments include:

(i) Whereas fossils and systematic compositional changes make it possible to define a stratigraphic sequence for the volcanic rocks in the Eel River segment, no diagnostic fossils have been found in the Danforth and Greenfield segments. In the latter, volcanic chemistry is heterogeneous, and it is difficult to even identify primary layering in most of the fine-grained tuffs.

(ii) Sayres (1986) suggested an internal stratigraphy for the Stetson Mountain Formation in which basal cryptocrystalline felsic and intermediate tuffs are overlain by an Fe-Mn horizon and then by coarser felsic and

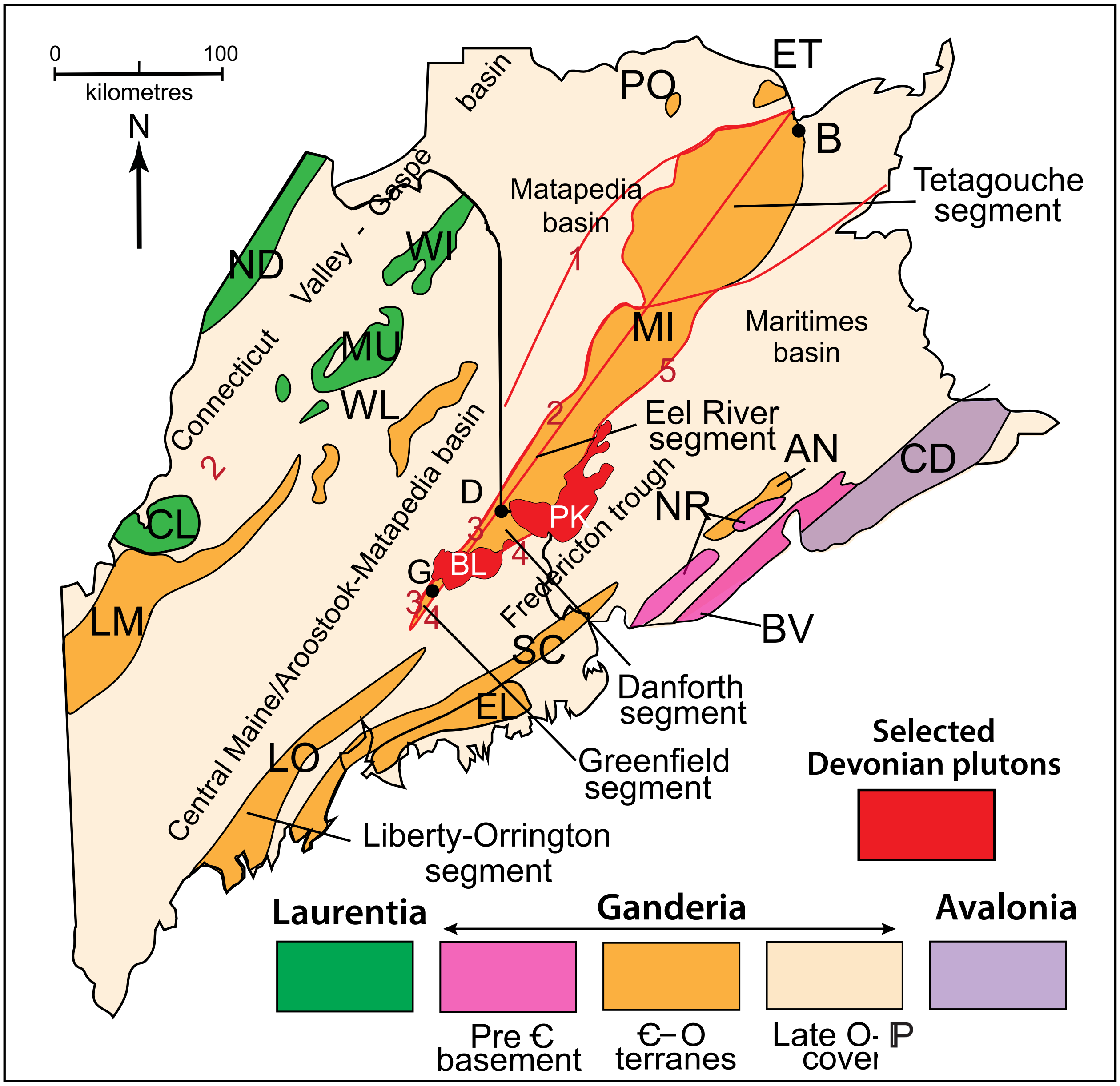

Figure 1. **Lithotectonic framework of New Brunswick and Maine. Modified from Ludman and Whittaker (2023) and Fyffe *et al.* (2023a, b). Attribution of Munsungun–Winterville and Chain Lakes terranes to Laurentia after Wang and Pollock. (2023) and Ludman *et al.* (2024). Abbreviations *Peri-Laurentian terranes*: CL-Chain Lakes; MU-Munsungun; ND-Notre Dame; WI-Winterville; *Ganderian terranes*: AN-Annidale; BV-Brookville; EL-Ellsworth; ET-Elmtree; LM-Lobster Mountain; LO-Liberty–Orrington; MI-Miramichi; NR-New River; PO-Popelogan; SC-St. Croix; WL-Weeksboro–Lunksoos Lake. *Avalonian terrane*: CD-Caledonia. Faults: 1-Rocky Brook-Millstream; 2-Catamaran–Woodstock; 3-North Bancroft; 4-Codyville; 5-Bamford Brook–Hainesville. *Plutonic complexes*: BL-Bottle Lake; PK-Pokiok. *Towns*: *B-Bathurst; D-Danforth; G-Greenfield.***

andesitic lavas, agglomerates, and volcaniclastic sedimentary rocks.

(iii) Cryptocrystalline felsic tuffs are the dominant lithology in the Olamon Stream Formation, and are interlayered with lava flows and sparse coarse agglomerates. Contacts between the volcanic rocks and the Greenfield member manganiferous siltstone appear to be gradational, but stratigraphic relationships are uncertain.

(iv) Volcanic rocks in the Eel River and Danforth segments are overlain unconformably by anoxic shales and grits of the Belle Lake and Mill Priveledge Brook formations, respectively. Unfortunately, there is no evidence for what might lie above the Olamon Stream Formation in the Greenfield segment.

(v) Basalts occur in all three Meductic Group formations in the Eel River segment, increasing in abundance upward from the Porten Road to the Eel River and becoming the dominant lithology in the Oak Mountain

