Late Ordovician to Early Devonian tectono-magmatic prequel to the Acadian Orogeny in northeastern North America and the British Isles

Pierre Jutras[a] and Jaroslav Dostal[a]

[a] *Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada*

ABSTRACT

Geochemical data from Katian to earliest Emsian (~453–405 Ma) igneous rocks in northeastern North America and the British Isles were compiled to identify tectono-magmatic events related to ocean closure and the formation of the Appalachian–Caledonian Belt. These rocks all have geochemical affinities with plate-margin settings, but only a few can be attributed to arc magmatism, whereas the others have slab-failure signatures or affinities with anhydrous, extensional plate-margin (A2-type) settings. Based on these setting attributions as well as constraints from the palaeomagnetic, palaeontologic, structural, stratigraphic and sedimentologic records, a model for Iapetus and Rheic ocean closure is proposed, which also involves three subordinate ocean plate segments: the Tornquist Sea, Acadian Seaway and Tetagouche–Exploits oceanic back-arc basin. The model includes several new perspectives, such as (1) an early Silurian rather than late Silurian closure of the Tetagouche–Exploits back-arc basin; (2) Acadian Seaway slab failure at the Ludlow–Pridoli boundary due to its interaction at depth with the overlying and slowly-sinking Tetagouche–Exploits slab, which generated profuse, extensional, A2-type volcanism; and (3) an Early Devonian reactivation of Acadian Seaway slab subduction, possibly due to Rheic Ocean closure and the convergence of a Gondwanan promontory against Avalonia, which was attached to oceanic lithosphere of the Acadian Seaway. Furthermore, age constraints allowed to identify chronological trends in the geochemical signatures of the igneous rocks under study, which suggest that development of a new tectono-magmatic signature was gradual due to compositional inheritance from the previous setting. These trends also suggest that, although the transition from active subduction to slab failure generates an increase in Nb/Y and light over heavy rare earth elements, these ratios tend to decrease with time due to a fading contribution of the sinking slab at the source, whereas high-field-strength element contents tend to increase due to a lack of new water input from subduction.

Keywords:

Appalachian–Caledonian Belt

Arc magmatism

Continental collisions

Slab failure

A2-type igneous rocks

West Avalonia

Composite East Avalonia

South and North Ganderia

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1. Introduction

The Appalachian–Caledonian Belt of eastern North America and northern Europe was formed by oceanic closure, which was accompanied by the accretion of various types of oceanic terranes and the collision of continental masses. The belt formed the most complex accretionary zone of Pangaea as it recorded collisions between Gondwana, Laurentia, Baltica and associated micro-continents that had detached from them (Nance et al., 2012).

In the geology of northeastern North America and the British Isles, the interval separating the Middle to early Late Ordovician Taconic–Grampian orogenies from the late Early to Middle Devonian Acadian Orogeny is problematic (Woodcock, 2012a-c; Strachan, 2012a,b; Dewey et al., 2015; Wilson et al., 2017). Based on palaeomagnetic, palaeontologic and provenance studies, most terranes associated with the peri-Gondwanan and peri-Baltican (*sensu* Landing et al., 2022) Avalonian and Ganderian domains (indicated in Fig. 1) were converging with Laurentia during most of the Ordovician and Silurian, but had already docked with it before the end of the Silurian (eg., Cocks and Torsvik, 2002; Murphy et al., 2004; van Staal et al., 2009, 2012, 2016; Woodcock, 2012a,b). However, the conclusions of these studies still need to be reconciled with the structural and igneous rock records, as the Katian to earliest Emsian interval (~453–405 Ma) in these terranes is characterized by a paucity of igneous rocks with a clear arc signature and by rare and not regionally extensive compressional structures (Dostal et al., 1989, 1993; Strachan, 2012a,b; Woodcock, 2012a-c; Wilson et al., 2017). This paper uses geochemical data on 417 samples of mafic to intermediate-felsic igneous rocks (45-70% SiO_2 contents on a volatile-free basis) from the problematic ~453–405 Ma interval in Ganderian, Avalonian and northeastern Laurentian domains to help clarify the complex tectono-magmatic history of that interval within the constraints of palaeomagnetic, palaeontologic, structural, stratigraphic and sedimentologic data.

