An overview of Early Paleozoic arc systems in New Brunswick, Canada, and eastern Maine, USA

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ABSTRACT

A plate tectonic model involving northwesterly retreat of an Iapetan subducting slab has been developed over the last three decades to explain the time span of volcanism recorded within the development of Early Paleozoic arc systems preserved in New Brunswick. These arc systems are referred as the Penobscot arc-backarc (514–482 Ma), and Popelogan–Meductic arc (478–460 Ma). Opening of the Tetagouche backarc basin associated with the Popelogan–Meductic arc was diachronous and heterogeneous and involved volcanism associated mainly with the crustal extension and rifting between 472–455 Ma. The complex evolution of the Tetagouche backarc basin is examined in respect to six sub-basins, containing relatively well documented stratigraphic sections in New Brunswick: namely from northeast to southwest the Fournier, California Lake, Bathurst, Sheephouse Brook, Napadogan, and Becaguimec sub-basins. Recently, alternate plate tectonic models have been proposed for the northern Appalachians based on newly acquired geochronological data from northern Maine. We integrate these new data with existing stratigraphic, structural, paleontological, and geochemical evidence to support and refine the previously proposed migrating-arc model for New Brunswick and Maine.

RÉSUMÉ

Un modèle de tectonique des plaques illustrant le recul vers le nord-ouest d'une plaquette plongeante de l'Iapétus a été créé durant les trois dernières décennies pour expliquer l'horizon temporel du volcanisme enregistré au cours de l'apparition des systèmes des arcs du Paléozoïque précoce préservés au Nouveau-Brunswick. Les systèmes en question sont appelés l'arc-arrière-arc de Penobscot (514 à 482 Ma) et l'arc de Popelogan–Meductic (478 à 460 Ma). L'ouverture du bassin arrière-arc de Tetagouche rattaché à l'arc de Popelogan–Meductic a été diachronique et hétérogène, et elle a comporté un volcanisme principalement associé à l'extension et distension crustale survenue entre 472 et 455 Ma. L'évolution complexe du bassin arrière-arc de Tetagouche est examinée par rapport à six sous-bassins abritant des secteurs stratigraphiques relativement bien documentés au Nouveau-Brunswick, en l'occurrence, du nord-est au sud-ouest, les sous-bassins Fournier, du lac California, Bathurst, du ruisseau Sheephouse, Napadogan et Becaguimec. Récemment, des modèles de tectonique des plaques de rechange ont été proposés pour le nord des Appalaches à partir de nouvelles données géochronologiques du nord du Maine. Nous intégrons ces nouvelles données aux observations géochimiques, paléontologiques, structurales et stratigraphiques existantes pour appuyer et raffiner le modèle d'arc migratoire précédemment proposé pour le Nouveau-Brunswick et le Maine.

[*Traduit par la redaction*]

INTRODUCTION

Detailed studies of stratigraphy, structure, geochemistry, and geochronology in the northern Appalachian Orogen over the past three decades have led to the development and refinement of a plate-tectonic model for the generation of Cambrian to Ordovician subduction-related volcanic rocks and associated volcanogenic massive sulfide deposits in the Ganderian terranes of Atlantic Canada and New England (Fig. 1). These Ganderian terranes are interpreted to have been created by the progressive early Paleozoic rifting of fragments from the Ganderian microcontinent, which itself was rifted from the continental margin of Gondwana in the Cambrian (van Staal *et al.* 2012; Waldron *et al.* 2022). The

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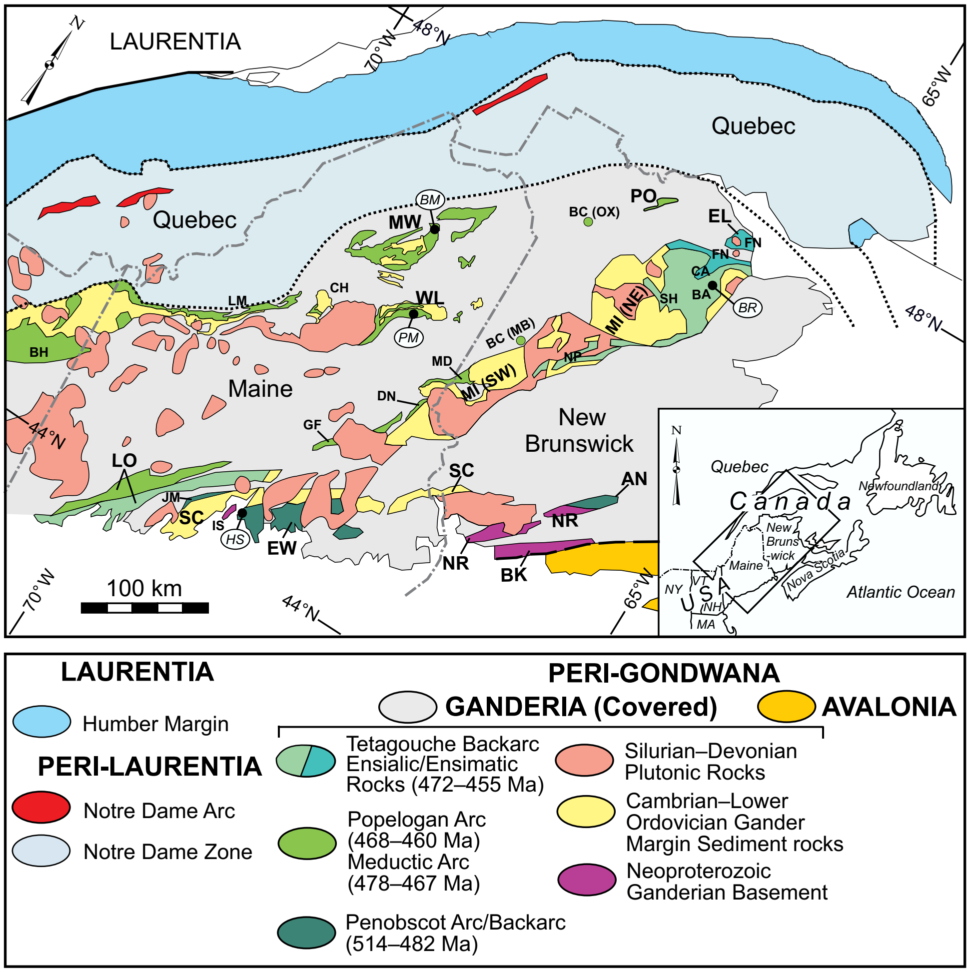

Figure 1. Geology and major tectonic elements in the Appalachians of New Brunswick and Maine showing distribution of Ganderian terranes: AN = Annidale; BH = Bronson Hill; BK = Brookville; EL = Elmtree; EW = Ellsworth; LO = Liberty–Orrington; MI = Miramichi (northeast and southwest); MW = Munsungun–Winterville; NR = New River; PO = Popelogan; SC = St. Croix; WL = Weeksboro–Lunksoos. Sub-basins: BA = Bathurst; BC = Becaguimec (MB and OX); CA = California Lake; FN= Fournier; NP = Napadogan; SH = Sheephouse Brook. Sulfide deposits: *BM* = Bald Mountain; *BR* = Brunswick; *HS* = Harborside; *PM* = Pickett Mountain. Other abbreviations; CH = Chesuncook Lake area; DN = Danforth area; GF = Greenfield area; IS = Islesboro Island; JB = Jam Brook area; LM = Lobster Mountain area; MD = Meductic area (modified after van Staal *et al.* 2016).

terranes were subsequently progressively amalgamated and accreted to the ancient North American continental margin (Laurentia) by the middle Paleozoic. Closure of the Iapetus Ocean and suturing of Ganderia to Laurentia, which terminated in the Silurian, involved two cycles of arc volcanism, arc rifting, and subsequent closing of backarc basins: the middle Cambrian to Early Ordovician Penobscot arc/backarc system and the Early to Middle Ordovician Popelogan–Meductic arc system, and associated Tetagouche backarc basin (Figs. 2 and 3). The accretionary history of these arc and backarc systems is considered to be analogous to complex Mesozoic and Tertiary interactions between the southwestern margin of the Pacific oceanic plate and the northern continental margin of the Gondwanan Australian plate (van Staal *et al.* 1998). In particular, the volcanic rocks lack an abundance of associated andesite and were deposited upon a widespread substrate of Cambrian to Early Ordovician, quartz-rich, marine sedimentary rocks, i.e., Gander Group in Newfoundland and Miramichi Group in New Brunswick (van Staal 1987, 1994; van Staal and Fyffe 1995; van Staal and deRoo 1995; van Staal and Barr 2012; van Staal *et al.* 1991, 1998, 2003, 2009, 2016, 2021; Fyffe *et al.* 1990, 2011; Winchester et. al. 1992a; Whalen *et al.* 1998; Rogers and van Staal 2003; Rogers *et al.* 2003a, b; Wilson 2003; Wilson *et al.* 2015; and Zagorevski *et al.* 2010).

Opening of Penobscot backarc basins of the Annidale and Ellsworth terranes in southern New Brunswick and coastal Maine (Fig. 4a), respectively, was followed by a lull in volcanic activity in the Early Ordovician (Tremadocian). This lull is attributed to shallowing of the southeasterly dipping Iapetan subducting slab (Fig. 4b) on the inferred arrival of a buoyant block such as an oceanic plateau or mid-oceanic ridge (van Staal *et al.* 2009, 2021; Pollock *et al.* 2022). Reactivation of arc magmatism in the late Early Ordovician (Florian) was a consequence of slab steepening and rollback, with rollback due to hinge retreat exceeding the rate of regional convergence. Progressive rollback and slab steepening resulted in stretching and thinning of continental crust underlying the former site of the Penobscot arc and backarc basin. Inflow of new asthenospheric mantle in the widening mantle wedge during slab steepening initially led to diffusely distributed upper plate magmatism that became more localized after the subduction angle stabilized, resulting in the establishment of the calc-alkaline Meductic arc on the southwestern Miramichi terrane between ca. 478 Ma and ca. 467 Ma (Fig. 4c).

Initial extension and develpoment of the Tetagouche backarc basin began with the formation of intra-arc grabens within the thinned crust, and arc magmatism effectively migrated to the northwest (Fig. 4c). Ongoing northwesterly rollback and rifting in the Tetagouche backarc basin led to the development of the calc-alkaline Popelogan arc in northwestern New Brunswick between 468 and 460 Ma. Increasing upwelling in the Tetagouche backarc basin culminated in true seafloor spreading in of the northeastern Miramichi terrane by ca. 464 Ma (Fig. 4d).

PENOBSCOT ARC

Early Paleozoic arc activity began in the New River terrane of southern New Brunswick (southwestern block of NR on Fig. 1) with the eruption of middle Cambrian volcanic flows and tuff of the Mosquito Lake Road Formation; a felsic breccia near the top of the section yielded a zircon date of 514 ± 2 Ma (McLeod *et al.* 2003). The volcanic rocks of the Mosquito Lake Road Formation range in composition from basaltic andesite and andesite to dacite and rhyolite and are locally interbedded with iron and manganiferous-rich volcaniclastic rocks. The basaltic andesite and andesite are enriched in light-REEs and exhibit a strong negative Nb anomaly characteristic of a calc-alkaline arc signature (Johnson and McLeod 1996, Johnson 2001).

The Mosquito Lake volcanic sequence is gradationally underlain by quartzose sandstone and intraformational quartzite-pebble conglomerate of the Matthews Lake Formation (Fig. 2); thin beds of felsic tuff and quartzose sandstone are intercalated at the contact. Although the contact between Neoproterozoic granodiorite, dated at 553 ± 2 Ma (McLeod *et al.* 2003), and the sedimentary rocks of the Matthews Lake Formation is bounded by a fault, clasts of granodiorite in the quartzose sandstone clearly establish a New River basement-Ganderian cover relationship (Fyffe *et al.* 2011).

Ordovician volcanic rocks are exposed along the northwestern margin of the St. Croix terrane in Maine (southwestern SC on Fig. 1), along Senebec Pond fault, a shear zone with a complex movement history (Stewart *et al.* 1995; Tucker *et al.* 2001; Berry *et al.* 2016). The Gushee volcanic suite occurs within a fault slice about 15 km in length and 2 km in width along this zone in the Jam Brook area (JM on Fig. 1). The Gushee suite includes amphibolite-facies felsic crystal tuff with rare lapilli fragments and plagioclase-phyric mafic volcanic rocks containing calcite-filled amygdules and sparse scoria bombs (Fig. 3). Samples of the felsic volcanic rocks yielded Late Cambrian (Furongian) U–Pb ages on zircon of 490 ± 1 Ma and 487 ± 1 Ma (Berry *et al.* 2016). The volcanic rocks range in composition from tholeiitic basalt to rhyolite (45–76 wt. % SiO_2). The mafic volcanic rocks exhibit flat to mildly enriched, light-REE patterns and negative Nb anomalies typical of a volcanic arc setting (Berry *et al.* 2016). The similar age and chemistry shared by the Gushee mafic volcanic rocks of the St. Croix terrane and East Scotch Settlement mafic volcanic rocks (Fig. 2) of the Annidale terrane in New Brunswick (AN on Fig. 1) suggest a paleogeographic arc-backarc relationship existed between them in the Late Cambrian. The Gushee volcanic siute is interpreted to represent a younger fragment of the Penobscot arc (Fig. 3) that rifted away from the earlier remnant Cambrian arc, part of which is preserved in the Mosquito Lake Road Formation in the New River terrane (Fig. 2).

A sequence of interbedded quartzose and calc-silicate sandstones, and quartz-pebble conglomerate, lying to the northwest of the Gushee suite, was originally correlated with the Megunticook Formation in coastal Maine (Berry *et al.* 2016). However, these rocks have recently been shown to contain a large cluster of detrital zircons centred at ca. 470 Ma (Cartwright *et al.* 2019) and so are too young to be equated to the Megunticook (see further details on the stratigraphy of the St. Croix terrane below). We suggest that the Benner Hill sequence, which contains zircons as young as 466 ± 24 Ma (Cartwright *et al.* 2019), would make a better match for the younger rocks identified along the Senebec Pond fault (Fig. 3). A sequence of marble and quartzite directly adjacent to Senebec Pond fault has been correlated with Proterozoic basement rocks of the Seven Hundred Acre Island Formation, which are exposed on and around Islesboro Island in Penobscot Bay; this correlation is supported by the recovery of detrital zircons no younger than 969 ± 82 Ma (Berry *et al.* 2016; Cartwright *et al.* 2019).