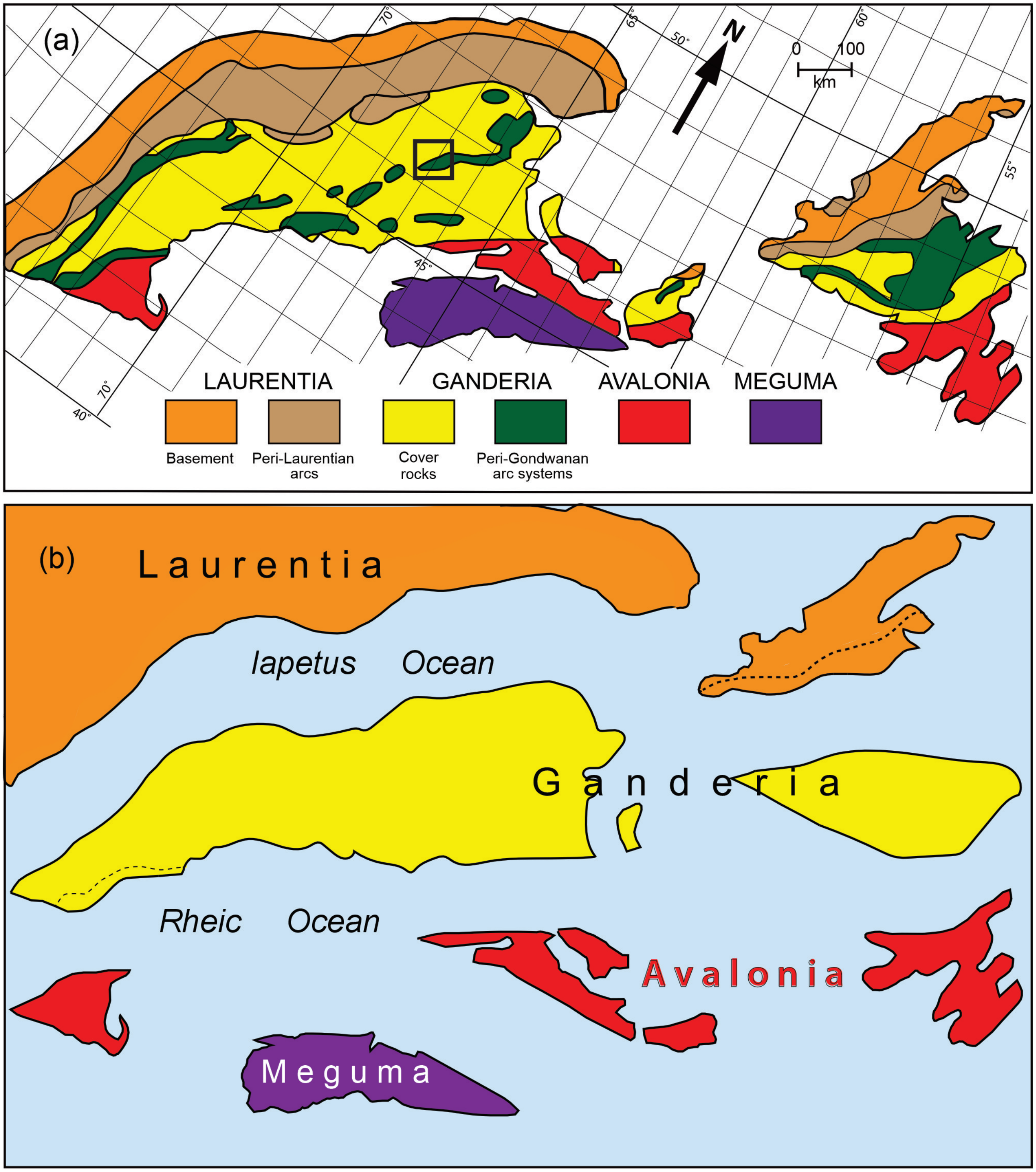

Figure 2. Evolution of the tectonic framework in the northern Appalachian orogen. The black square outlines the Miramichi terrane in Maine. (a) Tectonostratigraphic framework of the northern Appalachian orogen after Hibbard *et al.* (2006), but see Figure 1 for recent reinterpretation (Wang and Pollock 2023; Ludman *et al.* 2024) (b) Microplate fragments from supercontinent Rodinia prior to accretion to ancestral North America (after Ludman *et al.* 2021).

Formation. Basalts are absent from the Danforth segment and crop out in a small area isolated from the rest of the Olamon Stream Formation in the Greenfield segment so that their stratigraphic position is unknown.

PREVIOUS DATING IN MAINE AND SOUTHWESTERN NEW BRUNSWICK

Until recently, no volcanic rocks in the Eel River, Danforth, and Greenfield segments had been dated directly. The

Table 1. Northern Appalachian orogenic history (after Ludman *et al.* 2021).

AGE	OROGENY	TECTONIC EVENTS
Permian	Alleghanian	Gondwana accreted to previously amalgamated plates, forming supercontinent Pangea.
Late Devonian	Neoacadian	Meguma accreted to previously amalgamated plates
Early Devonian	Acadian	Avalon accreted to previously amalgamated plates
Middle to Late Silurian	Salinic B	Tetagouche back-arc basin closes, reuniting trailing edge of Ganderia with previously amalgamated leading edge
Latest Ordovician–Early Silurian	Salinic A	High-P, Low T deformation of Brunswick subduction complex during closing of Tetagouche back-arc basin
Late Ordovician	"Taconian"[1]	Leading edge of Ganderia collides with Laurentia
Early–Middle Ordovician	Penobscot	Miramichi continental arc develops during eastward subduction of Iapetus crust. Rifting and seafloor spreading create extensive Tetagouche back-arc basin
Cambrian–Ordovician		Ganderian components (Miramichi, Annidale) reunited near trailing edge of Ganderian microcontinent
Cambrian–Early Ordovician		Ganderia rifted from Gondwana, drifts toward Laurentia, and is fragmented by extension dring Iapetan subduction producing island arcs and back-arc basins
Latest Neoproterozoic		Breakup of Rodinia; opening of Iapetus Ocean
Neoproterozoic ca. 1Ga	Grenville	Assembly of supercontinent Rodinia

[1]This event is referred to commonly as the Taconic orogeny (e.g., Fyffe *et al* . 2023) but New Brunswick and Maine are far from the Taconic system in Massachusetts and New York. Although the two events are in part coeval, the nature of their deformation is different and, rather than adding a new name to the orogenic lexicon, we refer to this event in Maine and New Brunswick simply by its timing—Middle Ordovician.

first report from these segments was an age of 480 ± 3 Ma for a rhyolite at the base of the Porten Road Formation in the Eel River segment (Mohammadi *et al.* 2019). Two years later, Ludman *et al.* (2021) reported the first ages from the Greenfield segment—three samples of the Olamon Stream Formation between ca. 467 and 470 Ma—but failed in attempts to date samples from the Danforth segment.

Unfortunately, these initial ages generated more questions than answers. For example, the Porten Road and Olamon Stream formations are similar lithologically, lie conformably on very similar Cambrian–Ordovician strata (Fig. 4), and are typically correlated (van Staal *et al.* 2016; Ludman 2023; Fyffe *et al.* 2023b), but the measured ages of the Olamon Stream Formation (ca. 467 to 470 Ma) were 10 to 13 million years younger than the single date from the purportedly correlative Porten Road Formation.

SAMPLING AND ANALYTIC TECHNIQUES

Sampling in the summer of 2023 was designed to address the uncertainties mentioned above. In the Danforth segment, six fine-grained tuffs were collected in the western part of the Stetson Mountain Formation crop belt to resolve correlation issues with the Greenfield and Eel River segments. Coarse agglomerates that comprise much of the eastern part of the Stetson Mountain outcrop belt contain exotic volcanic and sedimentary rock fragments and were not sampled because of potential problems of mixed ages. Greenfield segment sampling sites were selected to achieve the broadest possible geographic distribution. A second attempt was made to date the Olamon Stream mafic member.

Attempts were also made in New Brunswick to date the two lowest units in the Meductic Group—a Porten Road dacite and Eel River andesite and basalt, to clarify correlation with Miramichi volcanic rocks in Maine and estimate the duration of Meductic phase volcanism.

Chemical analyses

Whole-rock chemical analyses of the samples were conducted for comparison with previously published data from the Eel River (Dostal 1989; Fyffe 2001; McClenaghan *et al.* 2006) and Maine suites (Sayres 1986; Ludman *et al.* 2021). Samples were analyzed by fusion mass spectrometry—New Brunswick samples by Activation Laboratories Ltd in

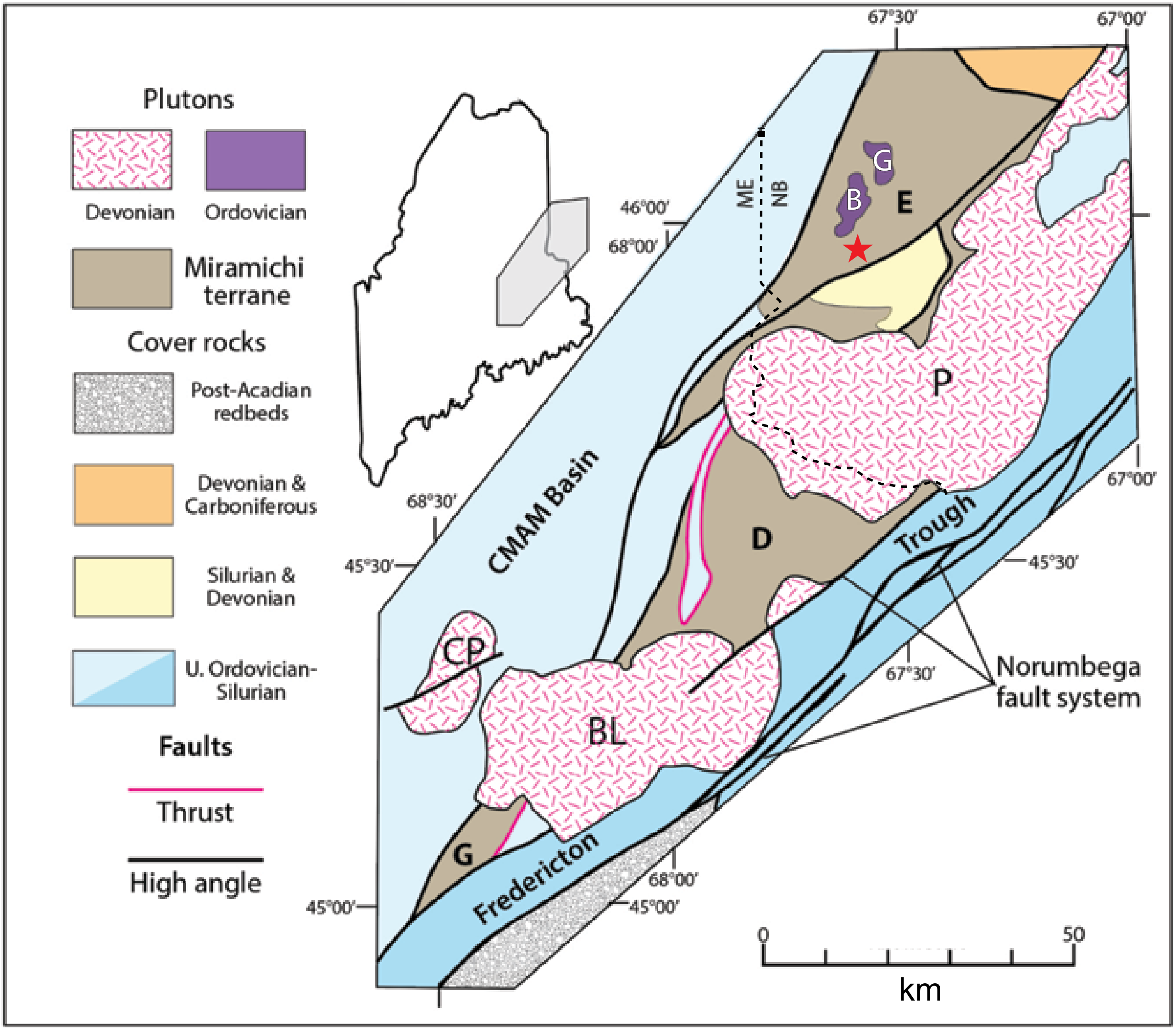

Figure 3. Interruption of the Eel River (E), Danforth (D), and Greenfield (G) segments of the Miramichi terrane by the Devonian Pokiok (P) and Bottle Lake (BL) plutonic complexes. Red star indicates locations of dated samples NBV-1 and NBV-2. Abbreviations: CP-Center Pond pluton. *Ordovician plutons*: B-Benton; G-Gibson. CMAM= Central Maine/Aroostook-Matapedia basin. Modified after Osberg *et al.* (1985) and New Brunswick Department of Natural Resources and Energy (2008).