2. Nomenclature

Waldron et al. (2022) discussed at length nomenclatural issues surrounding the interchangeable usage in the literature of the Gander, Avalon and Meguma zones of Williams (1979) as terranes, Late Precambrian to Early Ordovician (Tremadocian) peri-Gondwanan or peri-Baltican domains (ie., terrane assemblages), and drifting post–Tremadocian micro-continents. These problems were exacerbated by the identification of terranes that have affinities with the Ganderian and Megumian domains alongside Avalonian domains in the British Isles (eg. Waldron et al., 2011, 2019a; Pothier et al., 2015; Schofield et al., 2016), whereas geological evidence suggests that the three domain components were part of the same drifting micro-continent in late Early Ordovician (Floian) to Silurian times (Woodcock, 2012a; Waldron et al., 2014). Another problem stems from profuse evidence (eg. Wilson et al., 2004, 2017; van Staal et al., 2009, 2016; Zagorevski et al., 2008, 2010, 2012; Wilson, 2017) suggesting that the bulk of Ganderian domains drifted as two separate segments due to the opening of a wide, intra-Ganderian back-arc basin that evolved into oceanic lithosphere (the Tetagouche–Exploits back-arc basin of van Staal, 1994).

In this paper, we use the terms Ganderian, Avalonian and Megumian domains in reference to groupings of geological provinces with strong similarities in their Late Precambrian to earliest Ordovician histories (ie., preceding the late Tremadocian Monian–Penobscottian orogeny, *sensu* Waldron et al., 2022) along the Gondwanan and/or Baltican margins.

Furthermore, we restrict the terms "Ganderia and Avalonia" to inferred post–Tremadocian micro-continents in line with the common usage of the suffixes "a" or "ia" for other palaeo-continents, such as Laurentia, Gondwana and Baltica. In an attempt to minimize deviations from historical usage while avoiding cumbersome or confusing nomenclature, we refer to the "leading" and "trailing edges" of Ganderia (*sensu* van Staal et al., 2009, 2016; Zagorevski et al., 2010; Wilson et al., 2017) as respectively "North Ganderia" and "South Ganderia". We also maintain the commonly used terms "West Avalonia" (the "Avalon–Brookville terrane assemblage" of Waldron et al., 2022, now part of northeastern North America) and East Avalonia" (the "Gander–Lakesman terrane assemblage" of Waldron et al., 2022, now part of the British Isles) for drifting post–Early Ordovician continental assemblages that are mainly composed of Avalonian domains. However, because East Avalonia is now pictured as having travelled with some terranes that correlate better with the Ganderian and Megumian, we refer to this part of Avalonia as "composite".

2. Tremadocian to Sandbian precursor setting

Along the Laurentian margin of Iapetus, late Early to Middle Ordovician times were characterized by the accretion of terranes associated with the Taconic 2 (*sensu* van Staal et al., 2007, 2009) and Grampian orogenies, which peaked *circa* 463 Ma in both the British Isles (Chew and Strachan, 2014) and northeastern North America (Whitehead et al., 1996) (Fig. 2). Based mostly on palaeomagnetic and palaeontologic data, terranes associated with the Ganderian and Avalonian domains were migrating northward on the same plate towards Laurentia and away from Gondwana in late Early to Middle Ordovician times, closing the Iapetus Ocean to the north, and enlarging the Rheic Ocean to the south (Nance et al., 2010, 2012; van Staal et al., 2012 and references therein) (Fig. 3). At that time, Baltica (the Scandinavian craton) was separated from Laurentia by the Iapetus Ocean and from composite East Avalonia by the Tornquist Sea (Cocks and Torsvik, 2002; Torsvik and Rehnström, 2003) (Fig. 3).

According to Zagorevski et al. (2008), accretion of North Ganderia to the Laurentian margin occurred *circa* 455 Ma through south-dipping subduction in the third and last tectonic phase attributed to the Taconic Orogeny (Figs. 2 and 4). The collision was preceded by the accretion of the peri-Laurentian Rowe belt (west of the area covered by our palaeo-continental reconstructions) to the North Ganderian assemblage *circa* 475 Ma (MacDonald et al., 2014; Karabinos et al., 2017; van Staal et al., 2021) and subduction of a Iapetan mid-oceanic ridge beneath North Ganderia *circa* 459–455 Ma (Rogers and van Staal, 2003; Zagorevski et al. 2010, 2012; van Staal et al., 2016). Furthermore, the accretion of North Ganderia to the Laurentian margin was accompanied by the incomplete subduction of the Iapetan ridge beneath West and composite East Avalonia laterally along the same plate margin, which generated slab-window volcanism at ~454 Ma (Woodcock, 2012a, Jutras et al., 2020) (Figs. 2 and 4).