Part of the Jam Brook fault slice containing the Gushee volcanic and Proterozoic basement rocks is interpreted here to form the footwall of a splay off the northwesterly directed thrust duplex, referred to by Tucker *et al.* (2001) as the Graham Lake thrust. The immediate hanging wall would be represented by the black shale sequence of the middle Cambrian (Miaolinian) to Early Ordovician (Tremadocian) Penobscot Formation (Fig. 3). The northwestern boundary of thrust duplex with Silurian sedimentary rocks of the Fredericton trough has been interpreted on the basis of seismic data to be truncated by dextral strike-slip displacement along the steeply dipping Senebec Pond fault (Tucker *et al.* 2001; Ludman *et al.* 2017). Such strike-slip displacement would have further disrupted internal boundaries within the Jam Brook 'complex'. Movement along at least part of the Graham Lake–Sennebec fault had largely ceased by the

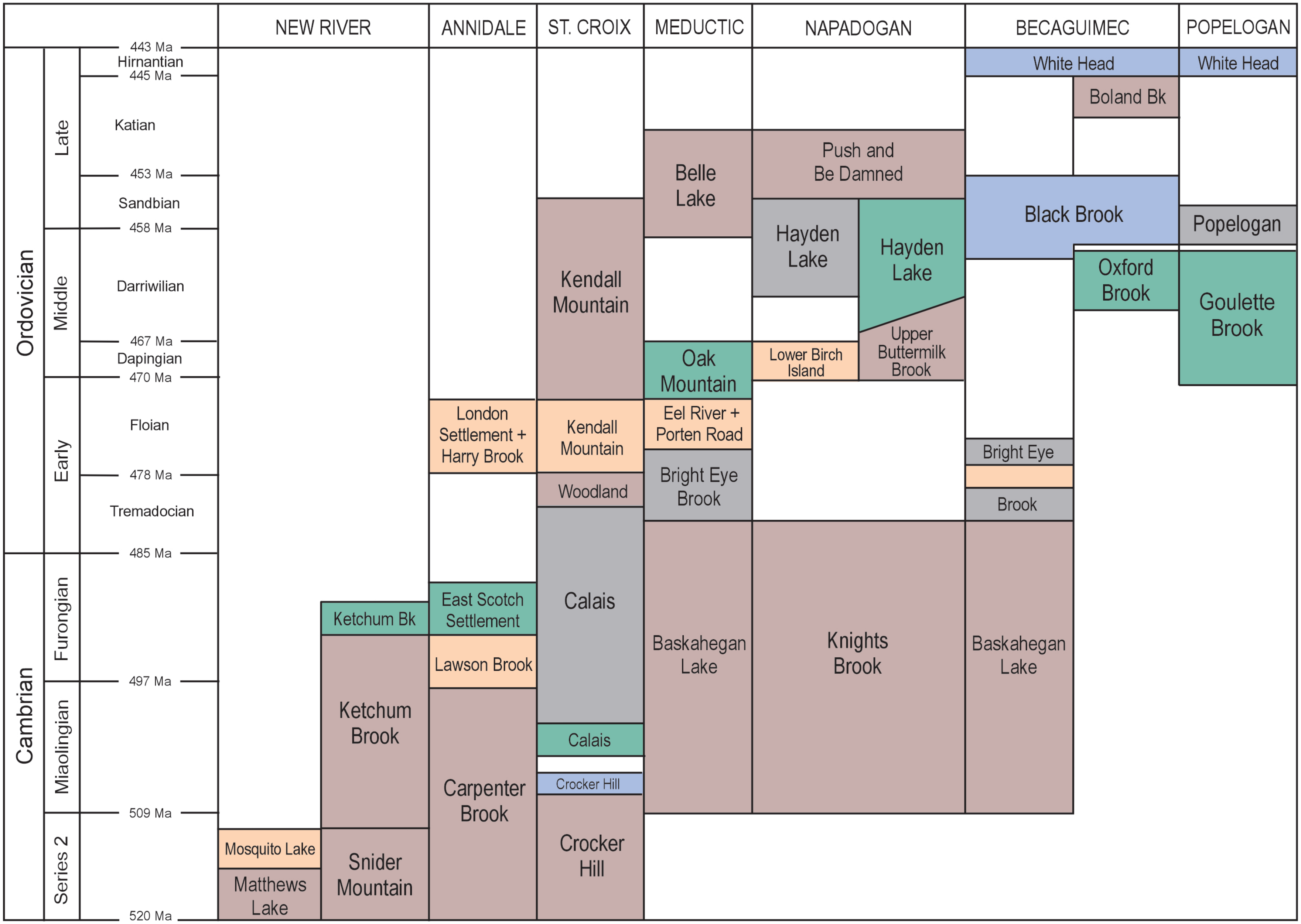

Figure 2. Simplified stratigraphic columns for Early Paleozoic formations in the New River, Annidale, Saint Croix, southwestern Miramichi (Meductic arc), and Popelogan terranes, and Tetagouche sub-basins (Napadogan and Becagumec) of western New Brunswick. See text for paleontological and geochronological age controls. The lower age limit of the underlying Ganderian sedimentary substratum is largely unknown. Formations for the northeastern Miramichi and Elmtree terranes are given in Wilson *et al.* (2015). See Figure 3 for colour codes.

Late Silurian as indicated by the emplacement of the stitching Pocomoonshine gabbro at 423 ± 3 Ma across the shear zone near the Maine–New Brunswick border (West *et al.* 1992; Ludman *et al.* 2017). The deformation along the fault system was likely related to terminal Salinic closure of the Tetagouche backarc basin farther to the north.

PENOBSCOT BACKARC

Early Paleozoic volcanic activity, related to northwesterly retreat of the Penobscot arc (Fig. 4a), is preserved in two areas along the rifted Gondwanan margin—the Ellsworth terrane of coastal Maine (EW on Fig. 1), and the Annidale terrane of southern New Brunswick (AN on Fig. 1).

Ellsworth rift

The Ellsworth terrane, located in the Penobscot Bay area of coastal Maine (EW on Fig. 1), including the Cambrian Ellsworth, Castine, and North Haven volcanic suites (Fig. 3), is separated from the St. Croix terrane (southwestern SC on Fig 1) to the northwest by Turtle Head fault. The fault zone is exposed on the eastern shore of Penobscot Bay where felsic volcanic rocks of the Ellsworth suite can be observed to have been thrust to the northwest over black shale of the Penobscot Formation. This thrusting must have occurred no earlier than the Tremadocian, the upper age limit of the Penobscot Formation (see below). Basal conglomerate of the Silurian Ames Knob Formation in southern Penobscot Bay, which lies unconformably on mafic volcanic rocks of North Haven suite, contains the brachiopod Pentamerus and foliated clasts of black shale, indicating that uplift associated with the thrusting took place prior to the Llandoverian (Stewart *et al.* 1995; Reusch *et al.* 2018; Pollock *et al.* 2022).

The Ellsworth terrane is characterized by the presence of greenschist-facies, middle Cambrian rhyolitic tuff of the Ellsworth volcanic suite, and younger rhyolite flows and rhyolite dome complexes of the Castine volcanic suite (Fig. 3), dated at 509 ± 1 Ma and 503 ± 2 Ma, respectively (Ruitenberg *et al.* 1993; Schulz *et al.* 2008). Beds of quartzose sandstone are locally intercalated with the Ellsworth tuffs. A thin basal conglomerate marks the contact between the Ellsworth and Castine suites (Stewart *et al.* 1995; Pollock *et al.* 2022). The rhyolitic tuffs in the Ellsworth suite are calc-alkaline and characterized by light-REE enriched patterns, positive Th anomalies, and negative Ta, Eu, and Ti anomalies. The rhyolite flows and domes in the Castine suite are tholeiitic and characterized by flat-REE patterns, positive Th anomaly, negative Ta and Eu anomalies, and a prominent negative Ti anomaly (Schulz *et al.* 2008).

Both the Ellsworth and Castine suites contain tholeiitic basalts with depleted light-REE patterns that exhibit neither positive Th nor negative Ta anomalies. The Castine suite also contains tholeiitic basalts with mildly enriched light-REE patterns and no Th or Ta anomalies. Tholeiitic pillow basalt of the North Haven volcanic suite, exposed beneath Early Silurian conglomerate on islands in the southern part of Penobscot Bay, also exhibit mildly depleted light-REE patterns (Pinette and Osberg 1989). Taken together, the tholeiitic basalts of the Ellsworth terrane have geochemical characteristics, in particular the general lack of positive Th and negative Ta anomalies, that suggest they were derived from a heterogeneous MORB source lacking significant contamination from a subduction-related source (Schulz *et al.* 2008).

Because of their lack of a subduction-related signature, the volcanic rocks of the Ellsworth terrane are interpreted to have erupted on the passive side of a wide backarc rift that opened behind the Penobscot arc (Fig. 4a). The rifting is attributed to Iapetan subduction-slab rollback that was associated with the opening of the Rheic Ocean and separation of Ganderia from Gondwana. Such an extensional setting is consistent with the formation of the Harborside Zn-Cu volcanogenic massive sulfide deposit *(HS* on Fig. 1) within the Castine suite (Ruitenberg *et al.* 1993), and with the presence of exhumed fault slices of serpentinized peridotite in the Ellsworth schist (Schulz *et al.* 2008; van Staal *et al.* 2009; Reusch *et al.* 2018).

Continental basement rocks marginal to the Ellsworth rift are exposed on Islesboro Island (IS on Fig. 1) in Penobscot Bay within an isolated fault sliver located along the Turtle Head fault zone. The Proterozoic Coombs limestone and overlying Hutchins Island orthoquartzite of the Seven Hundred Acre Island Formation exposed on Islesboro Island are older than 647 ± 3 Ma, based on the emplacement age of a cross-cutting pegmatite dyke (Stewart *et al.* 1995, 2001; Reusch *et al.* 2018). The Coombs and Hutchins Island formations are considered to be respective correlatives of the Kent Island and Thoroughfare formations on Grand Manan Island and the Ashburn Formation of the Brookville terrane (BK on Fig. 1) in southwestern New Brunswick (Miller *et al.* 2007; Fyffe *et al.* 2009; Fyffe 2015; Barr and Mortensen 2019; Barr *et al.* 2019).

Conglomerate and sandstone of the Turtle Head Cove Formation (Fig. 3), exposed on the southwestern shore of Seven Hundred Acre Island and in a fault block on the northern tip of Islesboro Island (Reusch *et al.* 2018), are interpreted to have been deposited with angular unconformably on the Proterozoic Seven Hundred Acre Island basement rocks and Cambrian volcanic rocks of the Ellsworth terrane (Berry and Osberg 1989). This unconformity is considered to be contemporaneous with the Penobscot unconformity identified in the Annidale terrane (AN in Fig. 1) in adjacent New Brunswick (see below) as the predominant population in the zircons recovered from the Turtle Head Cove sandstone has been dated at 515 ± 2 Ma (Reusch *et al.* 2018), and likely represent detritus sourced from uplifted Penobscot volcanic rocks.

A Ganderian platformal sequence, which defines the St. Croix terrane, unconformably overlies the Proterozoic basement rocks of the Seven Hundred Acre Island Formation along the shore of Penobscot Bay in Maine (southwestern SC on Fig. 1). The St. Croix sequence here includes (Fig. 3): the

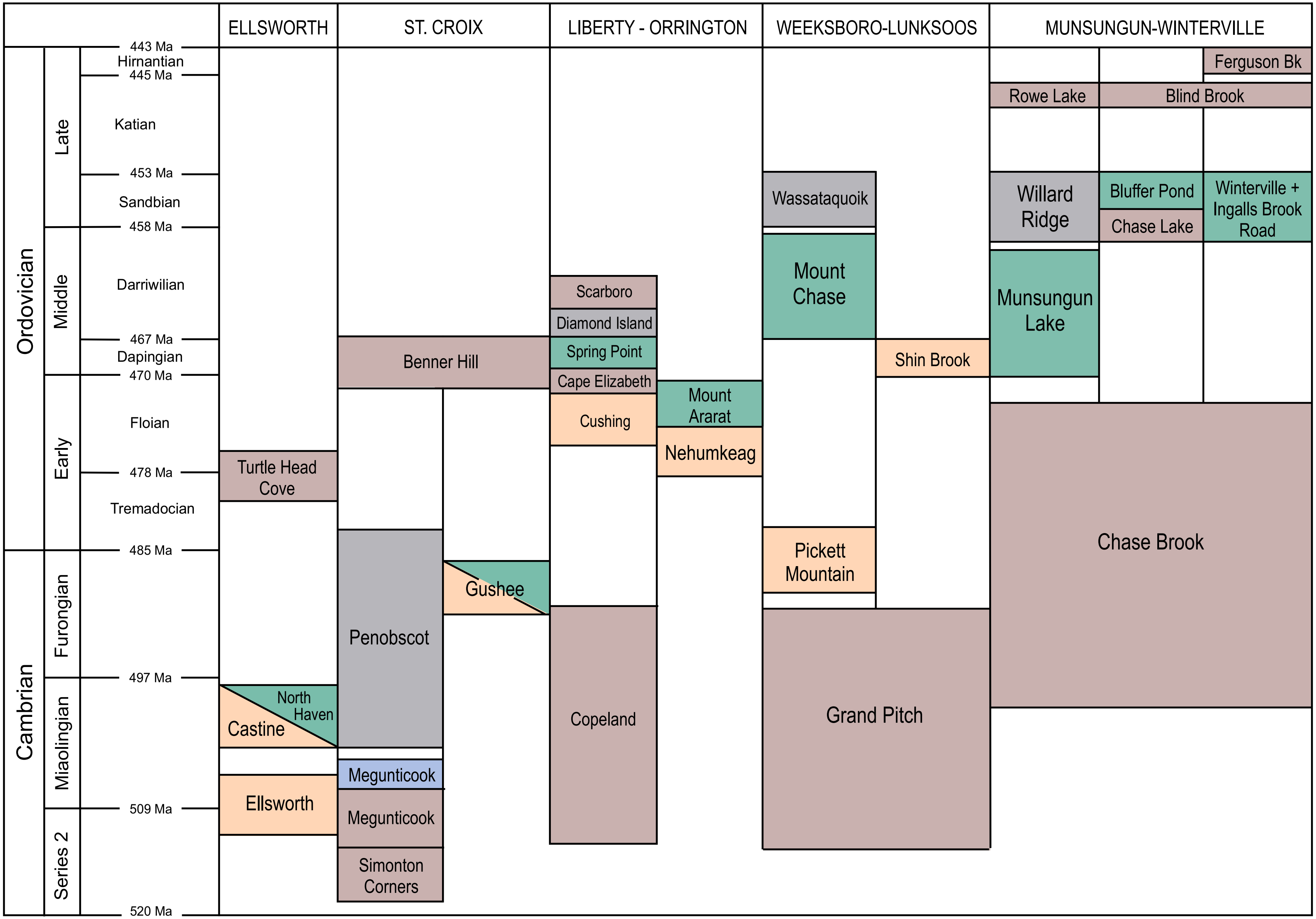

Figure 3. Simplified stratigraphic columns for Early Paleozoic formations in the Ellsworth, St. Croix, Liberty–Orrington, Weeksboro–Lunksoos, and Munsungun–Winterville terranes of eastern Maine. See text for paleontological and geochronological age controls. The lower age limit of the underlying Ganderian sedimentary substratum is largely unknown. Colours: brown = mainly clastic sedimentary rocks; blue = mainly limestone; grey = mainly black and red chert, black shale; green = mainly mafic volcanic rocks; orange = mainly felsic volcanic rocks.