Ancaster, Ontario, Canada, and Maine samples by ALS Geochemistry in Reno, Nevada, USA.

U–Pb analytical methods

Samples from the Olamon Stream, Porten Road, and Eel River formations were sent to Overburden Drilling Management in Ontario, Canada, for electric pulse disaggregation and preliminary mineral separation. Final separation and LA-ICP-MS analyses were conducted at the University of New Brunswick Geochronology Centre using methods described in Fyffe *et al.* (2023b). The other Maine samples were processed by GeoSeps Services in Idaho and LA-ICP-MS analyses carried out at Washington State University using methods described by Bradley *et al.* (2009), Hults *et al.* (2013), and Moore *et al.* (2015).

RESULTS

Chemistry of the dated samples

Compositions of the 2023 Maine and New Brunswick samples are shown in Table 2 and are compared (Fig. 6) with previously reported data from the Greenfield (Ludman *et al.* 2021), Danforth (Sayres 1986; Ludman *et al.* 2021) and Eel River (McClenaghan *et al.* 2006) formations. Major element data confirm that the new samples are representative of their

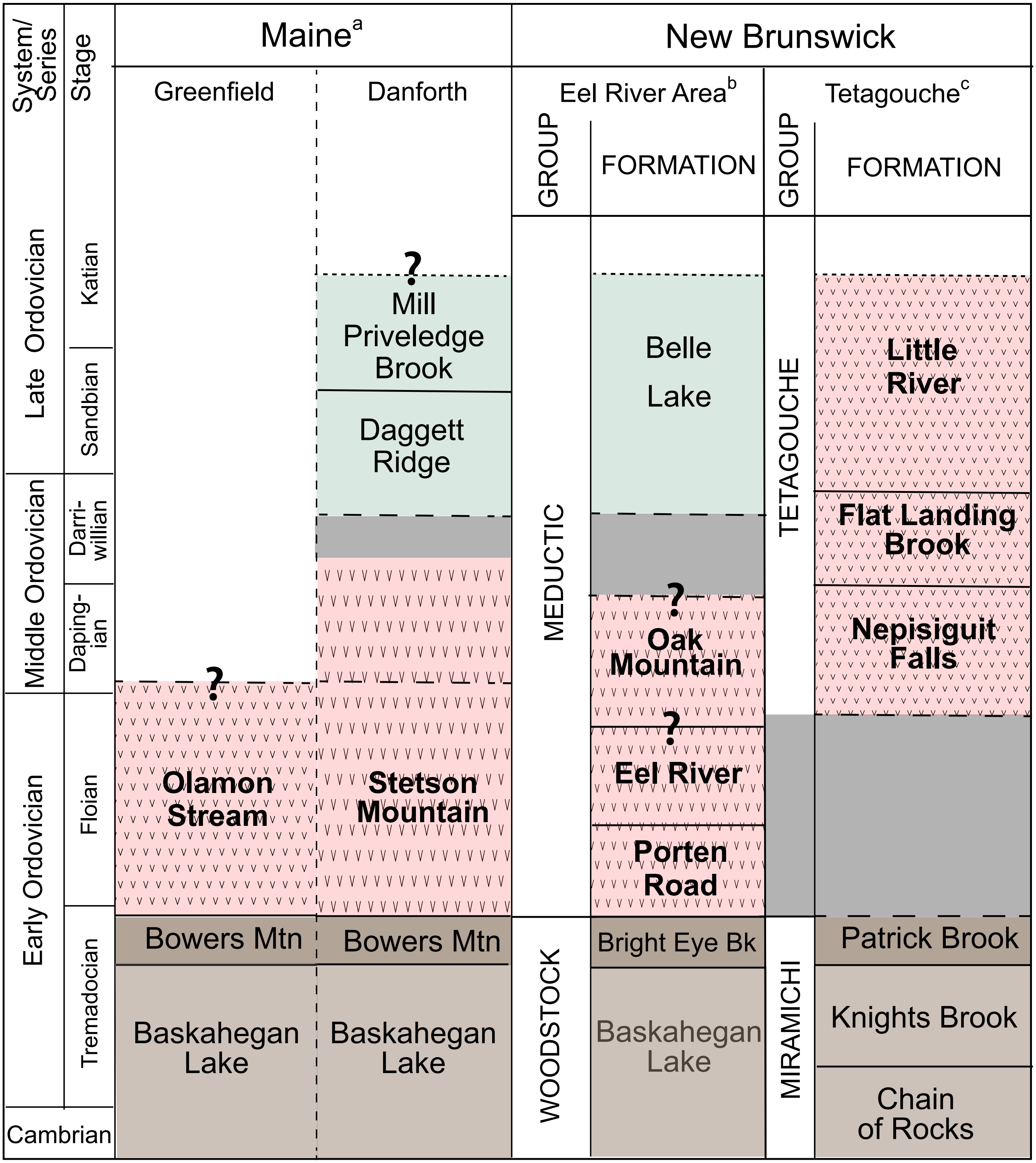

Figure 4. Stratigraphy of the four Miramichi segments. For simplicity, stratigraphy of only the Bathurst sub-basin of the Tetagouche area is shown. [a] Ludman (2023); [b] Fyffe (2001); [c] Rogers and van Staal (2003). Patterns indicate dominantly volcanic formations discussed below. Dashed lines indicate unconformities.