3. Late Ordovician to early Silurian tectonic setting

The shutdown of south-dipping Iapetan slab subduction is penecontemporaneous with the onset of southwest-dipping subduction of the Tornquist slab beneath the northeastern part of composite East Avalonia and the Late Ordovician convergence of the latter with Baltica (Pharaoh et al., 1993; Noble et al., 1993; Torsvik and Rehnström, 2003) (Fig. 5). Katian times also saw the development of north-dipping subduction zones beneath composite Laurentia, which produced the Brunswick subduction complex from consumption of the Tetagouche–Exploits back-arc slab (van Staal et al., 1990, 1998, 2009; van Staal, 1994; Wilson et al., 2004, 2015, 2017) while the Southern Uplands accretionary wedge was developing from consumption of the Iapetan slab beneath geological terranes now belonging to the British Isles and Greenland (McKerrow et al. 1977; Leggett et al., 1979; Ryan and Dewey, 1991; Strachan, 2012b; Hollocher et al., 2016; Chew and Strachan, 2014; McConnell et al., 2021) (Figs. 2 and 5).

In most palaeo-continental reconstructions (eg. van Staal et al. 2009; Piñán-Llamas and Hepburn, 2013; Tremblay and Pinet, 2016; Wilson et al., 2017), early Silurian convergence between composite Laurentia and West Avalonia occurred through northwest-dipping subduction of the Acadian Seaway slab (*sensu* van Staal et al. 2009), a remnant of oceanic crust that was trapped between them. The Silurian volcanic rocks of coastal Maine (Piñán-Llamas and Hepburn, 2013) and southern New Brunswick (Barr et al., 2002) are interpreted as products of this subduction zone. Hence, the Laurentian margin is pictured in some models as having been characterized by two closely spaced subduction zones dipping in the same direction in early Silurian times (van Staal et al. 2009; Tremblay and Pinet, 2016; Wilson et al., 2017). Based on the record of Silurian arc volcanic centres distributed along the southern margin of the British Isles, a north-dipping subduction zone had also developed beneath the East Avalonian–Baltican assemblage by the early Silurian at the latest (Fig. 2), contributing to Rheic Ocean closure (Woodcock et al., 2007).

4. Katian to earliest Emsian (~453–405 Ma) magmatic record in northeastern North America and the British Isles

In the following sub-sections, geochemical data on igneous rocks from the ~453–405 Ma interval that followed the Taconic and Grampian orogenies and preceded the Acadian Orogeny are subdivided into four sectors:

- (1) Mafic to intermediate-felsic rocks (45-70% SiO_2 contents on a volatile-free basis) located in the former micro-continent of South Ganderia to the south of the Dog Bay Line, which separates the two main Ganderian domain components in northeastern North America (Fig. 1). Occurrences are known from southern New Brunswick and coastal Maine (localities a-d in Fig. 1; Seaman et al., 1999; Barr et al., 2002; van Wagoner et al., 2002; Piñán-Llamas and Hepburn, 2013). These rocks have been associated with closure of the Acadian Seaway (Piñán-Llamas and Hepburn, 2013).
- (2) Mafic to intermediate-felsic rocks located to the north of the Dog Bay Line along the former margin of composite Laurentia (including the former micro-continent of North Ganderia) in northeastern North America (localities e-p in Fig. 1; Murphy, 1989; David and Gariépy, 1990; Dostal et al., 1993, 2016, 2021, 2022; Whalen et al., 1996, 2006; Giggie, 1999; Wilson et al., 2005, 2008; Walker, 2010; Wilson, 2017). These occurrences have been associated with closure of the Tetagouche–Exploits back-arc basin (van Staal, 1994; van Staal et al., 1998, 2009; Wilson et al., 2008, 2017).
- (3) Mafic to intermediate-felsic rocks located to the north of the Solway Line (Fig. 1) along the former margin of Laurentia in northwestern sectors of the British Isles (localities r-t in Fig. 1; Tindle and Pearce, 1981; Badenszki et al., 2019; Murphy et al., 2019; Archibald and Murphy, 2021). The latter authors associated these occurrences with Iapetus Ocean closure.
- (4) Mafic to intermediate-felsic rocks located in the former micro-continents of West Avalonia and composite East Avalonia to the south of the Solway Line, including occurrences from northeast England that have been associated with closure of the

Tornquist Sea (Thor Suture) (locality y in Fig. 1; Pharaoh et al., 1993), and occurrences from southeast Newfoundland (locality q in Fig. 1; Greenough, 1984, Greenough et al., 1993) and the southern end of the British Isles (localities u-x and y in Fig. 1; van de Kamp, 1969; Thorpe et al., 1989; Sloan and Bennett, 1990; Pharaoh et al., 1991) that have been associated with Rheic Ocean closure (Woodcock et al., 2007; Woodcock, 2012b).