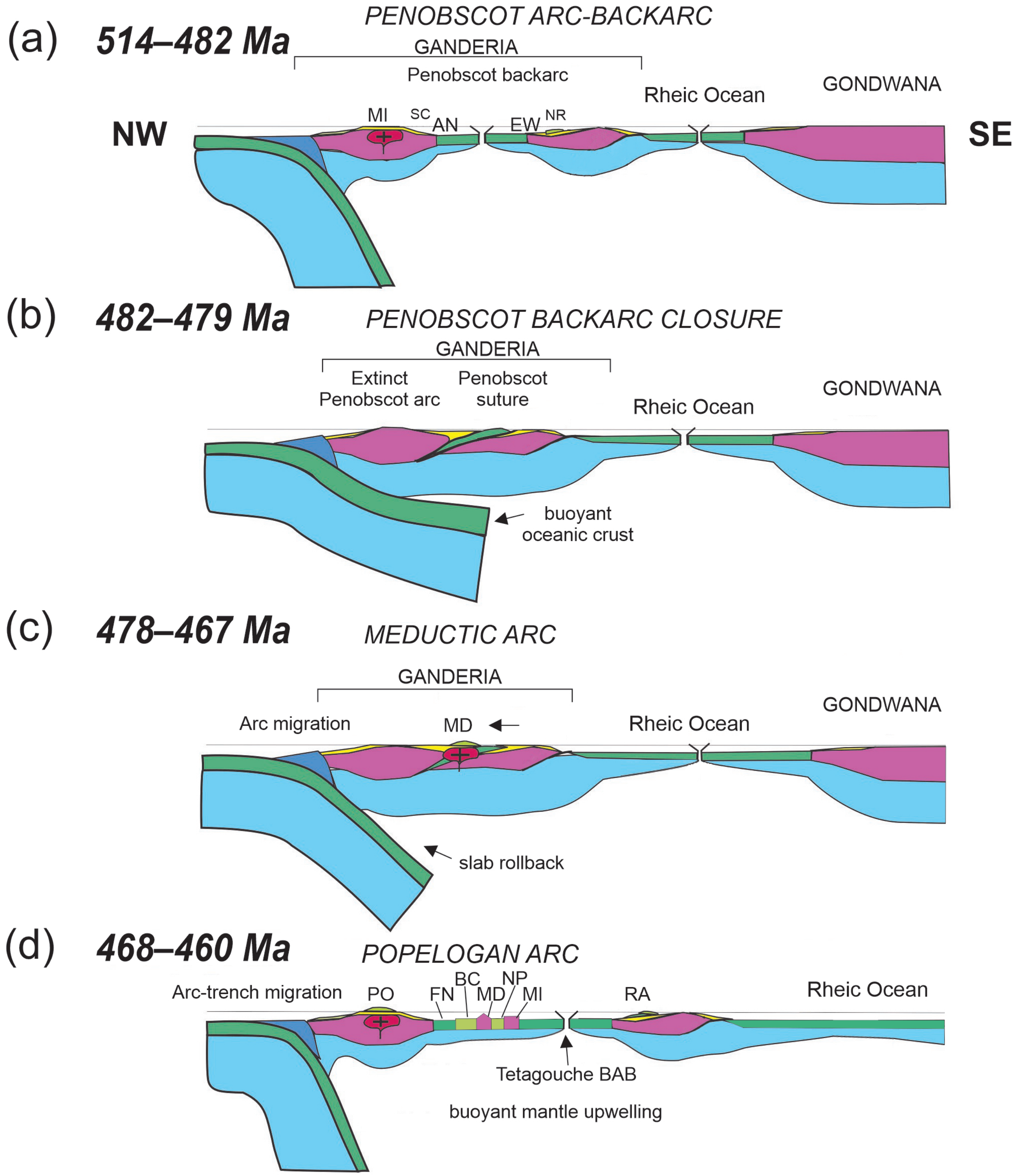

Figure 4. Tectonic model for the evolution of Early Paleozoic arc-backarc systems in New Brunswick and eastern Maine (modified from van Staal and Fyffe 1995; van Staal and Barr 2012; and van Staal *et al.* 2021). AN = Annidale terrane; BK = Brookville terrane; EW = Ellsworth terrane; MD = Meductic arc; MI = Miramichi terrane; NR = New River terrane; PO = Popelogan arc; RA = incipient Popelogan–Meductic arc remnant; SC = St. Croix terrane; Red 'pluton'= active arc. Tetagouche backarc sub-basins: Becaguimec (BC); Fournier (FN), and Napadogan (NP) including horst of Miramichi terrane (MI). California Lake, Bathurst, and Sheephouse Brook sub-basins are off-section. Earlier rifting in Tetagouche backarc basin associated with the Popelogan–Meductic arc system is illustrated in figure 8 of van Staal *et al.* 2003.

Cambrian Simonton Corners Formation (conglomerate and wacke); Megunticook Formation (coticule-bearing quartzite and schist, and Battie conglomerate); and the Cambrian to Early Ordovician Penobscot Formation (mainly graphitic schist). Deformed and metamorphosed brachiopods of Late Ordovician age have been reported from the Benner Hill sequence (Fig. 3) of the St. Croix terrane in Maine (Boucot 1972) but the preciseness of this age assignment has been disputed by Neuman (1973). Late Silurian granite plutons, dated at 421 ± 1, 421 ± 2 and 420 ± 2 Ma., intrude the sedimentary rocks of the St. Croix terrane (Tucker *et al.* 2001).

A paleostratigraphic linkage is suggested between the St. Croix and Ellsworth terranes by the presence of 510 ± 8 Ma detrital zircons (Fyffe *et al.* 2009) recovered from silty sandstone of the Late Cambrian to Early Ordovician Calais Formation exposed along the St. Croix River on the border between Maine and New Brunswick (northeastern SC on Fig. 1). Black shale of the Calais Formation on Cookson Island at the mouth of the St. Croix River contains Early Ordovician (late Tremadocian) graptolites belonging to the *Adelograptus tenellus* zone (Fyffe and Riva 1990). A thin unit of pillow basalt on the St. Croix River, lying below Calais black shale, is tholeiitic in composition and displays a light-REE depleted profile (Fyffe *et al.* 1988a) comparable to the light-REE depleted basaltic rocks of the Ellsworth terrane noted above (Figs. 2 and 3). Moreover, a sample of fragmental tuff, taken about 5 km west of Penobscot Bay in Maine, yielded a date of 503 ± 4 Ma (Tucker *et al.* 2001), providing evidence of a possible linkage between the St. Croix terrane and Castine / North Haven volcanic suites of the Ellsworth terrane.

Annidale backarc

Suprasubduction volcanism related to the Penobscot arc in southern New Brunswick is recorded in the Annidale terrane (Johnson *et al.* 2009, 2012), much of which is covered by Carboniferous strata on its northwestern side (AN on Fig, 1). The Lawson Brook volcanic suite, a sequence of pillowed basalt, hyaloclastic tuff, and minor andesite, associated with rhyolitic dome complexes, forms the northwestern part of the Annidale terrane (Fig. 2). The basaltic flows in the Lawson Brook suite possess a typical tholeiitic arc affinity, including mildly depleted to mildly enriched light-REE patterns and positive Th and negative Nb anomalies (Johnson *et al.* 2012). Zircon dating of a massive black rhyolite at 493 ± 2 Ma (McLeod *et al.* 1992) indicates that the Lawson Brook volcanic suite was erupted in the Late Cambrian (Furongian). Highly schistose felsic tuffs, exposed in the small O' Neill Brook inlier surrounded by a cover of Carbonifeous sandstone to the northwest of the main belt of Annidale volcanic rocks, have been dated at 497 ± 10 Ma (McLeod *et al.* 1992). The eruption of these tuffs may have been coeval with Castine volcanic activity in the Ellsworth terrane (Fig. 3).

The Lawson Brook volcanic suite is in fault contact to the southeast with the Carpenter Brook Formation, a sequence of quartzose wacke and siltstone interbedded with minor volcanic rocks. Both the Carpenter Brook Formation of the Annidale terrane in New Brunswick and the Ellsworth volcanic suite of the Ellsworth terrane in coastal Maine are intruded by Late Cambrian granitic plutons at 490 ± 2 Ma and 492 ± 2 Ma, respectively (Johnson *et al.* 2012; Pollock *et al.* 2022). The Carpenter Brook Formation, therefore, could represent a thrust panel of pre-Late Cambrian sedimentary substrate to the Lawson Brook volcanic suite. Such an interpretation is supported by the presence of detrital zircons in the Carpenter Brook sandstones (552 ± 2 Ma; 632 ± 2 Ma), which were most likely sourced from exposed New River basement, located to the southeast (Johnson *et al.* 2009, 2012).

The East Scotch Settlement volcanic suite, a sequence of hyaloclastic basaltic tuff and minor pillow basalt, basaltic andesite, andesitic flows, and picritic tuffs, interbedded with carbonaceous shale, structurally overlies the Carpenter Brook Formation (McLeod *et al.* 1994; Johnson *et al.* 2009, 2012). These mafic to intermediate flows display a transition between island arc tholeiite (IAT) and calc-alkaline arc affinity, indicated by mildly to strongly enriched light-REE patterns and high positive Th and negative Nb anomalies. The picritic tuffs contain high Mg (13.7–17.2 wt. % MgO), Cr (1180–4910 ppm), and Ni (39–880 ppm) and are strongly depleted in light-REEs. Tholeiitic basalts displaying mildly enriched light-REE patterns and lacking Nb and Th anomalies, similar to MORB, are also present in the East Scotch Settlement suite (Johnson *et al.* 2012). This occurrence of both arc-related and MORB-like geochemical signatures displayed by the Lawson Brook and East Scotch Settlement suites are characteristic of magmas generated on the active side of backarc basins (Fig. 4a).

Rhyolites in the Lawson Book and East Scotch Settlement suites possess calc-alkaline signatures characterized by enriched light-REE patterns, and positive Th and negative Nb, Eu, and Ti anomalies, similar to the rhyolitic tuffs in the Ellsworth suite (see above). A small subvolcanic intrusion of highly enriched light-REE plagiogranite, and another of highly depleted light-REE plagiogranite, both emplaced into the East Scotch Settlement suite, yielded zircon ages of 482 ± 2 Ma and 481 ± 2 Ma, respectively (Johnson *et al.* 2012), indicating that magmatic activity in the Annidale terrane extended into the Early Ordovician (early Tremadocian). Final closure of the backarc by the late Tremadocian is indicated by the 479 ± 2 Ma age of the Stewarton gabbro (Johnson *et al.* 2012), which stitches the faulted southeastern boundary between the Annidale and New River terranes (Fig. 4b).

The Penobscot unconformity in the Annidale area is represented by a polymictic conglomerate deposited along the margin of the mafic volcanic rocks of the East Scotch Settlement. The matrix-supported conglomerate contains clasts of sandstone, siltstone and minor felsite, largely derived from the Carpenter Brook Formation. The basal conglomerate is overlain by an olistostromal sandstone into which the London Settlement rhyolite dome complex was erupted (Fig. 3). Spherulitic rhyolite from the dome yielded an Early Ordovician (early Floian) age of 478 ± 2 Ma (Johnson *et al.* 2012). Emplacement of this domal complex is interpreted to mark initial extension that led to the development of a fully fledged Popelogan–Meductic arc system (see below). Other post-Penobscot magmatic activity in the region is recorded by the Harry Brook rhyolite dome emplaced into the East Scotch Settlement volcanic suite at 472 ± 2 Ma; and the West Scotch Settlement and Bull Moose Hill porphyries, which were emplaced into the New River terrane at 475 ± 2 Ma and 467 ± 2 Ma, respectively (Johnson *et al.* 2012, 2018*).*

Felsic tuff beds were deposited at 477 ± 4 Ma (Ludman *et al.* 2018) at the base of a Kendall Mountain quartzose sandstone sequence (Fig. 2) of the St. Croix terrane (northeastern SC on Fig. 1). The eruption of these tuffs in the Early Ordovician (Floian) suggests that an unconformity may exist between them and the overlying sedimentary rocks of the Kendall Mountain Formation. Black shale interbedded with the quartzose sandstone in the upper part of the Kendall Mountain Formation contain Ordovician (Sandbian) graptolites belonging to the *Climacograptus wilsoni* zone (Fyffe and Riva 1990). The presence of brachiopod fauna in the Benner Hill sequence (Fig. 3) and graptolite fauna in the Kendall Mountain sequence (Fig. 2) of the St. Croix terrane is consistent with an increasing depth of water more distal from the nearer inboard passive (southeastern) margin of the developing Tetagouche backarc basin (Reusch and van Staal 2012).