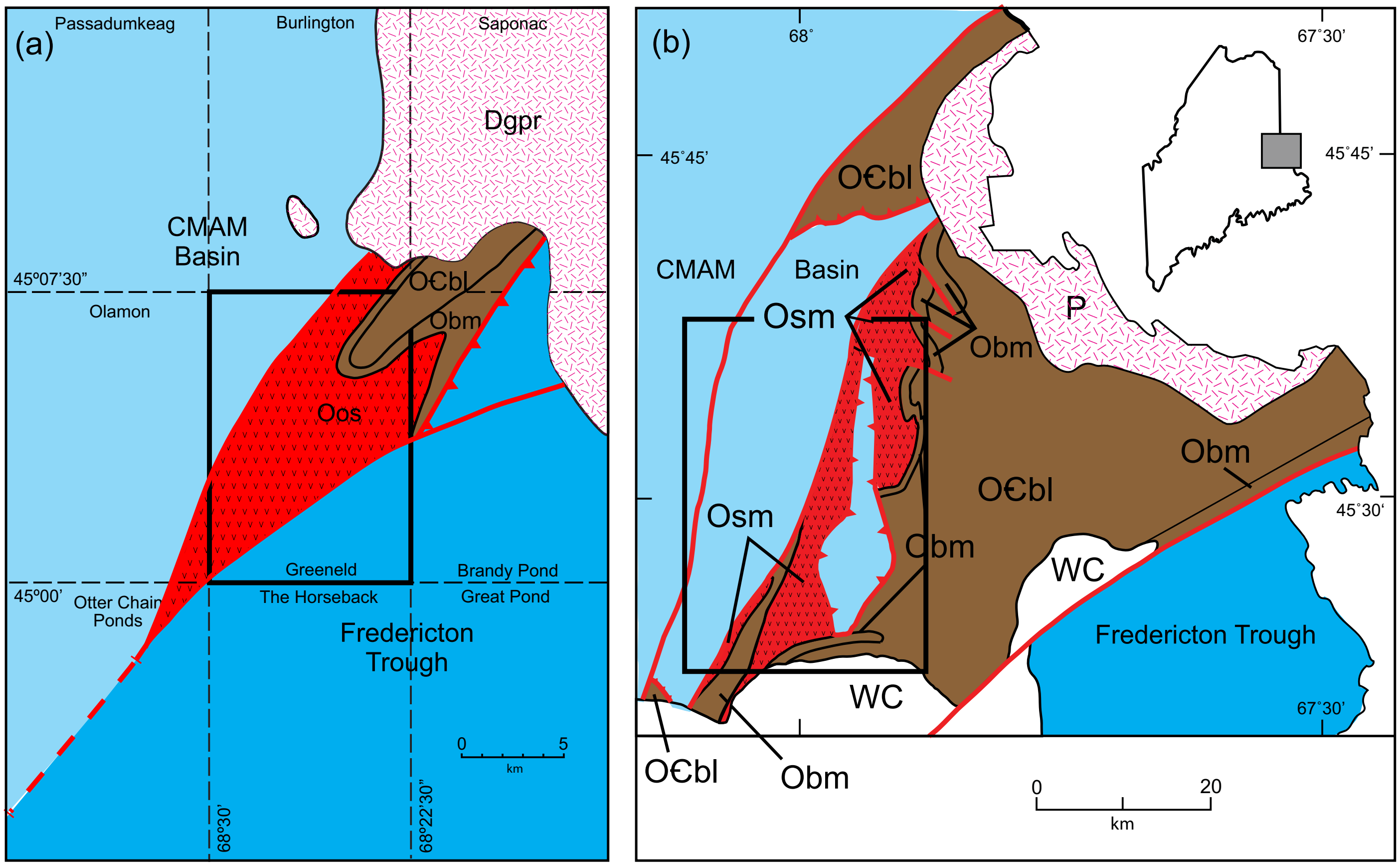

Figure 5: Simplified geologic maps of the Greenfield (a) and Danforth (b) segments. Rectangles show locations of Figures 8a and 8b. Abbreviations: CMAM-Central Maine/Aroostook-Matapedia basin. *Plutons*: Bottle Lake complex (Dgpr-Passadumkeag River; WC-Whitney Cove); P-Pokiok complex; *Sedimentary units*: OЄbl-Baskahegan Lake Formation; Obm-Bowers Mountain Formation; *Volcanic units (patterned)*: Oos-Olamon Stream Formation; Osm-Stetson Mountain Formation.

respective areas in compositional range (Figs. 6a, b) and calc-alkaline affinity (Fig. 6c). Trace element discrimination diagrams also confirm the continental arc tectonic setting (Fig. 6d) previously interpreted for these formations.

Ages of Greenfield, Danforth, and Eel River volcanic rocks

Three samples could not be dated. The mafic sample from the Olamon Stream Formation yielded no zircons, a basalt from the Eel River Formation yielded too few zircons for a reliable date, and one sample of the Danforth Formation proved to be a very fine-grained siltstone. Ages of samples from the remaining Stetson Mountain, Olamon Stream, Porten Road, and Eel River formations are reported in Table 3, complete geochronologic data in Supplementary Data File S1, and concordia diagrams and average weighted means in Supplementary Data File S2.

DISCUSSION

The new ages clarify relationships among the Greenfield, Danforth, and Eel River segments; improve constraints on the duration of subduction-related Miramichi volcanism; improve understanding of temporal and tectonic relationships with volcanic rocks in the Tetagouche segment of the Miramichi terrane (Fig. 7); and change the narrative of Early Paleozoic tectonism along the length of the Miramichi terrane.

Correlation

Before the volcanic rocks were dated, their ages and correlation were based largely on fossils in associated and correlated sedimentary units. The possible range of the Meductic Group in New Brunswick was bracketed broadly between Lower Ordovician (Tremadocian and Floian) graptolites in the underlying Bright Eye Brook Formation and Upper Ordovician graptolites in the unconformably overlying Belle Lake Formation (Fyffe 2001). Further constraints included ages of purportedly comagmatic plutons that intruded the

Table 2. Compositions of the 2023 Maine and New Brunswick geochemical samples.

Unit	Danforth Segment Stetson Mountain				Greenfield Segment Olamon Stream		Meductic Group Porten Rd.	Meductic Group Eel River	
Sample	23A7	23A8	23A10	23A11	23A13	23A14	NBV1	NBV2	NBV3
Major elements (wt. %)									
SiO_2	66.1	64.9	73.6	70.6	68.5	53.3	66.69	57.63	47.5
Al_2O_3	15.9	15.4	13.3	12.7	14.05	17.1	13.9	16.93	18.34
$Fe_2O_3^T$	5.75	6.09	3.58	2.83	4.56	11.55	5.55	8.01	9.68
MgO	1.66	1.89	1.11	1.13	1.35	3.42	2.06	3.7	5.59
CaO	1.18	3.1	0.24	2.18	0.96	5.42	0.91	2.94	5.75
Na_2O	4.52	3.13	3.42	1.48	5.83	5.56	4.2	5.64	1.72
K_2O	2.15	2.01	3.09	2.38	1.18	0.55	0.98	0.13	4.72
TiO_2	0.44	0.66	0.35	0.23	0.35	0.44	0.199	0.385	0.555
MnO	0.08	0.29	0.14	0.12	0.08	0.2	0.927	0.159	0.267
P_2O_5	0.12	0.15	0.07	0.06	0.08	0.1	0.04	0.06	0.16
LOI	2.71	2.31	1.46	4.74	2.51	4.12	3.08	2.19	5.25
Total	100.71	100.38	100.54	99.8	99.53	101.8	98.54	98.78	99.83
Trace and Rare Earth elements (ppm)									
Ba	714	2130	1415	>10000	694	248	339	63	1159
Cr	13	15	5	8	18	32	<20	30	50
Ga	16.4	17.2	15	18.2	13.4	20.9	15	16	15
Hf	2.84	3.45	4.23	7.01	2.76	0.84	5.3	1.3	1.4
Nb	5.59	7.76	8.47	17.2	5.39	0.89	7.7	1.4	3
Rb	66.6	51.7	62.4	83.5	24.3	18.7	33	3	74
Sr	140	1450	249	942	117.5	121	146	80	163
V	78	58	22	15	99	344	18	177	244
Y	22.9	24.9	30.6	50.6	19.2	9.5	46.3	13	10.3
Zr	105	113	148	237	99	30	175	46	49
La	18.4	14.8	22.5	28.8	12.7	4.9	33.7	7.04	12.6
Ce	36.4	34.3	48.6	66.2	27.3	11	78.1	14.9	27.6
Pr	4.77	4.38	5.75	7.94	3.25	1.34	7.95	1.8	3.55
Nd	18	19.5	24.4	34.8	12.1	5.6	31.7	7.5	13.9
Sm	3.9	4.34	6.01	7.69	3.03	1.6	7.07	1.96	2.84
Eu	0.87	1.4	1.39	1.38	0.71	0.51	1	0.586	0.386
Gd	3.77	4.45	5.22	7.99	3.09	1.63	6.99	2.01	2.24
Tb	0.56	0.65	0.87	1.33	0.5	0.26	1.23	0.36	0.34
Dy	3.66	4.14	5.63	8.75	3.27	1.78	7.69	2.24	2.05
Ho	0.74	0.82	1.05	1.86	0.7	0.37	1.55	0.46	0.4
Er	2.56	2.67	3.58	5.59	2.09	1.32	5.25	1.45	1.14
Tm	0.36	0.4	0.51	0.85	0.26	0.15	0.835	0.222	0.159
Yb	2.34	2.51	3.45	5.69	2.06	1.21	5.94	1.55	1.06
Lu	0.33	0.4	0.54	0.9	0.33	0.12	1.04	0.254	0.173

Samples were analyzed by fusion mass spectrometry—New Brunswick samples by Activation Laboratories Ltd in Ancaster, Ontario, Canada, and Maine samples by ALS Geochemistry in Reno, Nevada, USA.