Within those sectors, data from the literature on Katian to earliest Emsian igneous rocks of mafic to intermediate-felsic compositions were selected when including the right combination of trace elements to be plotted on at least one of four discrimination diagrams used in this paper: (1) the Hf/3 vs Th vs Ta diagram of Wood (1980) (Figs. 6a–11a), which is one of the most widely used and understood tectonic discrimination diagrams in the literature, and which is herein used for mafic to intermediate rocks; (2) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009) (Figs. 6b–11b), from which tholeiites are perhaps best separated from calc-alkaline subduction-related magmas, and which is herein used for mafic to intermediate-felsic rocks; and (3) the Nb+Y vs Nb/Y (Figs. 6c–11c) and (4) Ta+Yb vs La/Yb (Figs. 6d–11d) diagrams of Whalen and Hildebrand (2019), which reflect recent advances in the design of discrimination diagrams to differentiate arc magmas from slab failure and A-type magmas, and which are herein used for intermediate to intermediate-felsic rocks with an aluminium saturation index [molar $Al_2O_3/(CaO + Na_2O + K_2O)$] lower than 1.1, and SiO_2 contents ranging between 55 and 70 wt.% on a volatile-free basis. Data points on Figures 6 to 11 represent chemical analyses from individual samples (data compiled in Appendix A).

Because the lithospheric mantle components of the Appalachian–Caledonian have all experienced subduction-related metasomatism at some point in late Precambrian to early Palaeozoic times, Katian to earliest Emsian igneous rocks from all above-mentioned localities have trace element ratios that are overall characteristic of calc-alkaline arc environments (Figs. 6a–11a and 6b–11b). However, an extensional within-plate environment for these rocks has been inferred in many instances based on the bimodal composition of some suites and a tendency towards high contents in high-field-strength elements (HFSEs) paired with dominantly tholeiitic Si vs Fe/Mg trends (Dostal et al., 1989, 2016; Seaman et al., 1999; van Wagoner et al., 2002; Piñán-Llamas and Hepburn, 2013).

To further constrain the plate-margin tectono-magmatic environments, Whalen and Hildebrand (2019) developed diagrams that refined our means to differentiate between hydrous arc or slab failure magmatism and anhydrous extensional magmatism (A-type) with the use of immobile trace element contents and ratios (Figs. 6c,d–11c,d). Diagrams using Nb/Y ratios can also be used to subdivide the A-type range by allowing a differentiation to be made between the A1-type igneous rocks of intra-plate environments and the A2-type igneous rocks of plate margin environments (*sensu* Eby, 1992).

4.1. South Ganderian terranes

Barr et al. (2002) analysed intrusive and extrusive rocks from the South Ganderian Kingston terrane of southern New Brunswick (locality d on Fig. 1; Table 1), reporting U-Pb zircon ages ranging between 442 ± 6 and 435 ± 1.5 Ma (the younger date is from Doig et al., 1990). Piñán-Llamas and Hepburn (2013) studied other volcanic rocks in coastal Maine (the Dennys Formation; locality b on Fig. 1; Table 1) that are possibly coeval (ie., Llandovery to

Wenlock) based on biostratigraphic constraints, whereas volcanic rocks of the overlying Edmunds, Leighton and Eastport formations are considered to range from the Ludlow to the Pridoli. However, within the current framework of the International Commission on Stratigraphy (Melchin et al., 2020), studies by Miller and Fyffe (2002), van Wagoner et al (2002), Churchill-Dickson (2004), and Wilson et al. (2008) have shown significant discrepancies between radiometric ages and assigned Siluro-Devonian biostratigraphic ages in the region. Because stratigraphic subdivisions in this paper are mainly based on radiometric ages, the Dennys, Edmunds, Leighton and Eastport formations are here considered as undivided Silurian rocks.

The Cranberry Island volcanic series of coastal Maine (locality a on Fig. 1; Table 1) and the Passamaquoddy Bay volcanic sequence of southern New Brunswick (locality c on Fig. 1; Table 1) respectively yielded U-Pb zircon dates of 424 ± 1 Ma (Ludlow; Seaman et al., 1995) and 423 ± 1 Ma (Pridoli; van Wagoner et al., 2001). Although Seaman et al. (1999) and van Wagoner et al. (2002) referred to both successions as bimodal due to the presence of a SiO_2 gap within the intermediate range, the two successions include andesites and dacites.