The southeastern margin of the Late Cambrian Annidale terrane is faulted against the Grant Brook Formation of the New River terrane, a sequence of Neoproterozoic pyroclastic and sedimentary rocks, dated at dated at 541 ± 3 Ma (northeastern NR on Fig. 1). Local thrusting to the southeast along this margin during Penobscot backarc closure is recorded by ramp cut-offs in bedded volcanic tuffs of the Grant Brook Formation. The Grant Brook Formation is unconformably overlain by a Ganderian sedimentary cover, represented by the Almond Road Group. Youngest detrital zircons (529 ± 4 Ma) indicate that quartzose sandstone (Snider Mountain Formation) at the base of the Almond Road Group (Fig. 2) was deposited later than the Early Cambrian (Terreneuvian). Overlying quartzofeldspathic sandstone (Ketchum Brook Formation) is no younger than Early Ordovician (early Floian) as it is intruded by the high-level West Scotch Settlement porphyry at 475 ± 2 Ma. Basaltic lava flows interlayered with the Ketchum Brook sandstone exhibit a transition between tholeiitic arc and calc-alkaline arc affinities, characterized by moderately enriched light-REE patterns, and positive Th and negative Nb anomalies. These basalts may have erupted contemporaneously with volcanic arc activity in the Annidale terrane; if so the Ketchum Brook Formation is no younger than Tremadocian (Johnson *et al.* 2012, 2018).

MEDUCTIC ARC

Arc volcanism in the Meductic segment (MD on Fig. 1) of the Popelogan–Meductic arc system in the southwestern Miramichi terrane [MI (SW) on Fig. 1)] can be viewed as a continuum with Penobscot arc activity that was interrupted by a short volcanic hiatus of about 3 mya, following closure of the Ellsworth rift and Annidale backarc basin (Fig. 4b). Paleontological evidence indicates that the volcanic rocks in the Meductic Group range from Early to Middle Ordovician in age (Venugopal 1978, 1979; Fyffe *et al.* 1983; Fyffe 2001). The establishment of the long-lived Meductic arc to the northwest of the Penobscot backarc is attributed to the stabilization of a steepened subducting slab following a period of slab rollback and upper plate extension (Fig. 4c). The conformable nature of the boundary between the deep-water black shales of Bright Eye Brook Formation (Woodstock Group) and overlying Porten Road Formation (Meductic Group) indicates that the volcanic rocks were never exposed to shallow-water or subaerial erosion during the Early Ordovician (Fig. 2).

Post-Penobscot volcanism is recorded by the eruption of rhyolite domes (between 478–467 Ma) on the closed, formerly active site of the Penobscot backarc basin as noted above in the New River and Annidale terranes. The presence of a substratum of Cambrian to Early Ordovician quartzose sedimentary rocks in the southwestern Miramichi terrane (Baskahegan Lake Formation of the Woodstock Group), and Snider Mountain and Matthews Lake formations in the New River terrane (Figs. 2 and 3), suggest that these terranes were positioned proximal to each other prior to the inception of slab rollback in the Popelogan–Meductic arc system (van Staal and Fyffe 1995; Fyffe *et al.* 2011; Johnson *et al.* 2018).

The Meductic volcanic sequence (Fig. 2) possesses a complete range of chemical compositions from rhyolite, to dacite, basaltic andesite, and basalt. The Eel River Formation, which overlies dacitic and rhyolitic flows, tuffs, and breccias of the Porten Road Formation, contains a high proportion of andesitic crystal tuffs (Fyffe 2001). The basaltic flows and breccias of the Oak Mountain Formation, which occur at the top of the Meductic volcanic sequence, display a highly enriched light-REE pattern and strong positive Th and negative Nb and Ta anomalies, typical of calc-alkaline arcs formed on a continental margin (Dostal 1989; Winchester *et al.* 1992b; Fyffe 2001; McClenaghan *et al.* 2006). The eruption of this basaltic magma marks the end of arc volcanism in the Meductic segment of the Popelogan–Meductic arc system. Plutonic rocks considered to be comagmatic with the volcanic rocks of the Meductic Group include the Gibson granodiorite and Connell Mountain tonalite, which were emplaced into Cambrian to Early Ordovician quartzose sedimentary rocks of the Baskahegan Lake Formation to the east of Woodstock, New Brunswick, in the late Early Ordovician (middle Floian) at 473 ± 1 Ma and 475 ±1 Ma, respectively (Bevier 1989; van Staal *et al.* 2016).

A sample of crystal-lithic dacitic tuff from the Porten Road Formation, collected in the western part of the Eel River area near Benton yielded a zircon age of 480 ± 3 Ma (Mohammadi *et al.* 2019). This age overlaps the Tremadocian–Floian boundary and is consistent with the presence of late Tremadocian graptolites of the *Adelograpus tenellus* zone found in black shale of the Bright Eye Brook Formation, which conformably overlies the Baskahegan Lake Formation (Fyffe *et al.* 1983). The contact between the Porten Road volcanic rocks and underlying black shale of the Bright Eye Brook Formation is not exposed near Benton but was exposed in a separate fault slice farther to the east near the confluence of the Eel River with the St. John River (Fyffe and Pickerill 1993; Hennessey and Mossman 1996); the contact has since become covered by overburden. Early Ordovician (early Floian) graptolites of the *Tetragraptus approximatus* zone occur here in black shale of the Bright Eye Brook Formation just below the conformable contact with the overlying volcanic rocks assigned to the Porten Road Formation (Pickerill and Fyffe 1999; Fyffe 2001). The *Tetragraptus approximatus* zone defines the base of the Florian, which is dated at ca. 478 Ma (Cooper *et al.* 2004), so the late Tremadocian zircon date of 480 ± 3 Ma, obtained from the overyling Porten Road tuff farther to the west near Benton, appears to be a bit too old. Although the date from the tuff is consistent with the early Floian graptolite age within error limits, it is possible that the boundary between the volcanic rocks and black shales is diachronous and becomes younger to the east.

The Belle Lake Formation in the upper part of of the Meductic Group (Fig. 2) comprises a wacke-shale sequence that disconformably overlies the Meductic volcanic rocks. Grey silty shale, located just above the red chert horizon that defines the top of the Oak Mountain Formation, contains early Late Ordovician (early Sandbian) graptolites of the *Nemagraptus glacilis* zone (Fyffe *et al.* 1983; Fyffe 2001), so Meductic arc activity must have ceased prior to the late Darriwilian and possibly as early as the Dapingian of the Middle Ordovician.

The Ordovician felsic volcanic sequence (Stetson Mountain Formation) in the Danforth area of Maine (DN on Fig. 1), which is on trend with the calc-alkaline volcanic rocks of the Meductic Group in adjacent New Brunswick, include calc-alkaline pyroclastic rocks (lapilli tuffs and breccias) ranging in composition from andesite to rhyolite (Ludman *et al.* 2018, 2021). Farther along trend to the southwest in the Greenfield area of Maine (GF on Fig. 1), an andesitic tuff and rhyolitic tuff (Olamon Stream Formation) yielded Middle Ordovician (Dapingian to early Darriwilian) ages of 470 ± 4 Ma and 467 ± 4 Ma, respectively. The relationship of the Greenfield volcanic rocks to those in the Danforth area is uncertain and further work will be required to determine if a stratigraphic linkage exists between them.

The Liberty–Orrington terrane (LO on Fig. 1), extending from Bangor in south-central Maine to the Casco Bay area of coastal Maine, is underlain by Ordovician volcanic and sedimentary rocks, which have been metamorphosed to as high as the upper amphibolite facies (West *et al.* 1995, 2003, 2021), and intruded by Late Silurian granitic plutons ranging in age from 424 ± 2 Ma to 422 ± 2 Ma (Tucker *et al.* 2001). The southeast-verging Boothbay–Liberty–Orrington thrust separates the Liberty–Orrington terrane from the continuation of the Fredericton trough into Maine (Tucker *et al.* 2001; Reusch and van Staal 2012). The Liberty–Orrington terrane is divided into two belts separated by the Flying Point fault, a splay of the Norumbega fault system—the Casco Bay Group to the southeast and the Falmouth–Brunswick Group to the northwest (Hussey *et al.* 2010).

The Casco Bay Group includes from base to top (Fig. 3): the Cushing Formation, consisting of light grey, bedded felsic crystal tuff and breccia interlayered with dark grey, fine-grained, iron -rich exhalative beds; the gradationally overlying Cape Elizabeth Formation, consisting of interbedded light grey feldspathic wacke and dark grey pelite; the Spring Point Formation, consisting of mafic and minor felsic volcanic rocks; the Diamond Island Formation, consisting of black sulfidic and graphitic pelite; and the Scarboro Formation, consisting of pelitic and minor calc-silicate sedimentary rocks. Felsic volcanic rocks of the Cushing and Spring Point formations have been dated respectively at 465 ± 4 Ma (Hussey *et al.* 2010) and 469 ± 3 Ma (Tucker *et al.* 2001). The geochemistry of the Spring Point mafic volcanic rocks is consistent with eruption in a backarc tectonic setting (West *et al.* 2004). Recently, felsic volcanic rocks included in the East Harpswell Group (Yarmouth Island Formation) in Casco Bay have been dated at 472 ± 5 Ma (Johnson *et al.* 2022), suggesting correlation with adjacent rocks of the Casco Bay Group. The volcanic rocks of the Yarmouth Island Formation range in SiO_2 content from 47.9 to 77.5 wt. %, and the mafic volcanic rocks possess a prominent negative Nb anomaly. This, and the presence of interbedded marine sedimentary rocks, suggest a continental arc to transitional backarc setting (Johnson *et al.* 2022).

The Falmouth–Brunswick Group includes: the Nehumkeag Pond Gneiss, consisting of migmatized felsic gneiss and granofels, and minor calc-silicate granofels and graphitic schist (felsic volcanic and volcanogenic sedimentary protolith?), and dated at 472 ± 7 Ma (Hussey *et al.* 2010); and the Mount Ararat Gneiss, consisting of alternating thin layers of amphibolite and felsic granofels (mafic and felsic volcanic ash protoliths?), and dated at 472 ± 6 Ma (Hussey *et al.* 2010). In south-central Maine, deformed and metamorphosed igneous rocks of the Sheepscot Pond Gneiss (Newberg 1984; West and Peterman 2004), dated at 474 ± 2 Ma (Tucker *et al.* 2001), are mapped within the Falmouth–Brunswick Group. Collectively, there is a suggestion the Falmouth–Brunswick Group is slightly older than the Casco Bay Group and we suggest these rocks represent the arc associated with the backarc basin of the Casco Bay Group (Fig. 3). Furthermore, we suggest all of the rocks in the Liberty–Orrington terrane represent a continuation into Maine of the Meductic segment of the Popelogan–Meductic arc system and Tetagouche backarc basin (West *et al.* 2004; Hussey *et al.* 2010; Reusch and van Staal 2012). Thick-bedded quartzite of the Copeland Formation, arcing around the northeastern terminus of the Casco Bay sequence (Berry and Osberg 1989; Kaszuba and Simpson 1989), may represent Ganderian substratum to the Liberty–Orrington terrane (Fig. 3).

POPELOGAN ARC

The Popelogan terrane, a small inlier in northwestern New Brunswick (PO on Fig. 1), is composed of two units assigned to the Balmoral Group: the Goulette Brook Formation, a sequence of scoriaceous picritic tuffs and massive to amygdaloidal, plagioclase-phyric flows; and the conformably overlying Popelogan Formation, a sequence of black shale and chert (Fig. 2). The black shale contains graptolites of the *Nemagraptus gracilis* zone (Philpott 1987), indicating that the underlying mafic volcanic rocks of the Goulette Brook Formation were erupted immediately prior to the early Late Ordovician (early Sandbian). The Popelogan Formation is overlain by Late Ordovician to Early Silurian ribbon limestone of the White Head Formation, known to be derived from the Laurentian margin (St. Julien and Hubert 1975). Conodonts recovered from calcareous grit at the base of the White Head Formation (Matapédia Group), where it disconformably overlies the Popelogan black shale, are Hirnantian in age (latest Late Ordovician), suggesting that the Popelogan arc collided with Laurentia and was mildly uplifted between 454 and 450 Ma, terminating the Taconic orogenic cycle in this part of the Northern Appalachians (Wilson 2003; van Staal *et al.* 2008, 2009, 2016). Conodont zonation is after Bergstrom and Ferretti (2016).

The geochemistry of the Goulette Brook volcanic sequence is consistent with the interpretation that the Popelogan terrane represents a Middle Ordovician arc that was established in northwestern New Brunswick during northwesterly directed arc-trench migration as a result of continuing slab rollback and intra-arc rifting in the Popelogan–Meductic arc system (Fig. 4d). The picritic tuffs of the Goulette Brook Formation contain an average SiO_2 content of 49.7 wt. %, and related high-Mg andesitic tuffs, an average SiO_2 content of 56.8 wt. %. Values of MgO in the picritic tuffs range from 10.3–26.6 wt. %, Cr from 1010–2240 ppm, and Ni from 349–649 ppm. MgO in the high-Mg andesite ranges from 6.6–10.8 wt. %, Cr from 101–518 ppm, and Ni from 56–121 ppm. The plagioclase-phyric flows are basaltic andesites and fall into two groups: one with an average SiO_2 of 54.9 wt. % and average MgO content of 6.1 wt. %; and the other with an average SiO_2 content of 52.9 wt. % and average MgO content of 2.7 wt. %. The mafic tuffs and flows all exhibit enriched light-REE patterns and positive thorium and negative Nb anomalies, characteristic of calc-alkaline arc affinity; the low MgO basaltic andesite shows the greatest enrichment in light-REEs (Wilson 2003).

A porphyritic dacitic flow, exposed in the Oxford inlier [BC (OX) on Fig. 1] about 30 km to the southwest of the Popelogan inlier, contains relatively high contents of high-field-strength elements (Nb, Y, and, Zr) and REEs. Such enrichments are typically exhibited by volcanic rocks found in extensional settings, and are consistent with eruption in the backarc area of the Popelogan volcanic arc (see below). The dacite has yielded a Middle Ordovician (late Dapingian to early Darriwilian) age of 468 ± 1 Ma (van Staal *et al.* 2016). Thin-bedded felsic ash beds in the Prairie Brook Formation (upper Pointe Verte Group) of the Elmtree terrane (EL on Fig. 1), dated at 463 ± 3 to 457 ± 4 Ma (late Darriwilian), are interpreted to represent late-stage Popelogan arc activity recorded in the Tetagouche backarc (van Staal *et al.* 2016).