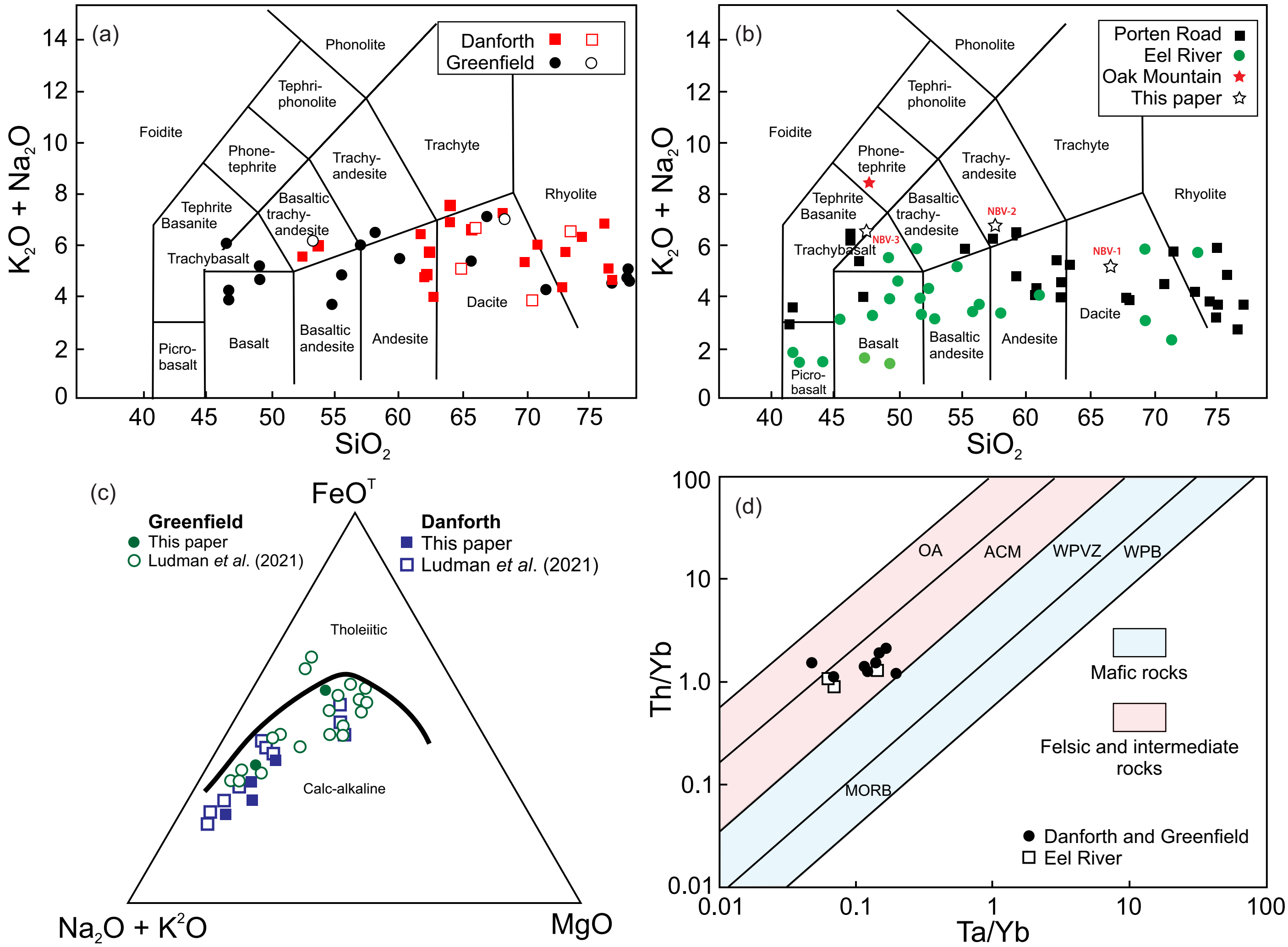

Figure 6. Comparison of 2023 volcanic sample compositions with previous reports. SiO_2/K_2O + Na_2O diagram (Le Bas *et al.* 1986) for(a) Greenfield and Danforth segments (Ludman *et al.* 2021). Unfilled symbols are from this study. (b) Eel River segment (McClenaghan *et al.* 2006). (c) AFM diagram for Danforth and Greenfield segments; (d) Th/Yb vs Ta/Yb discrimination diagram (Gorton and Schandl 2000) for 2023 samples showing continental arc tectonic setting. Major oxides in wt.% and trace elements in ppm. Abbreviations: OA=Oceanic arc; ACM=Active Continental Margin arc; WPVZ=Within plate volcanic zone; WPB=Within plate basalt; MORB=Mid-Ocean Ridge basalt.

underlying Baskahegan Lake Formation: the Gibson Granodiorite (479 ± 7 Ma; Whalen 1993), its satellite Connell Mountain pluton (474.5 +1/-4 Ma; van Staal *et al.* 2016), and the 467 ± 2 Ma Benton pluton that intruded the Baskahegan Lake and all three formations of the Meductic Group (Fyffe *et al.* 2023b). A single graptolite locality in the Danforth segment yielded a "possibly Middle or Upper Ordovician" age (Larrabee *et al.* 1965), but the outcrop has been destroyed and even this vague date cannot be confirmed.

Greenfield and Danforth segments

The structure in these segments is complex, with dominant NE (Greenfield)- and NNE (Danforth)- trending Acadian upright folds superimposed on middle Ordovician recumbent structures, and further complicated by the fault bounding the terrane on the west. Correlation of these segments had been uncertain because stratigraphic contacts and major faults are interrupted by the Passadumkeag River pluton of the Bottle Lake complex (Fig. 3; see Ludman and Whittaker 2023).

That uncertainty has been dispelled by the overlapping and nearly identical average ages of their volcanic rocks as shown in Table 3 and Figure 7. Unfortunately, the geographic distribution of ages in the Greenfield segment (Fig. 8a) failed to yield any insight into its internal stratigraphy. There is a hint of decreasing Olamon Stream formation ages to the southwest, away from the underlying Baskahegan Lake and Bowers Mountain formations (Fig. 8a), but within error, most ages are essentially the same.

Interestingly, the oldest and youngest volcanic ages from the Miramichi terrane in Maine are both from the Danforth

Table 3. All reported ages for the Danforth and Greenfield segment volcanic rocks in Maine and two new ages for the Meductic Group in New Brunswick.

Outcrop	Quadrangle	Location	Lithology	Concordia	Avg weighted mean
DANFORTH SEGMENT, MAINE					
23A11	Stetson Mountain	45.594821N 67.959692W	Dacite tuff	463.9 ± 2.9	463.4 ± 2.9
23A7	Bowers Mountain	45.411432N 68.009935W	Dacite tuff	466.6 ± 4.8	464.8 ± 5.1
23A12	Stetson Mountain	45.588504N 67.936582W	Not analyzed	472.8 ± 3.6	471.1 ± 3.6
23A10	Stetson Mountain	45.530310N 67.976864W	Rhyolite tuff	471.8 ± 4.2	475.0 ± 4.2
23A8	Dill Hill	45.485342N 67.992945W	Dacite tuff	479.8 ± 4.0	478.2 ± 4.3
			Average (Ma)	**471.0 ± 3.8**	**470.5 ± 4.0**
			Duration (myr)	**15.9**	**14.8**
GREENFIELD SEGMENT, MAINE					
20A15	Greenfield	45.054050N 68.464780W	Rhyolite tuff	467 ± 4	
13A78*	Greenfield	45.010226N 68.425420W	Dacite lava	469.3 ± 5	468.3 ± 4.4
23A13	Greenfield	45.024775N 68.463354W	Dacite tuff	466.4 ± 4.3	468.6 ± 4.4
20A13 18B70	Greenfield	45.067055N 68.463431W	Andesitic agglomerate matrix	470 ± 4	471 ± 4
23A16 18B53	Greenfield	45.058597N 68.457809W	Rhyolite tuff	472.0 ± 6.8	471.2 ± 7.1
23A14	Greenfield	45.114356N 68.424626W	Basaltic trachyandesite	474.1 ± 4.1	474.8 ± 4.3
			Average (Ma)	**469.0 ± 4.72**	**470.2 ± 4.8**
			Duration (my)	**7.7**	**7.8**
EEL RIVER SEGMENT, NEW BRUNSWICK					
NBV-1	Porten Road	45.989104N 67.467748W	Dacite	480.2 ± 4.1	478.6 ± 6.3
NBV-2	Eel River	45.960883N 67.594737W	Trachyandesite	468.6 ± 3.4	471 ± 4

*Float block (transport direction shown in Figure 8a).

segment (Fig. 8), and the proximity of 463 Ma and 471 Ma ages in the northwest part of that segment (Fig. 8b) suggests additional, hitherto unsuspected, structural complexities. Alternate tectonic explanaations are discussed below.

Greenfield, Danforth, and Eel River segments

The 480 ± 3 Ma age reported by Mohammadi *et al.* (2019) for a rhyolite near the base of the Porten Road Formation has been validated by the nearly identical 478 ± 4.3 Ma age of NBV-1 (this study). Fyffe *et al.* (2023a) regarded the former age as consistent with the late Tremadocian and early Floian ages of graptolites in the underlying Bright EyeBrook Formation (Fyffe *et al.* 1983; Fyffe 2001), placing the contact between the Woodstock and Meductic groups at or near the Tremadocian–Floian boundary.

As mentioned above, the major obstacle in earlier correlations between the Eel River and Maine segments was