4.1.2. Geochemistry

The Pridoli Passamaquoddy Bay volcanic sequence (~423 Ma) of southern New Brunswick clearly plots in the A2-type range determined by Whalen and Hildebrand (2019) (Fig. 6c,d). The limited amount of geochemical data from older Silurian andesites and dacites in South Ganderia does not allow a firm determination of the tectonic environment to be made, but although they straddle the three ranges, these volcanic rocks dominantly plot into the arc range (Fig. 6c,d). Previous authors concluded that the ~424 Ma Cranberry Island volcanic series and the undated Eastport Formation of coastal Maine have affinities with the within-plate

Passamaquoddy Bay volcanic sequence of southern New Brunswick (Seaman et al., 1999; van Wagoner et al., 2002; Piñán-Llamas et al., 2013). However, their trace element contents have more in common with older Silurian igneous rocks of the region (the Dennys, Edmunds and Leighton formations, as well as the Kingston Group volcanic rocks and associated plutons) that have been interpreted as arc related (Barr et al., 2002; Piñán-Llamas and Hepburn, 2013). Hence, the onset of arc volcanism in South Ganderian terranes of coastal Maine and southern New Brunswick may have occurred near the beginning of the Silurian based on a 442 ± 6 Ma U-Pb zircon age obtained from a dacitic tuff in the Kingston terrane of southern New Brunswick (Barr et al., 2002), and persisted until the end of the Ludlow Epoch based on the 424 ± 1 Ma U-Pb zircon age obtained by Seaman et al. (1995) in the Cranberry Island volcanic series of coastal Maine.

4.2. Laurentian margin and North Ganderian terranes in northeastern North America

4.2.1. Katian to Pridoli interval (~453–420 Ma)

The record of Late Ordovician magmatism along the composite Laurentian margin in northeastern North America is very scarce, being limited to a foliated granodiorite sheet in Newfoundland from which a 445.8 ± 0.6 Ma U-Pb zircon date was obtained (Brem et al., 2007), but which was not analyzed for its major and trace element contents. Furthermore, the Duncans Brook Formation of northern New Brunswick includes basalt flows intercalated with sedimentary rocks that bear detrital zircons as young as 444 ± 6 Ma (Wilson et al., 2015), suggesting that it is either uppermost Ordovician or early Llandovery.

Apart from possibly the Duncans Brook Formation of northern New Brunswick, the oldest Silurian igneous rock record along the composite Laurentian margin in northeastern North

America is from the granitic Glover Island and granodioritic Burlington plutons of northwest Newfoundland, which are both dated at 440 ± 2 Ma (early Llandovery) (Cawood and Dunning, 1993; Cawood et al., 1996; Whalen et al., 2006) (locality l on Fig. 1; Table 1). Other Silurian igneous rocks in northwest Newfoundland include the Boogie Lake and Main Gut complexes at respectively 435 ± 6 and 431 ± 2 Ma (Dunning et al., 1990), the Rainy Lake and Silver Pond complexes at respectively 435 ± 1 and 431.6 ± 4 Ma (Whalen et al., 2006), the Puddle Pond complex at 432.4 ± 1 (Lissenberg et al., 2005), and the Taylor Brook complex at 430.5 ± 2 Ma (Heaman et al., 2002) (all at locality m on Fig. 1; Table 1), as well as the Topsails and Springdale volcanic groups (both at locality o on Fig. 1; Table 1) at 429 ± 4 Ma (Whalen et al., 1987), and the Topsails intrusive suite (locality n on Fig. 1; Table 1) at 427 ± 1 Ma (Whalen et al., 2006) and 425 ± 4 Ma (van Staal et al., 2014). Moreover, slightly younger Silurian igneous rocks are found farther to the northeast, just to the north of the Dog Bay Line (locality p on Fig. 1), with U-Pb zircon ages ranging from 424 ± 2 Ma in the Mount Peyton Batholith to 421.2 ± 0.6 Ma in the Brimstone Head Formation of the Botwood Group (Dunning et al., 1990; Hamilton and Kerr, 2016) (Table 1).

Silurian volcanic rocks are also found along the composite Laurentian margin (including North Ganderian terranes) in southeastern Quebec (the Lac Raymond and Pointe aux Trembles formations; David and Gariépy, 1990) and northwest New Brunswick (Weir Formation; Wilson et al., 2008) (localities g and j respectively on Fig. 1; Table 1). Although volcanic successions from both localities are intercalated with or overlain by marine sedimentary rocks with brachiopod, conodont and ostracod assemblages assigned to the late Llandovery (Noble, 1976; Nowlan, 1983; David and Gariépy, 1990; Wilson et al., 2008), a U-Pb date of 429.2 ± 0.5 Ma was obtained from a dacitic tuff of the Weir Formation (Wilson et al., 2008), which is late

Wenlock according to the current Silurian subdivisions of the International Commission on Stratigraphy (Melchin et al., 2020). As biostratigraphic constraints imply that volcanic rocks of the Lac Raymond and Pointe aux Trembles formations are time-equivalent to those of the Weir Formation, they were possibly deposited near 429 Ma and are herein included within the Llandovery to Wenlock (~444–428 Ma) bracket. These rocks are in part equivalent to the Ristigouche volcanic rocks in the Gaspé Peninsula of southeastern Quebec (locality k on Fig. 1; Table 1) based on biostratigraphic constraints (Bourque and Lachambre, 1980; Bourque et al., 2000), but the latter succession is basaltic and does not include intermediate to intermediate-felsic rocks (Doyon and Dalpé, 1993).