TETAGOUCHE BACKARC

Although the Tetagouche backarc basin must have formed in response to northwesterly migration of the Popelogan–Meductic arc system, its extensional, rifting, and spreading history was diachronous and heterogeneous along the Meductic and Popelogan segments of the subducting plate boundary. Ordovician volcanic rocks are preserved in the Fournier (FN), California Lake (CA), Bathurst (BA), Sheephouse Brook (SH), Napadogan (NP), and Becaguimec (BC) sub-basins, each of which are interpreted to represent preserved (non- or partially subducted) remnants of distinctive sub-basins formed in separate parts of the Tetagouche backarc basin (Fig. 1). Following the collision of the Popelogan arc with the Laurentian margin in the Late Ordovician to Early Silurian, the Iapetan subduction zone stepped back into the Tetagouche backarc basin and reversed polarity. The sub-basins were subsequently amalgamated with each other during closure of the Tetagouche backarc basin by subduction of oceanic seafloor (van Staal 1994; van Staal and Fyffe 1995; Wilson *et al.* 2008; van Staal and Barr 2012; van Staal *et al.* 2009, 2021).

The Fournier and California Lake sub-basins were incorporated into the Salinic Accretionary Complex (Brunswick subduction complex of van Staal 1994) between ca. 450 and ca. 430 Ma. Blueschists and sedimentary mélanges are defining features of the accretionary complex (Helmstaedt 1971; Skinner 1974; Pajari *et al.* 1977; Rast and Stringer 1980; Trzcienski *et al.* 1984; van Staal 1994; Rogers and van Staal 2003; Winchester *et al.* 1992a; van Staal *et al.* 1990, 2003, 2008, 2016). A series of imbricated thrust panels derived from the dismemberment of the Fournier and California sub-basins were exhumed from the Salinic Accretionary Complex (see fig. 15 of Wilson *et al.* 2015) during Salinic orogenesis following the attempted subduction of continental crust underlying the Bathurst sub-basin. The stratigraphic, paleontological, geochemical, structural, and geochronological evidence for the interpreted role played by the six sub-basins in the development of the Tetagouche backarc basin is reviewed below from the northeast to southwest (Fig. 1).

Fournier sub-basin

The main part of the Fournier sub-basin (northern FN on Fig. 1) is located behind the Popelogan arc within the Elmtree terrane of northeastern New Brunswick (EL on Fig. 1). It contains the only remnant of true oceanic crust preserved in the Tetagouche backarc basin (Fig. 4d). The Devereaux Ophiolite Complex comprises the Black Point Gabbro, sheeted dykes, and overlying pillowed basalt of the Turgeon Road Formation (Pajari *et al.* 1977; Rast and Stringer 1980; Winchester *et al.* 1992b; van Staal and Fyffe 1995). The tholeiitic basalts of the Turgeon Road Formation possess flat-REE patterns and are classified as TMORB (i.e., transitional to EMORB) as they do not display the marked light-REE depletion characteristic of NMORB (Winchester *et al.* 1992a). Gabbroic pegmatite and associated plagiogranite dykes have yielded Middle Ordovician (middle to late Darriwilian) zircon dates of 464 ± 1 Ma and 460 ± 1 Ma, respectively (Sullivan *et al.* 1990; Spray *et al.* 1990). Although seafloor spreading had started in the Fournier sub-basin by at least 464 Ma, it probably started much earlier in some areas, as suggested by the presence of mafic-dominated, transitional oceanic crust flooring the California Lake sub-basin (see below). The Devereaux Ophiolite Complex was emergent by the Early Silurian as it is unconformably overlain by conglomerate and redbeds of the Chaleurs Group (Noble 1976).

The Pointe Verte Group, which structurally underlies the Devereaux Ophiolite Complex includes sedimentary rocks of the Prairie Brook Formation and conformably overlying mafic volcanic rocks of the Madran Formaton. The Prairie Brook Formation comprises a sequence of thick-bedded, quartzofeldspathic wacke, interstratified with dark grey shale and siltstone, and thin beds of ash. The ash beds have yielded Middle Ordovician (late Darriwilian) ages of 463 ± 3 to 457 ± 4 Ma (van Staal *et al.* 2016). The Madran Formation comprises a sequence of high-Cr (avg. 422 ppm) alkali pillow basalt and minor trachyandesite interbedded with black shale. The Madran Formation is separated from the structurally overlying Devereaux Ophiolite Complex by a thin zone of sedimentary mélange containing blocks of Madran alkali basalt (Winchester *et al.* 1992a). Interpillow limestone near the structural base of the Madran Formation contains conodonts belonging to the *Pygodus anserinu*s zone, and interbedded black shale near the structural top contains graptolites of the *Nemagraptus gracilis* zone, indicative of a late Middle to early Late Ordovician (late Darriwilian to early Sandbian) age of deposition (Fyffe 1986).

The Elmtree Formation of the Sormany Group comprises a sequence of quartzose wacke, shale, minor limestone, and thin flows of low-Cr (avg. 38 ppm) alkali basalt. It is separated from the structurally overlying Pointe Verte Group by the Belledune River mélange, a highly tectonized zone of grey to black shale containing blocks of serpentinized peridotite, gabbro, mafic volcanic rocks, and wacke (Winchester *et al.* 1992a). Black shale in the Elmtree Formation contains graptolites of the upper *Nemagraptus gracilis* zone to lower *Diplograptus multiden*s zone, indicative of a Late Ordovician (Sandbian) age of deposition (McCutcheon *et al.* 1995). The youngest population of detrital zircons recovered from quartz-pebble conglomerate of the Elmtree Formation yielded an age of 457 ± 3 Ma (Wilson *et al.* 2015), denoting a maximum depositional age of early Sandbian (early Late Ordovician).

A separate fault panel of the dismembered Fournier sub-basin is located along the northern margin of the northeastern Miramichi terrane [MI (NE) on Fig. 1]. The fault panel (southern FN on Fig. 1) contains pillowed mafic volcanic rocks of the Armstrong Brook Formation and conformably overlying sedimentary rocks of Millstream Formation, both included in the Sormany Group. The Armstrong Brook basalts typically have a high-Cr (avg. 281 ppm) tholeiitic signature similar to TMORB, but also include compositions with lower Ti, Cr, Ni, and Zr contents similar to island arc tholeiites (IAT); and with higher Ti, Nb, Zr, and light REE contents similar to EMORB (Rogers and van Staal 2003). The Millstream Formation comprises thick-bedded wacke interstratified with grey to black shale, and minor limestone. Conodonts contained in the limestone indicate that the Millstream Formation is no older than early Middle Ordovician (Dapingian). The abundance of diabasic dykes intruding the Millstream sedimentary rocks suggests the presence of a transitional to oceanic substrate. The mafic volcanic rocks of the Armstrong Brook Formation are unconformably overlain by Late Silurian conglomerate (Helmstaedt 1971).

California Lake sub-basin

The earliest significant rifting associated with the opening of the Tetagouche backarc basin is recorded by the ca. 472 Ma eruption of basalts of the Canoe Landing Lake Formation of the California Lake Group, preserved along the Popelogan segment of the Popelogan–Meductic arc system (see fig. 8 of van Staal *et al.* 2003). The volcanic rocks of the California Lake Group were subsequently incorporated into the Salinic Accretionary Complex and thrust over the Bathurst sub-basin along the northern margin of the northeastern Miramichi terrane [MI (NE) on Fig. 1]. Remnants of three distinct volcanic sequences (Canoe Landing Lake, Spruce Lake, and Mount Brittain formations), each of which occupy three separate thrust panels, are all conformably overlain by the largely sedimentary Boucher Brook Formation; these four formations are therefore included together in the California Lake Group (Rogers and van Staal 1996; Rogers *et al.* 2003a; Wilson *et al.* 2015; van Staal *et al.* 2016), and considered to be part of the dismembered California Lake sub-basin (CA on Fig. 1).

The Canoe Landing Lake Formation comprises a suite of mainly pillow mafic volcanic rocks and minor dacitic flows. The mafic volcanic rocks in the lower part of the suite have compositions transitional between EMORB and alkali basalt. Voluminous tholeiitic basalts interfinger with, and over-lie, the transitional EMORB basalts. Geochemical signatures in the tholeiitic basalts range upsection from mildly enriched light-REE patterns with a positive Th anomaly and a small negative Nb anomaly similar to IAT into slightly depleted light-REE patterns similar to NMORB, suggesting a progressive reduction in slab influence as the Popelogan arc migrated to the northwest. The arc-like tholeiites in the Canoe Landing Lake suite contain lower Cr, and higher Ti, Nb, Zr, Th, and light-REEs compared to the less evolved Mount Brittain and Spruce Lake tholeiites. Mafic volcanic rocks at the stratigraphic top of the Canoe Landing Lake suite also have compositions transitional between EMORB and alkali basalts. Such overall compositional variations in the Canoe Landing Lake mafic volcanic suite are consistent with their generation on the active side of the nascent Tetagouche backarc basin (Rogers and van Staal 2003). A porphyritic dacitic flow (similar to the Spruce Lake dacite), interlayered with the lower EMORB basalts, has been dated as late Early to early Middle Ordovician (late Floian to early Dapingian) at 472 ± 2 Ma (Sullivan and van Staal 1993).

The Spruce Lake Formation, which structurally underlies the Canoe Landing Lake Formation, comprises a suite of quartz- and feldspar-phyric dacitic lava flows and domes, and subordinate tuffs, interlayered with dark grey to black siltstone and shale, and minor pillow basalt. The felsic volcanic rocks have the highest K, P, Ga, Rb, U, and Y, and lowest Na, Ba, and Zr contents in the region (Rogers *et al.* 2003a). Both the Spruce Lake and Mount Brittain basalts possess a slightly depleted light-REE pattern combined with a positive Th anomaly and negative Nb anomaly similar to IAT. The Caribou volcanogenic sulfide deposit is hosted in Spruce Lake black shale. Dacites from widely spaced locations near the structural base of the Spruce Lake Formation have been dated at 471 ± 2 Ma, 470 ± 5 Ma, and 471 ± 3 Ma (Walker and McCutcheon 1996; Sullivan and van Staal 1996; Rogers *et al.* 1997).

The parautochthonous Mount Brittain Formation, which structurally underlies the Spruce Lake Formation, comprises a mainly felsic volcanic suite of quartz- and feldspar-phyric, dacitic and rhyolitic flows and tuffs, which are host to the Restigouche and Murray Brook volcanogenic sulfide deposits. Rare lenses of pillow lava interfinger with the felsic volcanic rocks. The Mount Brittain basalts are very similar in composition to the Spruce Lake basalts but contain slightly lower Nb and Zr contents. The felsic volcanic suite is conformably underlain by dark grey shales and siltstones of the Charlotte member of the Mount Brittain Formation, which grade down into wacke and shale of the Patrick Brook Formation of the Miramichi Group (Helmstaedt 1971; Rogers *et al.* 2003b). Crystal tuffs of the Mount Brittain Formation have been dated at 472 ± 2 Ma, and 468 ± 2 Ma (Wilson and Kamo 1997; van Staal *et al.* 2003).

The Boucher Brook Formation conformably overlies the volcanic rocks of the Mount Brittain, Spruce Lake, and Canoe Landing Lake formations in all three thrust panels. In the Camel Back Mountain area in the northwestern part of the northeastern Miramichi terrane [MI (NE) on Fig. 1], the Boucher Brook Formation consists of a thick sequence of mafic volcanic rocks intercalated with red shale and overlain stratigraphically by dark grey to black shale, siltstone, and chert. The mafic volcanic rocks are massive to amydaloidal, pillowed alkali basalts interlayered with minor riebeckite-bearing, comenditic flows. The basalts are highly fractionated and contain lower Mg and Cr and higher Nb, Zr, Th, and REE compared to the EMORB basalts of the Canoe Landing Lake Formation (Rogers and van Staal 2003). Limestone pods in the Camel Back Mountain basalt contain conodonts belonging to the *Amorphognathus tvaerensis* zone of Late Ordovician (Sandbian to early Katian) age (Nowlan 1981). By that time (ca. 455 to ca. 450 Ma), the California Lake sub-basin, floored by transitional crust, would probably have drifted away from the Popelogan arc and become separated from it by true oceanic crust.

The California Lake Group of the California Lake sub-basin is separated structurally from the overlying Sormany Group of the Fournier sub-basin by a high-pressure/low-temperature blueschist metamorphic zone of highly strained pillow basalt and gabbroic rocks that can be traced along trend for a distance of ca. 70 km. The blueschist zone is interpreted to have served as a ductile shear zone that accommodated transport of the Armstrong Brook Formation of the Fournier sub-basin over the greenschist-facies Canoe Landing Lake Formation of the California Lake sub-basin (van Staal 1994; van Staal *et al.* 1990, 2008).

Bathurst sub-basin

The Bathurst sub-basin (BA on Fig. 1), located along the Popelogan segment the Popelogan–Meductic arc system in the northeasternmost part of the Miramichi terrane, contains volcanic and sedimentary rocks of the Orodovician Tetagouche Group. The lower part of the Tetagouche Group comprises a thick sequence of Middle Ordovician (Dapingian to early Darriwilian) felsic volcanic rocks assigned to the Nepisiguit Falls and Flat Landing Brook formations (Langton and McCutcheon 1993; van Staal and Fyffe 1995; McCutcheon *et al.* 1997; van Staal *et al.* 2003). Basal limestone, calcareous siltstone, and minor conglomerate (Vallée Lourdes Member of the Nepisiguit Falls Formation) lies unconformably on Cambrian to Early Ordovician sedimentary rocks of the Miramichi Group and marks the initial opening of the Tetagouche backarc basin in this segment. The presence of large-scale cross-bedding and a Celtic brachiopod fauna within the Vallée Lourdes Member suggest shallow-marine deposition on the passive margin of the backarc basin (Fyffe 1976; Fyffe *et al.* 1997; Poole and Neuman 2002). Quartz-feldspar crystal tuff (Grand Falls member of the Nepisiguit Falls Formation) yielded an age of 469 ± 2 Ma at the base of the Nepisguit Falls dam (Sullivan and van Staal 1996; Rogers *et al.* 2003a), and 473 ± 1 Ma near the Heath Steele sulfide deposit (Rogers *et al.* 1997, 2003a). At Tetagouche Falls, reworked tuff (Little Falls member of the Nepisiguit Falls Formation) yielded an age of 471 ± 3 Ma (Sullivan and van Staal 1996; Rogers *et al.* 2003a). Iron formation (Austin Brook Member of the Nepisiguit Falls Formation), which overlies the Grand Falls crystal tuff, is host to the Brunswick volcanogenic massive sulfide deposit, the largest deposit in the Bathurst Mining Camp (*BR* on Fig. 1).