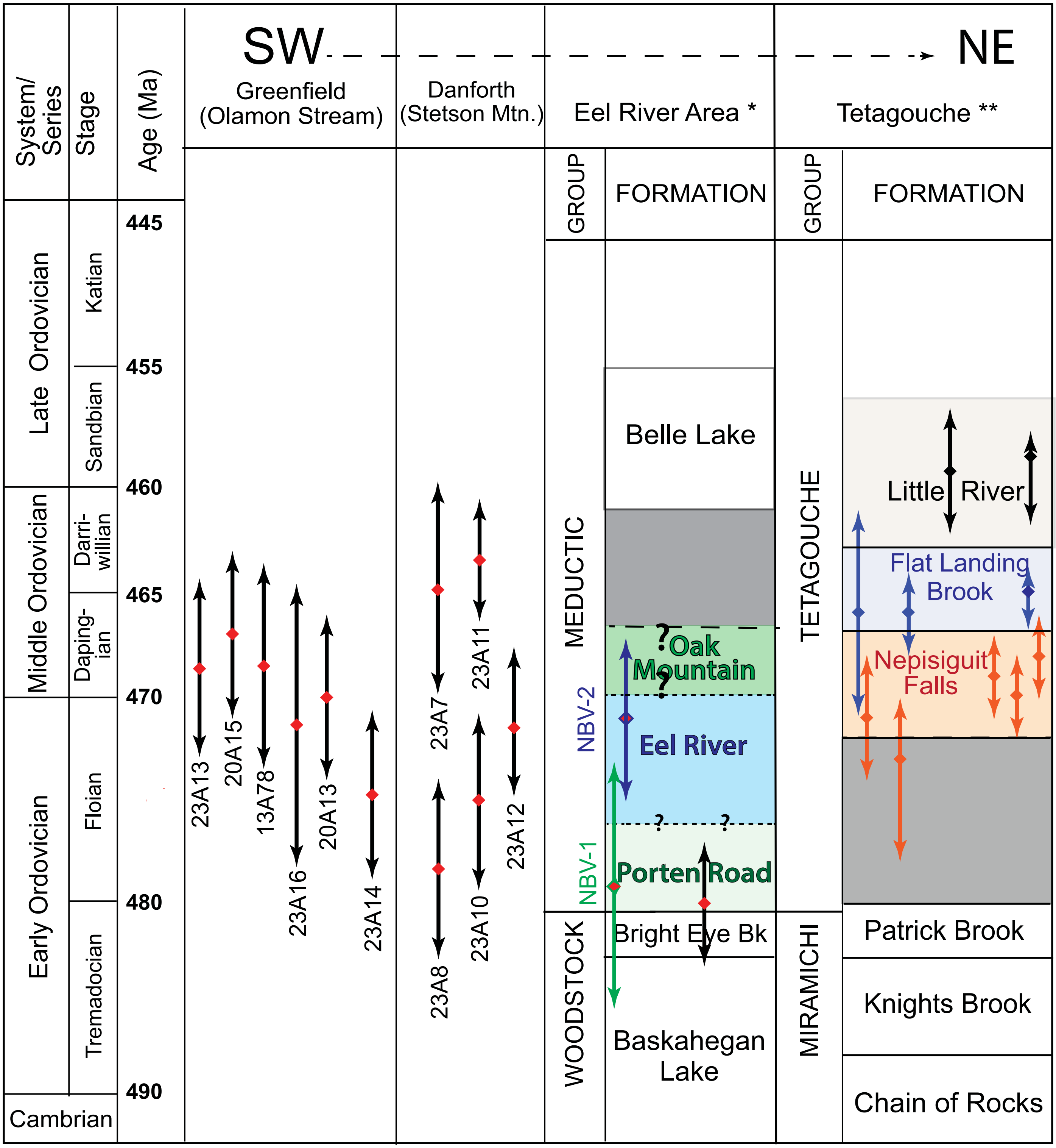

Figure 7. Comparison of volcanic rock ages from the four Miramichi segments shown in Figure 4. Stage boundary ages after Cohen *et al.* (2013, 2023 revision). * After Mohammadi *et al.* (2019) and this paper. **Rogers *et al.* (2003); Sullivan and van Staal (1996); Wilson *et al.* (1999).

a 13-million-year difference between the only dated rocks available in 2021. New ages from the Stetson Mountain (478.2 ± 4.3 Ma), Olamon Stream (474.8 ± 4.3 Ma), and Eel River (471 ± 4 Ma) formations essentially close that gap (Table 3), and we propose that volcanism in these segments was coeval. It was not identical, however, as mafic rocks are far more abundant in the Eel River area.

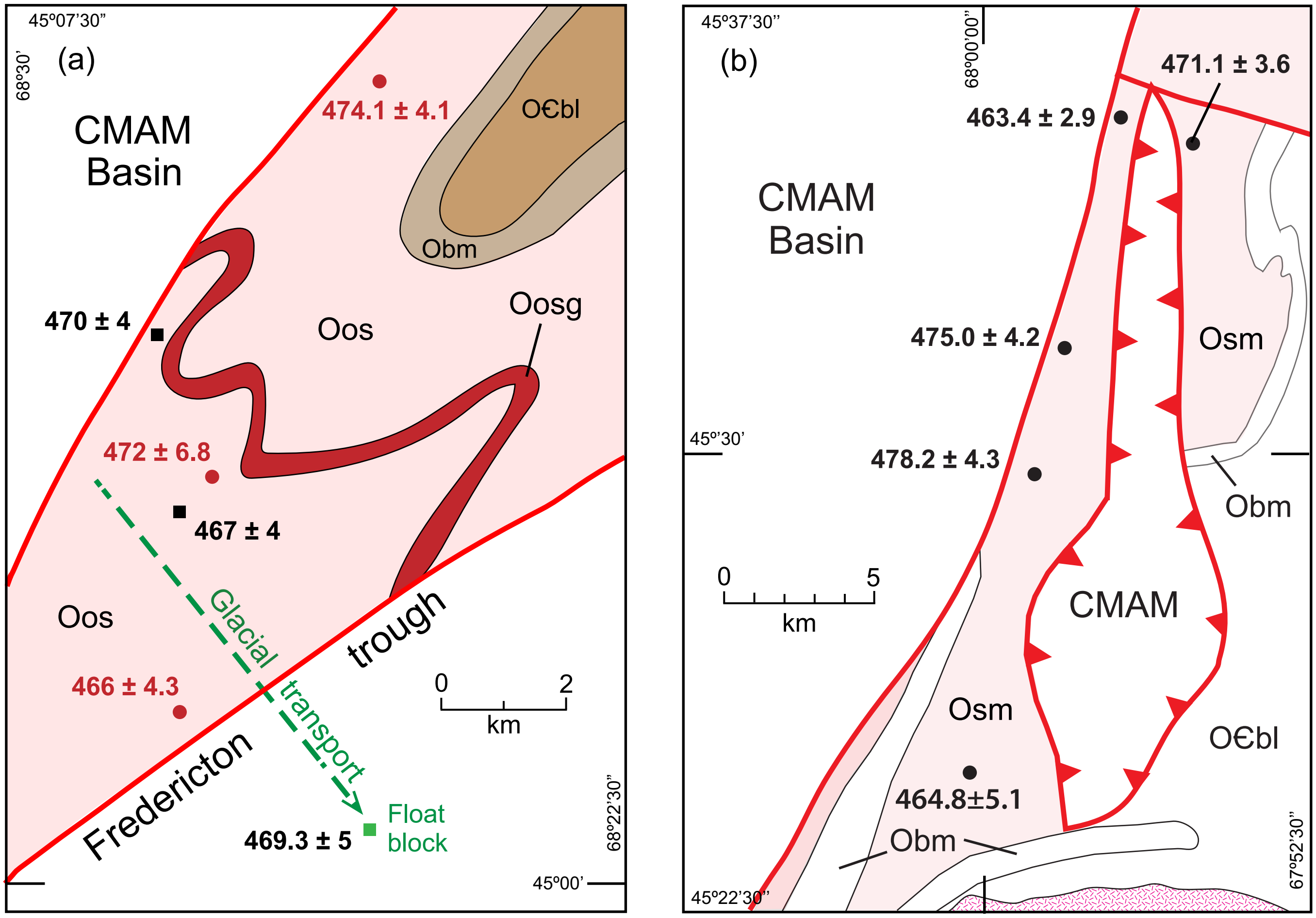

Figure 8. Simplified geologic maps showing distribution of dated Miramichi volcanic rocks in the Greenfield (a) and Danforth (b) segments. Ages depicted in (a) with black and green squares and those with black circles (b) are from Ludman *et al.* (2021). Those in red circles (a) are from this study Abbreviations: O€bl=Baskahegan Lake; Obm=Bowers Mountain; Oos=Olamon Stream, Oosg=Greenfield member; Osm=Stetson Mountain Formation.

Correlation with the Tetagouche segment

Prior to this study, Miramichi volcanism in the Eel River and Greenfield segments appeared to be limited to the Lower Ordovician, significantly older than most Tetagouche Group volcanic rocks. Figure 7 shows that the youngest rocks in the Danforth (Stetson Mountain) and Greenfield (Olamon Stream) segments extend into the Middle Ordovician and overlap with the two oldest Tetagouche Group units in northern New Brunswick. Tectonic implications of this discovery are discussed below.

Initiation and duration of arc-related Miramichi volcanism

Intitial arc volcanism

The timing of subduction and initial arc activity is bracketed between the ages of the youngest underlying basement unit (Bright Eye Brook Formation–Late Tremadocian to Early Floian)) and the oldest dated volcanic rocks (ca 480 Ma). These indicate that continental arc volcanism in Maine and southwestern New Brunswick began in the Lower Ordovician at or near the Tremadocian–Floian boundary (ca. 477.7 Ma): 474 Ma in the Greenfield segment, ca. 478 Ma in the Danforth segment (this study), and ca. 480 Ma (Mohammadi *et al.* 2019) or ca. 479 Ma (NBV-1 in this paper) in the Eel River area (Table 3, Fig. 7).

Duration of arc volcanism

Based on ages currently available, volcanic activity spanned about 8 million years (ca. 475–467 Ma) in the Greenfield segment, 15 million years (ca. 478–463 Ma) in the Danforth segment, and at least 12 million years in the Eel River segment (ca. 480–468 Ma). Voluminous basalts of the Oak Mountain Formation that overlie the Eel River Formation are undated but the 467 ± 2 Ma age (Fyffe *et al.* 2023b) of the Benton Granite that intrudes the Oak Moun-tain sets a maximum span of 13 million years, similar to that of the Danforth segment.

TECTONIC IMPLICATIONS

The single migrating arc model

Van Staal *et al.* (2016) proposed a comprehensive tectonic model for Ordovician volcanism before any ages were known from the Miramichi terrane in Maine. A more detailed version (Fyffe *et al.* 2023a) cited uncertainties about the Greenfield and Danforth segments and mentioned the existence of the first three Greenfield ages (Ludman *et al.* 2021), but did not incorporate them in their model. As a result, the history of volcanism in the Miramichi terrane has been based almost entirely on ages from the dominantly back-arc volcanic rocks of the northernmost Tetagouche segment. Until this study, only the single age of the basal Porten Road Formation in the Eel River segment (Mohammadi *et al.* 2018) represented the three southwestern segments.