Following a volcanic hiatus of a few million years and a period of uplift and erosion (Salinic B unconformity of Wilson et al., 2017), voluminous volcanism was recorded in the Pridoli Dickie Cove Group of northwest New Brunswick (Dostal et al., 2016, 2021, 2022) (locality h on Fig. 1; Table 1). This group yielded U-Pb zircon ages of 422.3 ± 0.3 Ma in the basal Bryant Point Formation, and of 420.8 ± 0.4 and 419.7 ± 0.3 Ma in respectively the lower and upper parts of the Benjamin Formation at the top of the succession (Wilson and Kamo, 2008, 2012). The two volcanic formations are separated by coarse volcaniclastic conglomerate of the New Mills Formation. This group is in part equivalent to the Siluro-Devonian Tobique Group of central-west New Brunswick (locality e on Fig. 1; Table 1), in which stratigraphic relationships are less well constrained (Wilson, 2017).

4.2.1.1. Geochemistry. North of the Dog Bay Line along the composite Laurentian margin of northeastern North America, available data on intermediate to intermediate-felsic rocks of the Llandovery to Wenlock interval (~444–428 Ma) dominantly plot within the slab failure range in the Nb+Y vs Nb/Y and Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019; Fig. 7c,d), including those from the Lac Raymond, Pointe aux Trembles and Weir formations, which were previously attributed to arc volcanism (David and Gariépy, 1990; Wilson et al., 2008). In contrast, volcanic rocks from the late Pridoli (the ~421–420 Ma Benjamin Formation of the Dickie Cove Group in northwest New Brunswick) plot entirely within the A2-type range. These two clearly differentiated populations are somewhat linked by rocks that are dated as Ludlow (the ~427–424 Ma Topsails intrusive suite of northwest Newfoundland) to early Pridoli (the ~423–422 Ma Bryant Point Formation of the Dickie Cove Group). Based on limited age constraints, the Llandovery to Ludlow interval records a gradual increase in HFSE contents accompanied by a gradual decrease in Nb/Y and La/Yb ratios, whereas the Pridoli interval mostly shows a pronounced increase in HFSE contents (Fig. 7c,d).

4.2.2. Lochkovian to earliest Emsian interval (~419–405 Ma)

Early Devonian igneous rocks in northeastern North America include a series of felsic intrusions in the Miramichi Highlands (Brunswick subduction complex of the North Ganderian assemblage) in northern New Brunswick (locality f on Fig. 1; Table 1), which range between ~418 and ~402 Ma (Whalen et al., 1996), as well as coeval volcanic rocks of the Dalhousie Group, which straddle the New Brunswick / Quebec border (locality i on Fig. 1; Table 1), and which range between 417.5 ± 0.4 Ma (Wilson et al., 2017) and 407.4 ± 0.8 Ma (Wilson et al., 2004). The latter group disconformably overlies the Silurian Ristigouche volcanics and Dickie Cove Group (Doyon and Dalpé, 1993; Bourque et al., 2000; Wilson, 2017). Based on stratigraphic constraints, the Baldwin and Lyall volcanic rocks in the Gaspé Peninsula of eastern

Quebec (locality k on Fig. 1; Table 1) are possibly time-equivalent to volcanic rocks of the Dalhousie Group (Doyon and Dalpé, 1993).

Early Devonian plutons also occur in the Fogo Island Batholith of northern Newfoundland, with a monzogranite yielding a 408 ± 0.8 Ma U-Pb zircon age, and a quartz diorite yielding a 410 ± 2 Ma U-Pb titanite age and a 420 ± 2 Ma U-Pb zircon age (Aydin, 1995). We consider the significantly older zircon population as probably inherited.