The Flat Landing Brook Formation, a sequence of aphyric to feldspar-phyric dacitic to rhyolitic lava flows and related pyroclastic tuffs, interlayered with minor pillowed to massive basaltic flows, overlies the Nepisiguit falls Formation (van Staal *et al.* 2003; Rogers and van Staal 2003). The basaltic flows vary from high Cr-Ni tholeiites with slightly depleted light-REE patterns (NMORB-like) to low Cr-Ni tholeiites with enriched light-REE patterns and positive Th and negative Nb anomalies (continental arc-like). The arc-like signature is considered to be the result of crustal contamination (Rogers and van Staal 2003). A sample of aphyric rhyolite, collected from drillcore just below the contact with overlying alkali basalt of the Little River Formation, yielded a Middle Ordovician (early to middle Darriwilian) age of 466 ± 2 Ma (Rogers *et al.* 1997, 2003a). The eruption of mafic and felsic volcanic rocks in the Flat Landing Brook Formation demonstrates that rifting took place later in the Bathurst sub-basin than in the California Lake sub-basin (ca. 466 versus ca. 472 Ma ago).

The Little River Formation in the upper part of Tetagouche Group comprises a sequence of Late Ordovician hyaloclastic and pillowed alkali basalt, trachyandesite, and minor comendite, interbedded with ferromanganiferous chert and black shale related to sea-floor spreading and deep-water oceanic conditions in the Tetagouche backarc basin (van Staal and Fyffe 1995; van Staal *et al.* 2003; Rogers and van Staal 2003; Rogers *et al.* 2003b). Trachyandesite interlayered with alkali basalt of the Little River Formation north of the city of Bathurst yielded an early Late Ordovician (early Sandbian) age of 457 ± 1 Ma (Sullivan and van Staal 1996). Graptolites in black shale of the Little River Formation exposed on the the Tetagouche River near its mouth belong to the *Dicranograptus clingani* zone, indicative of a Late Ordovician (early Katian) age of deposition (Skinner 1974; Riva *in* Fyffe 1987). Thus, backarc spreading was ongoing later in the Bathurst sub-basin than in the Napadogan sub-basin, where it had ceased by the middle Sandbian of the Late Ordovician (see below). The Tomogonops Formation, a sequence of wacke and shale overlying the Little River Formation along the southeastern margin of the northeastern Miramichi terrane, records the onset of closure of the backarc basin. The total age spectrum of detrital zircons indicate a Laurentian provenance and hence was deposited after the accretion of the Popelogan Arc to Laurentia. The youngest detrital zircon population in the Tomogonops Formation dates at 455 ± 5 Ma, indicating a maximum depositional age of middle Sandbian of the Late Ordovician (Wilson *et al.* 2015).

Sheephouse Brook sub-basin

The Sheephouse Brook sub-basin (SH on Fig.1) is preserved in the southwestern part of northeastern Miramichi terrane (Fig.1) and is separated from the Bathurst sub-basin to the north by the east-southeasterly trending Moose Lake–Mountain Brook fault. The lower part of the Sheephouse Group comprises a sequence of Middle Ordovician (Dapingian to early Darriwilian) felsic volcanic rocks assigned to the Clearwater Stream and Sevogle River formations (Wilson and Fyffe 1996; Wilson *et al.* 1999). These felsic volcanic rocks are essentially coeval respectively with the Nepisiguit Falls and Flat Landing Brook formations in the Bathurst sub-basin but their lithological and geochemical characteristics are distinct (Fyffe 1995). The basal plagioclase-phyric crystal tuff of the Clearwater Stream Formation, host to the Chester volcanogenic sulfide deposit, has been dated at 469 ± 1 Ma (Wilson and Kamo 2007). The Clearwater Stream crystal tuff is dacitic in composition compared to the rhyodacitic to rhyolitic composition of the quartz-feldspar crystal tuff typical of the Nepisiguit Falls Formation and contains higher contents of high-field-strength elements (Nb, Ti, V, Zr) and REEs. The alkali feldspar-phyric rhyolite of the overlying Sevogle River Formation, dated at 466 ± 2 Ma (Wilson *et al.* 1999), contains higher K, Nb, and Zr contents than the Flat Landing Brook Formation, its counterpart in the Bathurst sub-basin (Fyffe 1995; Wilson *et al.* 1999).

The depositional contact between the Clearwater Stream dacitic tuff and underlying Patrick Brook Formation, which forms the uppermost sedimentary unit of the Cambrian to Early Ordovician Miramichi Group, was likely conformable although it is highly sheared. The Patrick Brook Formation consists of medium-bedded, quartzofeldspathic wacke intercalated with dark grey shale. The volcanogenic black quartz 'eyes' in the wacke were derived from a source not available to the relatively mature quartzose sandstones and shales of the underlying Knights Brook and Chain of Rocks formations, which would have been derived mainly from Ganderian basement. Shales in all three formations of the Miramichi Group contain lower Ni and Cr and higher Zr contents than in Ordovician shales overlying the Miramichi Group, reflecting a greater felsic igneous provenance relative to mafic igneous provenance for the former versus the latter. Moreover, shales from the Patrick Brook Formation contain lower Cr, Ni, Ti, and Fe contents then the underlying two formations of the Miramichi Group, suggesting a higher felsic igneous component in the former. This extra juvenile felsic component was likely derived from erosion of remnants of the Penobscot arc (Rogers *et al.* 2003b). A thin felsic tuff bed interlayered with wacke and shale of the Patrick Brook Formation in the vicinity of the Chester sulfide deposit has been dated at 477 ± 1 Ma, similar to the age the Porten Road Formation at the base of the Meductic Group (Dahn and Kamo 2022). Andesitic volcanic rocks, intersected in drillcore beneath Carboniferous sedimentary rocks to the southeast of Bathurst, have been dated at 477 ± 4 Ma, suggesting that some volcanic activity coeval with that of the Meductic arc has also occurred in the Bathurst sub-basin of the northeastern Miramichi terrane (Mohammadi *et al.* 2019; Walker and McCutcheon 2022). A flow-banded rhyolite in the Middle River area to the southwest of Bathurst is also likely coeval with Meductic volcanism, having been dated at 479 ± 6 Ma (McNicoll *et al.* 2002). The rhyolite lens is interstratified with the wacke sequence of Patrick Brook Formation (Miramichi Group) just below its unconformity with overlying Vallée Lourdes calcareous beds of the Nepisiguit Falls Formation (Tetagouche Group).

The Slacks Lake Formation, a sequence of mafic volcanic rocks interbedded with black shale and minor maroon chert and ironstone, comprises the upper part of the Sheephouse Brook Group. The mafic volcanic rocks, which conformably overlie rhyolitic volcanic rocks of the Sevogle River Formation, possess both tholeiitic and alkali affinities. The tholeiitic basalts display a within-plate-like signature with a moderately enriched light-REE pattern. The alkali basalts vary to trachyandesites and are intruded by domes of comendite (Fyffe 1995, Wilson *et al.* 1999), suggesting that a major rift structure may have existed between the Bathurst and Sheephouse Brook sub-basins in the late Middle to early Late Ordovician (see fig. 6 of van Staal *et al.* 2003).

Napadogan sub-basin

Remnants of the Napadogan sub-basin (NP on Fig. 1) are preserved along the Popelogan–Meductic arc system in the southwestern Miramichi terrane [MI (SW) on Fig. 1]. The sub-basin is faulted to the northwest against Cambrian–Ordovician psammite, pelite, and amphibolite that were metamorphosed up to sillimanite-facies in the core of the Miramichi Highlands during the Silurian; and against greenschist-facies Silurian sedimentary rocks of the Fredericton trough to the southeast (Fyffe *et al.* 1988b). The Tetagouche Group in the Napadogan sub-basin comprises the Turnbull Mountain, Hayden Lake, and Push and Be Damned formations (Fig. 2). The Turnbull Mountain Formation was introduced by Poole and Neuman (2002) in their study of the distribution of Celtic brachiopods in the Napadogan sub-basin. Exposures at the type-section, located at Turnbull Mountain in the western part of the sub-basin about 5 km north-northeast of the community of Napadogan, includes a lens of quartzite-pebble conglomerate of the Upper Buttermilk Brook member overlain by brachiopod-bearing calcareous siltstone of the Lower Birch Island member. The conglomerate lens is correlated with quartzite-pebble conglomerate exposed in the Upper Buttermilk Brook area, located about 12 km to the north-northeast of Turnbull Mountain. The calcareous siltstone is correlated with brachiopod-bearing calcareous siltstone exposed on the southwest Miramichi River near Lower Birch Island, about 30 km northeast of Turnbull Mountain. The two members were previously referred to as the Buttermilk Brook and Lower Birch Island formations by van Staal and Fyffe (1995).

The Lower Birch Island member, on the southeastern margin of the Napadogan sub-basin at Lower Birch Island (Fig. 2) comprises a sequence of calcareous siltstone intercalated with thin lenticular beds of felsic tuff, lying disconformably on quartzose sandstone of the Cambrian to Early Ordovician Knights Brook Formation of the Miramichi Group (Irrinki 1980; van Staal and Fyffe 1995). No quartzite pebble conglomerate of Upper Buttermilk Brook member is present at this location. Brachiopods and the conodont species *Microzarkodina flabellum* indicate that the felsic tuffs were deposited in shallow water along the southeastern margin of the Napadogan sub-basin in the Early to Middle Ordovician (late Florian to late Dapingian) from ca. 472 to ca. 467 Ma ago, during ongoing extension and crustal thinning in the Tetagouche backarc (Nowlan 1981; van Staal and Fyffe 1995; Poole and Neuman 2002). Felsic volcanic rocks equivalent to the Flat Landing Brook Formation of the Bathurst sub-basin are lacking or very scarce in the Napadogan sub-basin, suggesting a lesser degree of extension proximal to the passive margin of the Tetagouche backarc basin in the southwestern Miramichi terrane.

The Lower Birch Island member is overlain to the northwest by Hayden Lake Formation, a sequence of red ferromanganifeous chert and siltstone overlain by black carbonaceous chert and shale (Fig. 2). Graptolites in black chert, northeast of Napadogan, belong to the *Glyptograptus terretiusculus* zone, and in the Lower Birch Island area to *Nemagraptus gracilis* zone, indicating a Middle to Late Ordovician (middle Darriwilian to early Sandbian) time of deposition. A one-metre-thick bed of coarse-grained sandstone at the base of the Hayden Lake Formation suggests a period of mild uplift preceded deposition of the deep-water ferromanganiferous beds (Irrinki 1980, 1981; Crouse 1981a; Fyffe *et al.* 1988b). This hiatus marks the interval between the cessation of volcanism in the Meductic arc and subsequent eruption of mafic volcanic rocks associated with rifting along the northwestern margin of the sub-basin (Fig. 2).

The Upper Buttermilk Brook member is exposed along the northwestern margin of the Napadogan sub-basin in the Upper Buttermilk Brook area (Fig. 2). It is composed of lenses of monomictic conglomerate interbedded with sandstone (Crouse 1981b; van Staal and Fyffe 1995). The clasts, which are well rounded and up to 25 cm in diameter, are clearly derived from the underlying Miramichi Group. The lower contact of the member is not exposed, but the conglomerate is assumed to lie disconformably on quartzose sandstone of the Miramichi Group (Crouse 1981b). Poole and Neuman (2002) reported a few unidentifiable brachiopod fragments in sandstone on-trend to the southwest of the Upper Buttermilk Brook conglomerate but no calcareous siltstone characteristic of the Lower Birch Island member was observed. The conglomerate and sandstone of the Upper Buttermilk Brook member are interpreted to have been deposited along normal fault scarps formed along the northwestern margin of the Napadogan sub-basin during ongoing extension within the Tetagouche backarc basin.

Conglomerate and sandstone of the Upper Buttermilk Brook member is overlain to the southeast by mafic pillowed flows and minor aphanitic felsic volcanic rocks. These volcanic rocks are included in the Hayden Lake Formation since they are intercalated with red and black chert and shale and were therefore likely erupted in the deeper northwestern part of the Napadogan sub-basin in the Middle to Late Ordovician (middle Darriwilian to early Sandbian) at 462–455 Ma (Fig. 2). The mafic volcanic rocks have both within-plate-like tholeiitic and alkalic affinities. The tholeiitic basalts contain significantly higher Cr (272–882 ppm) and lower TiO_2 (1.1–2.7 wt. %) compared to Cr (13–64 ppm) and TiO_2 (2.6–3.6 wt. %) contents in the alkaline basalts. A comenditic composition was obtained from a felsic flow, which contained 2851 ppm Zr and 371 ppm Nb (Fyffe *et al.* 1988b; Winchester *et al.* 1992b). Eruption of alkalic volcanic rocks in the Napadogan sub-basin is interpreted to have occurred during rifting in the Tetagouche backarc basin although the Meductic arc itself had shutdown by this time (Fig. 2).

The Push and Be Damned Formation, a sequence of medium- to thick-bedded, lithic wacke and shale, and minor polymictic conglomerate (Fig. 2), conformably overlies the Hayden Lake Formation (Irrinki 1980, 1981; Crouse 1981a, b). The post-volcanic sedimentary rocks of the Push and Be Damned Formation must have been deposited in the later Sandbian and early Katian of the Late Ordovician since they immediately overlie Hayden Lake chert containing graptolites of the *Nemagraptus gracilis* zone. Deposition of the Push and Be Damned Formation in the Napadogan sub-basin therefore began somewhat later than that of the wacke sequence of the Belle Lake Formation, which was eroded from the extinct Meductic arc and contains graptolites of the *Nemagraptus gracilis* zone (Fig. 2).