The van Staal *et al.* (2016) and Fyffe *et al.* (2023a) models envisage progressive northwestward migration of continental-floored Popelogan volcanic arc volcanism from the Miramichi terrane in New Brunswick to the Weeksboro–Lunksoos Lake and Munsungun–Winterville terranes in northern Maine (Fig. 9; see also Fig. 1). With respect to the Miramichi terrane, the single migrating arc model posits:

(i) ca. 480–to 468 Ma: Eastward subduction and early Meductic phase continental arc volcanism recorded by the Meductic Group in the Eel River segment.

(ii) Meductic phase volcanism ceased around 470 Ma with onset of arc extension and rifting that produced the Tetagouche back-arc basin.

(iii) ca. 470–467 Ma: Steepened subduction and slab rollback led to renewed volcanism (Balmoral phase) and a northwestward shift to the Popelogan area.

(iv) ca. 467–460 Ma: Continued northwestward migration of subduction-related volcanism to the Munsungun–Winterville terrane.

Testing the single migrating arc model

The ages and geochemistry of Miramichi volcanic rocks from the Greenfield and Danforth segments and two new ages from the Eel River segment permit a more rigorous test of the migrating arc model than was possible previously. We focus here on the initial Meductic phase; details of the Balmoral phase and the volcanic history of northern Maine terranes (Wang 2018, 2019a, b, 2021a, b, 2023a, b) are beyond the scope of this paper and will be discussed in a later publication.

Chemical data for the newly dated rocks in the Greenfield, Danforth, and Eel River segments confirm their previously reported calc-alkaline affinity (Fig. 6; Ludman *et al.* 2021) and support the interpretation of a continental arc setting.

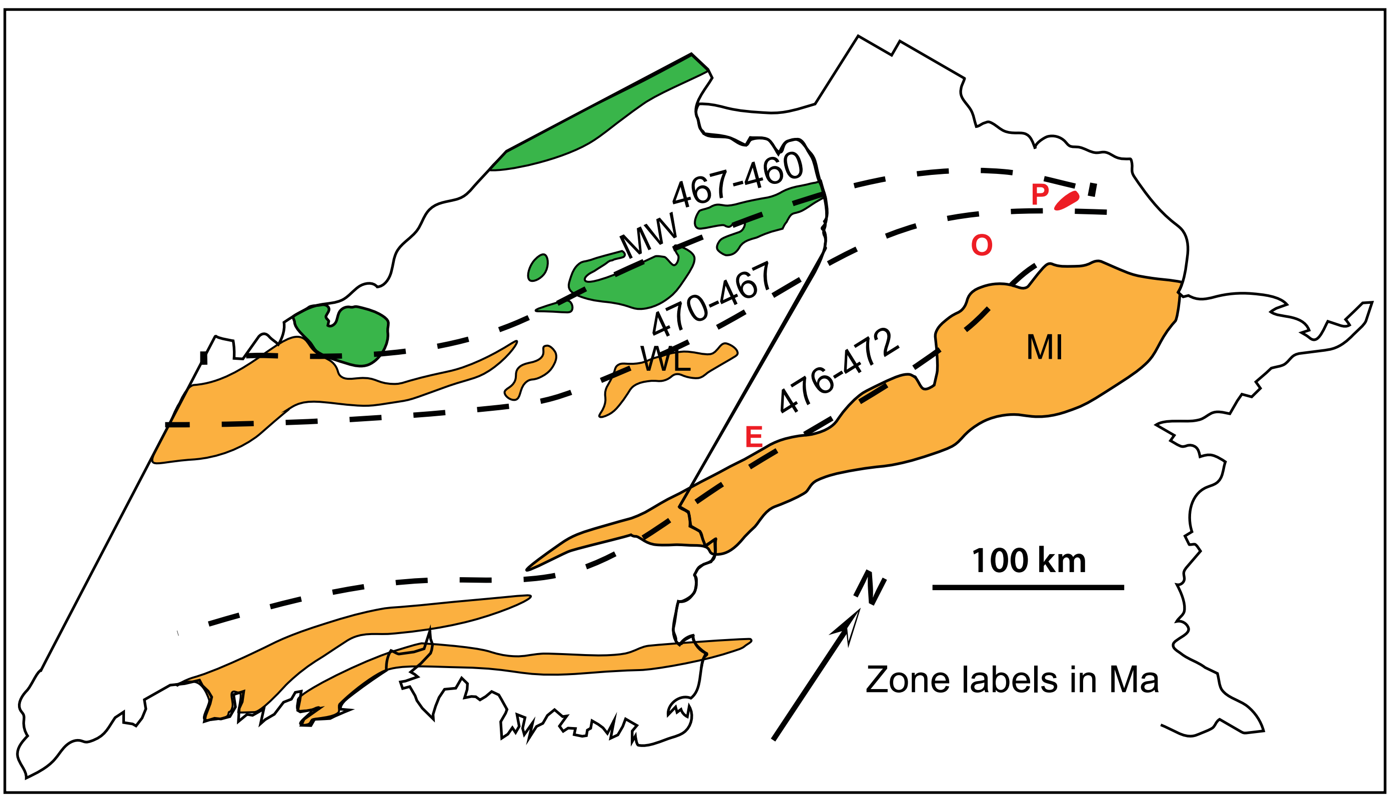

Figure 9. Proposed northwestward migration of the Popelogan from its Meductic phase (ca. 476–472 Ma) to Balmoral phase (ca. 470–457 Ma (van Staal *et al.* 2016). Terrane abbreviations: MI-Miramichi; WL-Weeksboro–Lunksoos Lake; MW-Munsungun–Winterville. E-Eel River; O-Oxford Brook /Goulette Brook; P-Popelogan.

Timing of rifting

Rifting leading to the Tetagouche back-arc basin caused the shutdown of Meductic phase arc volcanism around ca. 470 Ma. Several Middle Ordovician ages from the Greenfield and Danforth segments are younger than the proposed ca. 470 Ma Meductic phase shutdown and overlap early Tetagouche arc extension and rifting (Table 3, Fig. 7). Continental arc volcanism in the southwestern part of the Miramichi terrane was thus coeval with Tetagouche back-arc basin development for at least 4 million years in the Greenfield segment and at least 7 million years in the Danforth segment (Fig. 7).

It is conceivable that the youngest Maine Miramichi rocks might represent a hitherto unrecognized initial episode of arc extension and rifting in the southern part of the Miramichi terrane. However, several lines of evidence indicate that this hypothesis is not valid:

(i) Geochemistry of pre- and post-470 Ma volcanic rocks confirms the calc-alkaline nature of *all* Olamon Stream, Stetson Mountain, and Meductic Group rocks, including those as young as 463 Ma (Fig. 6).

(ii) Most Tetagouche silicic rocks (rhyolites and dacites) fall in within-plate fields on trace element discrimination diagrams (Rogers *et al.* 2003), but the Maine Miramichi rocks, including those coeval with Tetagouche rocks, plot in different volcanic arc/syn-collisional fields on the same diagrams (Figs. 10, 11).

(iii) Comparison of basalts from these segments yields the same result (Fig. 11). Unfortunately, the numerous Meductic Group basalt compositions reported by McClenaghan *et al* (2006) did not include lanthanum, precluding direct comparison with the reported Tetagouche rocks. Figure 11 can thus include only the mafic member of the Olamon Stream Formation and the one Eel River basalt whose age is reported here.

(iv) Andesites are reportedly very rare in Tetagouche volcanic suites (Rogers *et al.* 2003) but the youngest Maine volcanic rocks are intimately mixed with abundant andesites (Fig. 8).

Another possibility is that the ca. 463 Ma arc rocks were related to an arc during the closing of the Tetagouche back-arc basin, rather than its opening. After a brief hiatus following cessation of eastward subduction, the oceanic floor of the basin might have been consumed in a west-dipping subduction zone, above which the younger calc-alkaline volcanics could have been erupted. However, this alternative is unlikely, as the timing coincides with the peak of back-arc extension and seafloor spreading.