4.2.2.1. Geochemistry. Although the Lower Devonian volcanic rocks of northern New Brunswick and southeastern Quebec are traditionally linked to the same post–Taconic overstep succession as the Pridoli Dickie Cove Group (the Matapedia cover sequence of Fyffe and Fricker, 1987), they differ from the latter unit by the lack of a gap in the intermediate range (*sensu* Daly, 1925) when the succession is taken as a whole (Wilson, 2017). They also show distinct trace element contents that straddle all three ranges in the Nb+Y vs Nb/Y and Ta+Nb vs La/Yb diagrams of Whalen and Hildebrand (2019) (Fig. 8c,d), but that are skewed towards the arc and slab failure ranges, whereas data from the Dickie Cove Group are skewed towards the A2-type range (Fig. 7c,d). Moreover, contrary to the Silurian successions, an overall decrease in HFSE contents is observed with time (Fig. 8c,d). Hence, a change in tectono-magmatic setting must have occurred in association with the disconformity at the Siluro-Devonian boundary in the region.

In northern Newfoundland, available data on Lower Devonian igneous rocks are constrained to the Pragian, and although they are compatible with age-equivalent rocks in northern New Brunswick (Figs. 8 and 9), they show a tendency for lower Nb/Y and therefore a stronger affinity with typical arc environments (Fig. 9c).

4.3. Laurentian margin in the British Isles

Following the Middle Ordovician Grampian Orogeny, evidence from structures and syn-tectonic sedimentary rocks reviewed by Strachan (2012b), Stone et al. (2012) and McConnell et al. (2021) indicates that a northwest-dipping subduction zone developed beneath Laurentia, although the Late Ordovician magmatic record for this subduction is scarce because of subsequent burial beneath younger rocks covering the Midland Valley terrane of Scotland and its extension in Ireland. Badenszki et al. (2019) obtained a 453.6 ± 8 Ma U-Pb zircon age (Sandbian/Katian boundary) from a metadioritic xenolith within upper Palaeozoic intrusive rocks of the Midland Valley terrane (locality s on Fig. 1; Table 1).

In northwest Ireland, the polymodal Donegal composite batholith (locality r on Fig. 1; Table 1) yielded U-Pb zircon ages ranging from 428 ± 4 to ~424 Ma (latest Wenlock to Ludlow) in the Ardara Pluton and in an enclave within the Thorr Pluton, but the composite batholith is volumetrically dominated by Early Devonian plutons with U-Pb zircon ages ranging between 420 ± 3 and ~400 Ma, and clustering between ~418 and 411 Ma (Lochkovian) (Archibald et al., 2021).

An appinite and lamprophyre suite near the Donegal composite batholith yielded a U-Pb zircon age of 437 ± 5 Ma (Kirkland et al., 2013), $^{40}Ar/^{39}Ar$ hornblende ages ranging from 434.2 ± 2.1 to 433.7 ± 5.5 Ma (Murphy et al., 2019), and U-Pb titanite ages ranging from 431 ± 6 to 419 ± 5 Ma (Archibald et al., 2021) (late Llandovery to early Lochkovian). However, these rocks have an aluminium saturation index greater than 1.1 and therefore cannot be used in the discrimination diagrams of Whalen and Hildebrand (2019). Samples from this suite plotted in

Fig. 10a,b are from rocks ranging from 434.2 ± 2.1 to 431 ± 6 Ma (Murphy et al., 2019) (late Llandovery to Wenlock).

In terms of Early Devonian occurrences, an Rb/Sr age of 408 ± 1.5 Ma (Pragian) was obtained by Piper (2007) for the Loch Doon pluton in the Southern Uplands of Scotland (locality t on Fig. 1; Table 1), and U-Pb zircon dates of 410 ± 1 and 406 ± 2 Ma were reported by Stone et al. (2012) for the same pluton. Badenszki et al. (2019) obtained a weighted average of 415 ± 3 Ma (Lochkovian) for U-Pb zircon ages obtained from metadioritic xenoliths within Permo–Carboniferous igneous rocks of Scotland's Midland Valley (locality s on Fig. 1; Table 1).

4.4.2. Geochemistry

The only retrieved sample from Katian to Hirnantian (~553-444 Ma) igneous rocks along the Laurentian margin in the British Isles plots into the arc range defined by Whalen and Hildebrand (2019), whereas mid–Silurian to Early Devonian igneous rocks plot almost exclusively within the slab failure range (Fig. 10c,d). However, the Pragian Loch Doon pluton (data from Tindle and Pearce, 1981) plots notably closer to the A-type range than the Lochkovian xenoliths as well as the mid–Silurian to Lochkovian Donegal plutons, and the associated increase in HFSE contents is paired with a decrease in Nb/Y and La/Yb ratios.