Becaguimec sub-basin

The Becaguimec sub-basin (BC on Fig. 1) is characterized by a sequence of Middle to Late Ordovician limestone deposited along the northwestern margin of the Miramichi terrane and largely hidden beneath a cover of latest Ordovician to Silurian rocks. Thick-bedded styolitic, nodular limestone of the Black Brook Formation is exposed in a small inlier exposed along Markey Brook [BC (MB) on Fig. 1], located about 40 km north of Meductic [MD on Fig. 1]. Conodonts from the nodular limestone belong to the *Pygodus serrus* zone of the Middle Ordovician (late Darriwilian). Sandy limestone and associated limestone pebble conglomerate is exposed about 150 m downstream (St. Peter 1982). The sandy limestone contains the conodont species *Gamachignathus ensifer*, characteristic of the Late Ordovician (Hirnantian), and accordingly it and the pebble conglomerate are assigned to the White Head Formation (Fig. 2).

The type-section of the Black Brook Formation is located in a fault slice about 3 km to the east of Markey Brook, along the west side of the North Becaguimec River just to the north of its confluence with Black Brook (misidentified as Craig Brook on old base maps). Thin-bedded, lithographic limestone interstratified with calcareous siltstone (ribbon rock) on the North Branch Becaguimec River about 800 m upstream from Black Brook contain conodonts belonging to the *Pygodus Serrus* through to *Pygodus anserinus* zone of the Middle to Late Ordovician (late Darriwilian to early Sandbian). Thick-bedded crystalline limestone farther upstream contains conodonts belonging to the *Prioniodus gerdae* subzone of the *Amorphognathus tvaerensis* zone of the Late Ordovician (late Sandbian) age (St. Peter 1982; Nowlan *et al.* 1997). An inlier of Black Brook nodular limestone, exposed in the Ashland quarry about 7 km to the southwest of the Markey Brook, contains conodonts belonging to the *Pygodus anserinus* zone of Middle to Late Ordovician (latest Darriwilian to earliest Sandbian) age (St. Peter 1982).

An outlier (fault sliver?) of thick-bedded, crystalline limestone of the Black Brook Formation is exposed in the Central Waterville quarry, located about 15 km northeast of Meductic, where it is inferred on the basis of fossil evidence to unconformably overly Early Ordovician black shale of the Bright Eye Brook Formation (Fig. 2). The limestone beds (now largely mined out) are extensively boudinaged and the adjacent black shale is deformed into tight kink folds. Thin beds of felsic tuff, interbedded with the black shale, likely correlate with felsic volcanic rocks in the lower part of the Meductic Group. The limestone contains conodonts species found near the boundary between the *Pygodus serrus* zone and *Pygodus anserinus zone,* indicative of a Middle Ordovician (late Darriwilian) age (Hamilton 1965; Venugopal 1979; Nowlan 1981).

The abundance of fragmented shelly fauna in the Black Brook Formation suggests deposition in the Becaguimec sub-basin occurred in a high energy, relatively shallow-water environment (St. Peter 1982). Deposition of the limestone spanned the time period from late Darriwilian to late Sandbian and overlapped with the time of deposition of the graptolite-bearing Belle Lake Formation (early Sandbian), which covers the volcanic succession of the extinct Meductic arc. The Black Brook limestone is therefore interpreted to represent a near-shore facies that was deposited on the rifted margin of the Becaguimec sub-basin during opening of the Fournier sub-basin hehind the Popelogan arc (Fig. 4d).

Fossiliferous limestone and spatially associated felsic volcanic rocks are tectonically interleaved with Late Ordovician (middle to late Katian) wacke and shale of the Boland Brook Formation (Grog Brook Group) in the Oxford Brook area [BC (OX)], about 20 km southwest of the Popelogan inlier (PO on Fig. 1). The Oxford Brook area is transected by several faults interpreted to be splays of the major Rocky Brook–Millstream fault system; the fossiliferous limestone is exposed in one of the fault slices about 20 m from an outcrop of felsic tuff, but the contact is not exposed. Conodonts recovered from the limestone belong to the *Prioniodus variabilis* to *Prioniodus gerdae* subzones of the *Amorphognathus tvaerensis* zone (A.D. McCracken, personal communication to R. A. Wilson 2017), indicative of a Late Ordovician (Sandbian) age (Fig. 2). The felsic tuff is interpreted to be correlative with a calc-alkaline rhyolite exposed in a small inlier about 10 km along strike to the southwest, which has been dated as Middle Ordovician (late Dapingian to early Darriwilian) and included with the mainly mafic volcanic sequence of the Goulette Brook Formation (see above under Popelogan Arc (Fig. 2). This age difference implies a disconformable or more likely faulted relationship between the limestone and nearby felsic tuff. A sample of mafic volcanic rock exposed near the northern end of the Oxford Brook inlier displays a signature typical of tholeiitic basalts erupted in an extensional backarc basin setting, including a relatively flat pattern REE pattern and lack of a pronounced negative Nb anomaly (Wilson 2003). The Oxford Brook basalt (Fig. 2) was likely erupted into the Becaguimec sub-basin during extension in the Tetagouche backarc in the Late Ordovician. The limestone at Oxford Brook overlaps in age with limestone in the upper part of the Black Brook Formation preserved in the fault sliver along the North Becaguimec

River (Fig. 2), indicating that both areas represent parts of the same structurally dismembered Becaguimec sub-basin that once extended along the full length of the northwestern margin of the Miramichi terrane.

The deposition of the Black Brook limestone of Becaguimec sub-basin also overlaps with deposition of the limestone associated with the Camel Back Mountain alkali basalt of the California Lake sub-basin (CA on Fig. 1) and interbedded with sedimentary rocks of the Millstream Formation (southern FN on Fig. 1), suggesting that these sub-basins may once have been linked. The initiation of arc-like tholeiite and MORB-like mafic volcanism associated with the formation of backarc oceanic and transitional crust in the California Lake sub-basin occurred in the Dapingian (470–467 Ma), just prior to the cessation of Meductic calc-alkaline arc magmatism (Rogers and van Staal 2003; van Staal *et al.* 2016). We propose that the Tetagouche back-arc basin progressively widened behind the Popelogan segment of the Popelogan–Meductic arc system and evenually an arm of the basin propagated lengthwise into the former forearc area of the Meductic segment after it had shut down (Figs. 2 and 4d).

PICKETT MOUNTAIN ARC

Recent surface mapping and exploration drilling in and around the Pickett Mountain massive sulfide deposit (*PM* on Fig. 1; previously known as the Mount Chase deposit) has provided much new data (McCormick 2021) on the poorly exposed Ordovician volcanic sequence that underlies the southeastern margin of the Weeksboro–Lunksoos terrane in eastern Maine (WL on Figs. 1 and 3). Fine-grained rhyolitic tuffs containing lenses of ferruginous chert comprise the immediate hanging wall of the deposit; mafic tuffs and varicoloured siltstone and mudstone interbedded with felsic tuffs occur higher in the section. Quartz crystal tuff and felsic breccia dominate in the footwall. The felsic volcanic rocks in the hanging wall are tholeiitic whereas those in the footwall display a transitional tholeiitic to calc-alkaline affinity. The basaltic volcanic rocks intercalated with the felsic volcanic rocks in the hanging wall display moderately enriched light-REE patterns and a negative Nb anomaly. These calc-alkaline geochemical characteristics are consistent with generation in a continental arc or backarc setting (Scully 1988; Schulz and Ayuso 2003; McCormick 2021).

Ayuso *et al.* (2003) previously reported a zircon date of 467 ± 5 Ma from an altered dacite porphyry dyke or dome cutting footwall volcanic rocks of the Pickett Mountain deposit, thus providing a minimum age for the volcanic sequence. McCormick (2021) collected a drillcore sample of crystal tuff from the footwall and a hand sample of rhyolite tuff from the hanging wall of the Pickett Mountain deposit for zircon dating. These samples yielded Early Ordovician (Tremadocian) ages of 485 ± 2 Ma and 481 ± 3 Ma, respectively. Both Ayuso *et al.* (2003) and McCormick (2021) correlated the Pickett Mountain volcanic sequence with the Shin Brook Formation, although the type-area of the latter occurs well to the northwest of the deposit and cannot be shown with confidence to continue into the southeastern part of the Weeksboro–Lunksoos terrane (Neuman 1967; Ekren and Frischknecht 1967). Since the boundary zone between the two sequences is intruded by the Rockabema pluton, it can be surmised that the Pickett Mountain and Shin Brook vol-canic rocks were juxtaposed against each other prior to the Early Silurian (Neuman 1967).

According to Neuman (1967), the Shin Brook Formation, a steeply dipping sequence of felsic tuffs exposed in the northwestern part of the Weeksboro–Lunksoos terrane, lies with apparent unconformity on the Grand Pitch Formation, a sequence of complexly folded Cambrian quartzose sandstone and wacke interbedded with grey, green, and red siltstone and shale (Fig. 3). The tuffs contain a unique brachiopod fauna that define the Celtic biogeographic assemblage, which is found in Ganderian terranes from Maine to Newfoundland (Neuman 1964, 1967, 1984). Local, thin beds of conglomerate, lying conformably below the fossiliferous tuffs, contain sedimentary pebbles derived from Grand Pitch strata. Boulder-sized clasts of volcanic rock are also locally present in the basal conglomerate (Ekren and Frischknecht 1967), suggesting the existence of an earlier eposode of volcanism in the Shin Brook area.

The period of tectonic uplift associated with the Shin Brook unconformity was referred to as the 'Penobscot Disturbance' by Neuman (1967). Neuman (in Poole and Neuman 2002) in his review of the paleontological evidence from Maine and New Brunswick, concluded that the Shin Brook tuffs above the unconformity were deposited in the late Arenigian (Dapingian) between ca. 470 and ca. 467 Ma ago. Neuman further noted that the pebble conglomerate, lying conformably below the tuffs in Maine, is likely no older than middle Arenigian (late Floian). Thus, subsidence related to the Penobscot Disturbance in the Weeksboro–Lunksoos terrane appears to have occurred later than the early Floian subsidence that followed the closure of the Penobscot backarc basin in the Annidale terrane. We therefore conclude that the Shin Brook unconformity is related to late Early to early Middle Ordovician tectonic uplift and subsidence associated with extension in the Popelogan–Meductic arc system (Poole and Neuman 2002; van Staal *et al.* 2016).

We contend that if Neuman's Shin Brook age assignment (470–467 Ma) is correct, then the two Early Ordovician dates (485 ± 4 Ma and 481 ± 3 Ma) obtained from the Pickett Mountain volcanic sequence, even after allowing for some inheritance, do not represent volcanic samples from the Shin Brook Formation. It is noteworthy that the fossiliferous Shin Brook horizon has not been identified on the southeastern margin of the Weeksboro–Lunksoos terrane. Instead, a fault-bounded block of poorly documented, mainly mafic rocks underlies the Mount Chase area to the southeast of the Pickett Mountain sequence. To quote Ekren and Frischknecht (1967), who mapped the area around the Pickett Mountain deposit prior to its discovery in 1979, "The [Shin Brook] formation was not recognized along the northwest flank of the Mount Chase ridge, where lavas are in depositional or fault contact with the Grand Pitch. The volcanic strata there contain neither conglomerate nor fossiliferous beds of tuffaceous sandstone".

Neuman (1967) described the continuation of the Mount Chase mafic rocks into his map-area under "Unnamed Volcanic Rocks". He noted that pillows in these mafic rocks were infilled by red and green chert and that a tuff breccia near the contact with the underlying Grand Pitch Formation contained fragments of quartzite. The minimum age of the Mount Chase mafic rocks is constrained by the presence of Late Ordovician (late Sandbian) graptolites of the *Climacograptus bicornis* zone in conformably overlying black chert of the Wassataquoik Formation (Fig. 3) and are, therefore, at least in part younger than the Shin Brook felsic volcanic rocks (Neuman 1967; Ekren and Frischknecht 1967). In a reconnaissance geochemical study, Winchester and van Staal (1994) showed that the Mount Chase mafic volcanic rocks are within-plate-like tholeiitic basalts with a mildly enriched light-REE pattern, consistent with eruption during Tetagouche backarc rifting. Schulz and Ayuso (2003) found that some of the tholeiitic basalts from the Mount Chase area have a small negative Nb anomaly but locations of their analyzed samples are unknown. Obviously, more detailed work is needed on these rocks.

Scully (1988) tentatively correlated sedimentary rocks beneath the footwall tuffs of the Pickett Mountain sulfide deposit with the Cambrian Grand Pitch Formation. The only photograph of these rocks shown in his thesis is a thin-bedded, black, carbonaceous siltstone, which is not particularly characteristic of the typically quartz-rich sedimentary rocks of the Grand Pitch Formation but could be a facies equivalent of it. Scully (1988) also considered the presence of some sedimentary clasts in a footwall volcanic breccia to be evidence of an unconformable relationship with the underlying sedimentary rocks. This may well be the case but the character of the unconformity would be unlike that seen along Shin Brook. McCormick (2021) did not present any field evidence for an unconformity on his regional map in the vicinity of the Pickett Mountain deposit. Note that if a Shin Brook unconformity can be shown to exist in the Pickett Mountain section, then the two new dates from the sulfide deposit would appear to be far too old based on Neuman's paleontological evaluations.

The two recent Early Ordovician ages (485 ± 4 Ma and 481 ± 3 Ma) overlap (within error) with 482 ± 2 Ma and 481 ± 2 Ma dates obtained from plagiogranites in the Annidale terrane, so the Pickett Mountain deposit may be hosted by volcanic rocks that represent a remnant of the Penobscot arc system. The existence of Penobscot remnants in the more northern parts of Maine and New Brunswick is suggested by the presence of volcanic clasts in volcanogenic wackes of the Patrick Brook Formation, which lies at the top of the Miramichi Group, beneath the Penobscot unconformity exposed on the Tetagouche River in the northeastern Miramichi terrane (Fyffe 1976; Lentz *et al.* 1996; Fyffe *et al.* 1997; McNicoll *et al.* 2002; Rogers *et al.* 2003b).

The Weeksboro–Lunksoos terrane thus appears to be composite in that it contains Pickett Mountain calc-alkaline volcanic rocks interpreted as a remnant of the Penobscot arc system as well as Shin Brook felsic volcanic rocks related to extension in the Tetagouche backarc basin, respectively (Fig. 3). The close association of Celtic faunas with disconformities in the Shin Brook area of Maine and Napadogan area of New Brunswick (Fig. 3) suggests that the Weeksboro–Lunksoos terrane was proximal to the continuation of the southwestern Miramichi terrane into Maine prior to Tetagouche backarc rifting. Neuman (1967) referred to a broad, highly deformed, boundary zone between the Ordovician volcanic rocks and Silurian sedimentary rocks along the southeastern margin of the Weeksboro–Lunksoos terrane as a 'fault complex', and interpreted displacement along the boundary to be mainly right-lateral. We therefore propose that the present location of the Early Ordovician Pickett Mountain remnant and its attached Middle Ordovician Shin Brook remnant (WL on Fig. 1) is at least partly due to dextral displacement along this fault system during the Acadian orogeny.