Arc migration

Arc migration purportedly began when Meductic phase volcanism in the Miramichi terrane ceased and was followed by Balmoral phase activity that shifted to the northwest to the Popelogan and Oxford Brook inliers in New Brunswick and the Weeksboro–Lunksoos Lake terrane in Maine. However, ages from the Greenfield a nd D anforth segments appear to demonstrate that the locus of volcanism did not shift to the northwest, because ages from those segments (described earlier) are younger than those reported

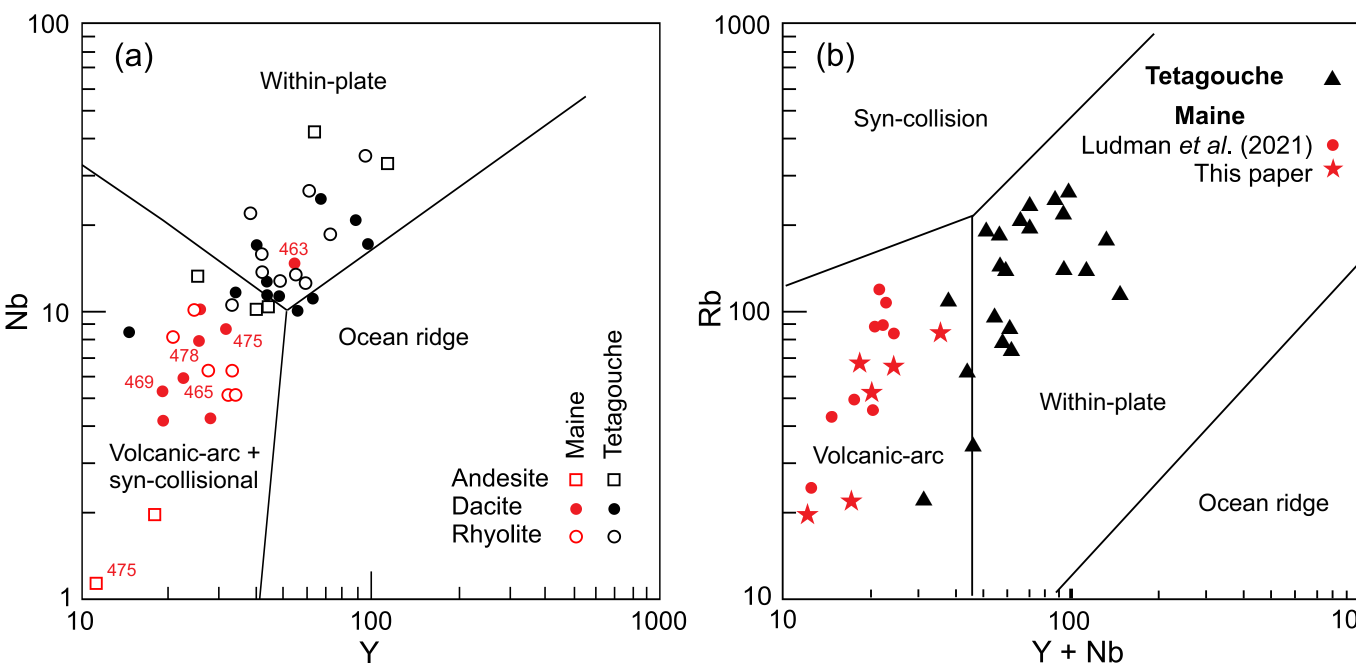

Figure 10. Discrimination diagrams showing tectonic setting of silicic volcanic rocks from the Tetagouche Group (Rogers *et al.* 2003) and Maine Miramichi segments (this paper). Discrimination diagrams from Pearce *et al.* (1984). (a) Y vs. Nb diagram showing ages of new samples. (b) Y + Nb vs. Rb diagram. Stars indicate new ages reported in this paper. Trace elements in ppm.

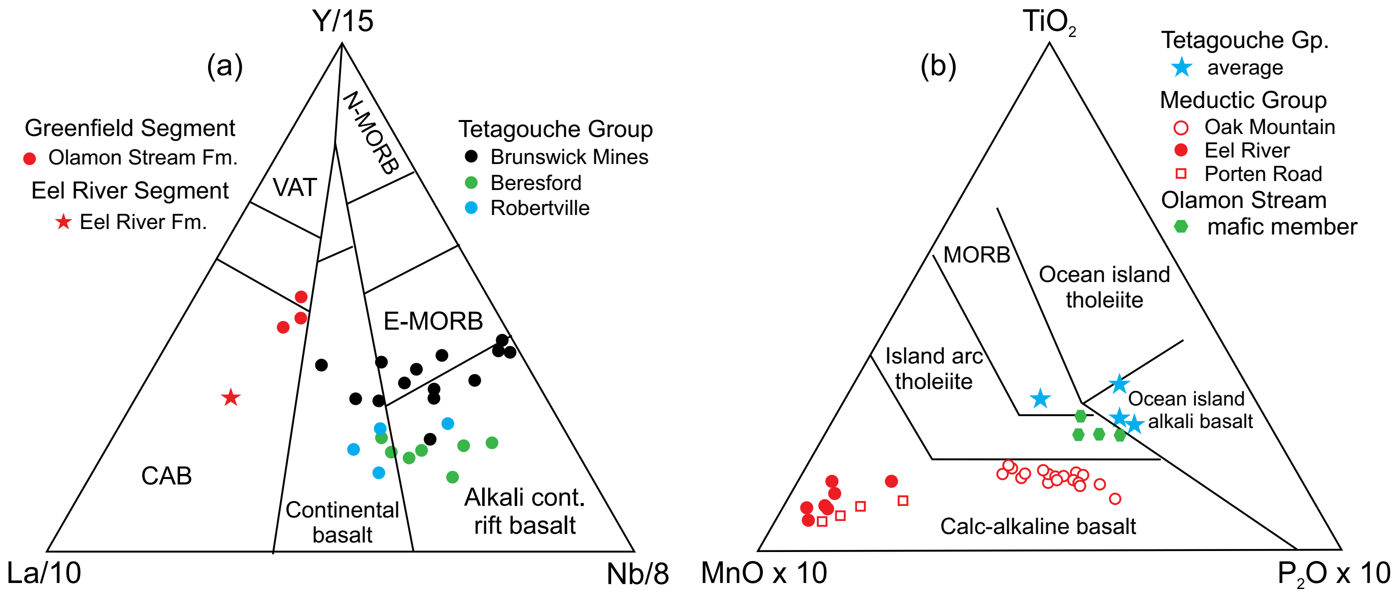

Figure 11. Comparison of Tetagouche basalts with those from the two Maine and Eel River, New Brunswick segments. Data sources: Tetagouche-(Rogers *et al.* 2003); Olamon Stream Formation mafic member (Ludman *et al.* 2021). Eel River Formation-(this paper); Oak Mountain-(Dostal 1989). (a) La-Y-Nb diagram of Cabanis and Lecolle (1989); (b) MnO-TiO_2-P_2O_5 diagram of Mullen (1983). Major elements in wt. % and trace/rare earth elements in ppm.

in the Popelogan and Weeksboro–Lunksoos Lake belts by Ayuso *et al.* (2003) and van Staal *et al.* (2016; Table 3, Fig. 8). In addition, Middle Ordovician ages reported here from the Greenfield, Danforth, and Eel River segments are inconsistent with the migrating arc model that shows Middle Ordovician arc rocks only in the Munsungun-Winterville terrane.

The mafic rocks in the Olamon Stream formation plot close to the average Tetagouche basalts in Figure 11b, suggesting that (a) the mafic rocks in the Olamon Stream segment might represent the initiation of arc rifting, and (b) the mafic tuffs and sub-volcanic intrusive rocks are the youngest Miramichi volcanic rocks in the Greenfield segment.

CONCLUSIONS

1. The first ages of volcanic rocks from the Danforth (Maine) segment of the Miramichi terrane and new ages from the Greenfield (Maine) and Eel River (New Brunswick) segments indicate that volcanism in the southwestern two-thirds of the terrane ranges in age from Early to Middle Ordovician.

2. Volcanic geochemistry confirms a continental arc setting for all dated rocks in the three segments.

3. Overlapping ages confirm coeval eruptions and correlation of the three segments, but different proportions of mafic volcanic rocks suggest different subduction conditions or/and eruption from multiple volcanic centres along the arc.

4. The range of ages currently available suggests a ca. 13–15 myr duration of volcanism recorded in the three segments of the Miramichi terrane.

5. Calc-alkaline continental arc volcanism in the three southwestern segments was contemporaneous for at least 4 to 7 myr with extensional and back-arc basin volcanism in the northernmost Tetagouche segment.

6. The ages reported here are incompatible with the geographic distribution of ages proposed in tectonic models calling for northwestward migration of a single volcanic arc from the Miramichi terrane. Alternatives, including a multiple arc scenario should be considered (e.g. Ludman *et al.* 2021).

Additional work needed

This study shows that the ages and chemistry of even a small number of samples can contribute significantly to long-standing issues of timing, correlation, and tectonic settings of Miramichi volcanism in the southern part of the terrane and clarify relationships along its entire length. Not everyone will agree with our conclusions, but all should concur that additional geochemical and geochronological data are needed. Specifically:

(i) Meductic Group: Two essentially identical dates now confirm a Lower Ordovician age for the thin basal Porten Road Formation, but only a single age is available from the more extensive overlying Eel River Formation and none from the youngest Oak Mountain Formation. Additional dating of the Eel River Formation would clarify its span of volcanism and aid in more precise correlation with the Stetson Mountain and Olamon Stream formations in Maine. The Oak Mountain Formation is dominantly basaltic and not a good candidate for U–Pb zircon dating, but other methods could be attempted.

(ii) Stetson Mountain Formation: The coarsely fragmental part of the Stetson Mountain Formation in the eastern part of its outcrop belt is similar to andesites and andesite breccias of the Eel River Formation. It has not been dated for reasons described above but doing so would greatly improve understanding of the Danforth segment.

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URL LINK TO SUPPLEMENTARY DATA

Supplementary Data File S1 (Complete geochronologic data) and Supplementary Data File S2 (Concordia and weighted mean figures) are available at https://doi.org/10.-10.25545/1KZBX8

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