MUNSUNGUN LAKE ARC

The Munsungun–Winterville terrane in northern Maine (MW on Fig. 1) is composed of two parts: the Munsungun inlier to the southwest and the Winterville inlier to the northeast. Hall (1970) divided the Ordovician volcanic rocks in the southwestern part of the Munsungun inlier into two main sequences. The Munsungun Lake Formation comprises felsic pyroclastic rocks, red chert, mafic breccia, and rare pillow basalt, whereas the Bluffer Pond Formation, exposed to the northwest of the Munsungun Lake Formation, is distinguished by the predominance of pillow basalt and the absence of red chert (Fig. 3).

Hall (1970) considered that the Munsungun Lake volcanic rocks occupied a higher position in the stratigraphic section than the Bluffer Pond pillowed basalt; however, recent geochronological evidence obtained from the northeastern part of the Munsungun inlier (Auyso *et al.* 2003; Wang 2018, 2019) indicates that the Munsungun Lake Formation extends back to the early Middle Ordovician (Dapingian) and hence is older than the Bluffer Pond Formation (see below). Graptolites collected by Hall (1970) from the black Willard Ridge chert at the top (Hall's base) of the Munsungun Lake Formation belong to the *Climacograptus bicornis* zone (late Sandbian), which limits the minimum age of eruption for the Munsungun Lake volcanic rocks in the southwestern part of the Munsungun inlier to ca. 455 Ma ago (Bergstrom 1977; Wang *et al.* 2018). The Munsungun Lake Formation in the southwestern part of the Munsungun inlier locally contains high Mg-Cr-Ni calc-alkaline basalt enriched in light REEs (Winchester and van Staal 1994). The Munsungun Lake volcanic sequence is structually underlain by the Chase Brook Formation, a shaley mélange containing blocks of wacke and shale. Conodonts from a limestone clast in the

Chase Brook Formation indicate a maximum Early to Middle Ordovician (Floian to Dapingian) age of formation for the mélange (Wang *et al.* 2018; Pollock 2020).

Graptolites collected by Hall (1970) from black chert interbeds in the Bluffer Pond volcanic rocks belong to the *Climacograptus bicornis* zone of the Late Ordovician (late Sandbian, ca. 455 to ca. 453 Ma ago). The Bluffer Pond basalts possess a within-plate-like tholeiitic affinity with moderately enriched, light-REE patterns (Winchester and van Staal 1994). The Bluffer Pond Formation is conformably underlain by the Chase Lake Formation, a local sequence of conglomerate and sandstone that contains a poorly preserved shelly and graptolite fauna. A Late Ordovician (*Nemagraptus gracilis* zone) fossil assemblage suggests deposition of these sedimentary rocks occurred during early Sandbian, just prior to the eruption of the Bluffer Pond pillow basalt.

The Blind Brook Formation, a sequence of conglomerate, sandstone, and shale, unconformably overlies the volcanic rocks of the Bluffer Pond Formation (Fig. 3). Shale beds in the Blind Brook Formation contain graptolites belonging to the *Orthograptus truncatus var. intermedius* zone indicative of a Late Ordovician (Katian) age of deposition (Hall 1970). The Blind Brook unconformity indicates that volcanism in the Munsungun–Winterville terrane had ceased by ca. 450 Ma ago, presumably due to the collision of the Munsungun Lake arc and attempted subduction of the Laurentian margin during the later stages of the Taconic orogeny (Hall 1970; Pollock 2020).

The Munsungun Lake Formation with its characteristic red chert has been traced along the southeastern margin of the Munsungun inlier to the area of the Bald Mountain massive sulfide deposit (*BM* on Fig 1), located at the northeastern corner of the inlier (Wang 2018, 2019, 2021a; Pollock 2020). The deposit is hosted by a homoclinal, northwesterly younging volcanic sequence previously included in the Winterville Formation (Foose *et al.* 2003), but now shown to be part of the Munsungun Lake Formation (Wang 2021a). The host volcanic rocks are dominated by a lower, locally pillowed sequence of basaltic lava flows and hyaloclastic breccias, possessing a primitive tholeiitic signature (IAT) characterized by a mildly depleted light-REE pattern and a strong negative Nb anomaly. Pyroxene-phyric tholeiitic basalt, containing high Mg (12.1–12.6 wt. % MgO), Cr (410–765 ppm), and Ni (80–169 ppm) and a depleted light-REE pattern, are a minor component of the lower sequence. An elongate body of tonalite, which intrudes the footwall section of the Bald Mountain sulfide deposit, has the geochemical characteristics of an oceanic plagiogranite.

The mafic sequence is overlain by an upper predominantly pyroclastic sequence of massive to locally bedded dacitic to rhyolitic tuffs. The Bald Mountain sulfide deposit is located near the base of the felsic pyroclastic sequence and is capped by a ferruginous chert. The felsic tuffs range from tholeiitic in the lower part of the section to calc-alkaline in the upper part. Minor basaltic and andesitic flows intercalated with the felsic tuffs in the lower part of the pyroclastic section display a tholeiitic, flat-REE pattern and negative Nb anomaly (Foose *et al.* 2003; Schulz and Ayuso 2003; Busby *et al.* 2003).

Two samples of felsic tuff from the lower primitive tholeiitic part of the Munsungun Lake Formation, and a sample of felsic tuff from the upper calc-alkaline part, yielded Middle Ordovician ages of 468 ± 2 Ma and 471 ± 4 Ma (Dapingian), and 467 ± 4 Ma (early Darriwilian), respectively (Wang 2018, 2019; Wang *et al.* 2018; Ayuso *et al.* 2003). These ages demonstrate that the Bald Mountain deposit is younger than the Pickett Mountain deposit in the Weeksboro–Lunksoos terrane (McCormick 2021) and is similar in age to the Brunswick sufide deposits in the Tetagouche backarc basin. The volcanic rocks of the Munsungun Lake Formation in the Bald Mountain area have been thrust to the west (Foose *et al.* 2003) over the Rowe Lake Formation, a sequence of Late Ordovician conglomerate and sandstone that was deposited no earlier than the late Katian (Fig. 3), based on the ca. 447 Ma date of the youngest cluster of detrital zircons; older contained zircons in the sandstone were clearly sourced from the Laurentian margin (Wang 2021a, b).

The Ingalls Brook Road Formation, located in the northwestern part of the Munsungun inlier to the west of the Bald Mountain area, comprises a sequence of basaltic flows and breccias, and minor bedded pyroclastic rocks. This volcanic sequence overlies the Chase Brook mélange and is unconformably overlain by the Blind Brook Formation (Fig. 3). The basalts have a tholeiitic-arc affinity and were erupted in Late Ordovician (early Sandbian) as indicated by a zircon date of 457 ± 2 Ma from a felsic tuff (Wang 2021b). The southwestern portion of the Winterville inlier in the Fish River Lake and Carr Pond areas is underlain by the Winterville Formation, a sequence of amygdaloidal and pillowed basalt and agglomerate, interlayered with lesser porphyritic dacitic and rhyolitic flows, and felsic lapilli tuff. The basalts exhibit a transition between a tholeiitic and calc-alkaline affinity with negative Nb and Ta anomalies and a moderately enriched light-REE pattern, characteristic of an ensialic arc-setting (Winchester and van Staal 1994; Wang 2021b, 2022a, b), and may correlate with the Ingalls Brook Road Formation. The Ferguson Brook Formation (Fig. 3), a sequence of wacke, slate and minor conglomerate, unconformably overlies the Winterville volcanic rocks (Wang 2022b). The Ferguson Lake Formation was deposited no earlier than the Hirnantian of the Late Ordovician, based on the 443 ± 3 Ma date of the youngest cluster of detrital zircons; older contained zircons in the wacke exhibit a Laurentian spectrum (Wang 2021a). Alkaline basalts have been reported from the the Winterville inlier in the Portage Lake area to the east of the Fish River Lake volcanic-arc rocks (Winchester and van Staal 1994). Eruption of the Middle Ordovician Kennebec felsic volcanic suite and the Late Ordovician Lobster Mountain mafic volcanic suite in the Lobster Mountain area (LM on Fig. 1) likely was contemporaneous respectively with volcanic activity in the Munsungun Lake and Bluffer Pond formations of the Munsungun–Winterville terrane (Boone *et al.* 1989; Winchester and van

Staal 1994; Moench and Aleinikoff 2003).

The Middle Ordovician volcanic suites of the Munsungun–Winterville and the Popelogan terranes (Fig. 1) are comparable in age and geochemistry and may have undergone a similar evolutionary history (van Staal *et al.* 2016). The presence of Ordovician alkaline volcanic rocks in the Portage Lake area of the Winterville inlier supports the proposal that backarc rifting and northwesterly trench migration has affected both the Munsungun–Winterville and Popelogan terrane. We propose that Munsungun Lake arc and associated forearc had migrated to the northwest and were subjected to ridge subduction and shallowing of the subduction angle (van Staal *et al.* 2003; Wilson 2003; van Staal *et al.* 2016). Ridge subduction would then be followed by underthrusting of Laurentian-sourced sediments derived from the converging Laurentian margin. A similar model of ridge subduction was proposed in the Chesuncook Lake area (CH on Fig.1) by Schoonmaker and Kidd (2006) but with opposite slab polarity. In our hypothesis, shallowing of the southeasterly dipping slab angle following southeasterly subduction of the buoyant ridge in the late Middle Ordovician led to cessation of Munsungun Lake arc volcanism at ca. 460 Ma ago. The subsequent eruption of the Ingalls Brook Road and Winterville basalts at ca. 457 Ma ago (early Sandbian of the Late Ordovician) would mark the return to extensional arc volcanism following steepening of the slab angle. Conglomerate and sandstone of the Chase Lake Formation may have been deposited in the forearc region associated with the eruption of within-plate-like tholeiitic basalts of the Bluffer Pond Formation into the rifted Middle Ordovician Munsungun arc following ridge subduction. Alternatively, Wang *et al.* (2022) have proposed that subduction polarity reversed to the northwest following accretion to Laurentia and that the Iapetan suture should be placed to the southeast of the Munsungun–Winterville terrane (Fig. 1). In either case, volcanism in the Munsungun–Winterville terrane had ceased with accretion to Laurentia and slab break-off by ca. 443 Ma.

The Bronson Hill terrane of southwestern Maine and New Hampshire (BH on Fig. 1) contains two volcanic suites of similar age and chemistry to the Munsungun–Winterville terrane. The Ammonoosuc volcanic suite has been dated 465 ± 6 and 461 ± 8 Ma (Moench and Aleinikoff 2003), and at 475 ± 5 and 460 ± 3 Ma (Valley *et al.* 2020). The overlying Quimby suite has been dated at 453 ± 2 and 449 ± 3 Ma (Tucker and Robertson 1990), and 443 ± 4 Ma (Moench and Aleinikoff 2003). The Ammonoosuc volcanic suite was considered by van Staal *et al.* (1998) to have formed beneath a southeasterly dipping Iapetan subducting slab on the Gondwanan side of Iapetus Ocean. However, Moench and Aleinikoff (2003) argued for a peri-Laurentian setting and therefore placed the Iapetan suture to the southeast of the Ammonoosuc arc. Later geochemical studies by Dorais *et al.* (2012) and the age profile exhibited by detrital zircons from underlying sedimentary rocks of the Dead River Formation (Macdonald *et al.* 2014) support the peri-Gondwanan model. Ongoing field mapping and geochronological work currently being conducted by researchers in New England will hopefully lead to a better understanding of the tectonic relationship between the the older and younger volcanic suites in the Bronson Hill terrane.

CONCLUSIONS

The above review of geological information from Ganderian terranes (Fig. 1) indicates a pattern consistent with progressive, episodic, northwesterly migration of Early Paleozoic Penobscot and Popelogan–Meductic arc-backarc systems in New Brunswick and Maine (Figs. 2 and 3). Post-Penobscot, calc-alkaline volcanism in the Meductic arc of the southwestern Miramichi terrane of west-central New Brunswick and adjacent Maine began in the Floian of the Early Ordovician at ca. 478 Ma and ended in in the Dapingian of the Middle Ordovician at ca. 467 Ma, spanning a period of about 10 million years. Arc volcanism in the Popelogan terrane lasted at least from the late Dapingian at ca. 468 Ma to the late Darriwilian at ca. 460 Ma of the Middle Ordovician. Volcanism associated with opening and spreading of the Tetagouche backarc basin lasted from the late Floian of the Early Ordovician at ca. 472 Ma to the Sandbian of the Late Ordovician at ca. 455 Ma (Fig. 4).

Volcanic rocks hosting the Pickett Mountain sulfide deposit in the Weeksboro–Lunksoos terrane of Maine, previously considered to have erupted in the Middle Ordovician, have now been dated as Tremadocian of the Early Ordovician at 485 ± 4 Ma and 481 ± 3 Ma (McCormick 2021), and so are considered to represent a remnant of the Penobscot arc system. However, Ludman *et al.* (2021) claimed that these new dates required that a separate, southeasterly dipping subduction zone is required beneath the Weeksboro–Lunksoos terrane, presumably because the Pickett Mountain sequence is slightly older than the volcanic rocks of the Meductic arc, located farther to the southeast.

The Bald Mountain sulfide deposit, which is hosted by a Middle Ordovician volcanic arc sequence within the Munsungun–Winterville terrane, is therefore significantly younger than the Pickett Mountain deposit, rendering previous models relating the two inapplicable. The Weeksboro–Lunksoos terrane also contains felsic and mafic volcanic rocks related to extension and rifting in the Tetagouche backarc basin (Shin Brook Formation and Mount Chase volcanics). The Weeksboro–Lunksoos terrane is therefore considered to be underlain by remnants of a Penobscot arc that became isolated by mantle upwelling and rifting in the Tetagouche backarc basin during the Middle and Late Ordovician. The Munsungun–Winterville terrane contains evidence of possible ridge subduction followed by accretion to Laurentia and slab break-off in the Late Ordovician.

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