4.5. Terranes associated with the former micro-continents of West and composite East Avalonia

Late Ordovician to earliest Silurian plutonic and volcanic rocks intercepted by wells in northeast England to the southeast of the Solway Line (locality y on Fig. 1; Table 1) have been interpreted as related to subduction of the Tornquist slab beneath Avalonia (Pharaoh et al., 1993). These rocks yielded U-Pb zircon dates of 452 +8–5 Ma (Pidgeon and Aftalion, 1978), as well as 449 ± 13 Ma, 457 ± 20 Ma, and 442 ± 3 Ma (Noble et al., 1993). They are thought to be related to calc-alkaline rocks of approximately the same age in the Brabant Massif of Belgium (locality z on Fig. 1; Table 1) (André et al., 1986).

At the southernmost end of the British Isles, Silurian volcanic rocks are distributed along an east-west trend (Woodcock et al, 2007; Woodcock, 2012b). They include the Llandovery Skomer Volcanic Group of south Wales (Thorpe et al., 1989) (locality w on Fig. 1; Table 1), the Llandovery to Wenlock Tortworth volcanics of southern England (van de Kamp, 1969; Pharaoh et al., 1991) (locality x on Fig. 1; Table 1), and the late Wenlock Dunquin Group of southern Ireland (Sloan and Bennett, 1990) (locality u on Fig. 1; Table 1), with ages that are based on biostratigraphic constraints.

Also within the composite East Avalonian assemblage, southeast of the Solway Line, intrusive units in the northern part of the Leinster Batholith of southeast Ireland yielded U-Pb zircon ages ranging from 417.4 ± 1.7 to 404.9 ± 2.6 Ma (Fritschle et al., 2018a) (locality v on Fig. 1; Table 1). However, trace element geochemical data that would be relevant to this study are only available for southern units of the batholith (Sweetman, 1987) that were long considered to be Early Devonian, but from which U-Pb zircon dates of 462.0 ± 2.7 Ma and 460.5 ± 3.2 Ma (Middle Ordovician) were subsequently obtained (Fritschle et al., 2018b). Furthermore, mafic to intermediate sills at Cape St. Mary's in the Avalon Peninsula of Newfoundland (West Avalonia) (locality q on Fig. 1; Table 1) yielded a U-Pb baddeleyite date of 441 ± 2 Ma (Greenough et al., 1993).

4.5.2. Geochemistry

Late Ordovician to earliest Silurian intermediate to intermediate-felsic rocks along the inferred Thor Suture to the northeast of the Midland Microcraton (locality y on Fig. 1; Table 1) straddle the arc and slab failure ranges (Fig. 11c,d). Along the inferred Rheic Suture (*sensu* Woodcock et al., 2007, and Woodcock, 2012b) at the southern edge of composite East Avalonia, Silurian andesites and dacites mostly plot into the arc range (Fig. 11c,d), which is consistent with the conclusions of previous workers (van de Kamp, 1969; Thorpe et al., 1989; Sloan and Bennett, 1990; Pharaoh et al., 1991). In contrast, the Cape St. Mary's sills of West Avalonia (Greenough, 1984) are constrained within the A2-type range (Fig. 11c,d).

5. Discussion

5.1. General chronological trends in the geochemical signature of slab-failure-related magmatism

Along the composite Laurentian margin in northeastern North America and the British Isles, a trend towards increasing HFSE contents as well as decreasing Nb/Y and La/Yb ratios is observed with time in igneous rocks associated with slab failure (Figs. 6c,d and 11c,d). Hildebrand and Whalen (2017) and Whalen and Hildebrand (2019) interpreted the rise in Nb/Y and LREE/HREE ratios from arc to slab failure magmatism as being related to partial melting of the Nb-enriched metabasaltic/gabbroic upper portion of the failing slab, leaving HREE-rich residual garnet in the eclogitic residue. This would be especially true in the early stages of slab failure, when the failing slab is still close to the base of the lithosphere. Hence, although slab-failure-related magmatic systems will tend to develop high Nb/Y and La/Yb ratios, the observed decrease of these ratios with time could reflect a gradually fading contribution of the sinking slab at the source, whereas the observed increase in HFSE contents (Nb+Y and Ta+Yb) suggests that a gradual dehydration of the mantle source occurs in such setting due to a lack of new water input from subduction.

5.2. Katian to Hirnantian interval (~453–444 Ma)

The Katian to Hirnantian igneous rock record is very scarce in the Appalachian–Caledonian Belt, and the subduction zones depicted in Fig. 5 are mainly inferred from structures and metamorphic features (eg. Woodcock, 2012a; van Staal et al., 1998, 2008, 2012, 2016; Wilson et al., 2017; and references therein) as well as evidence for convergence from palaeomagnetic (Johnson and Van der Voo, 1985, 1990; Mac Niocaill, C., 2000; Cocks and Torsvik, 2002; Smethurst and McEnroe, 2003; Torsvik and Rehnström, 2003; Thompson et al., 2010, 2022) and palaeontologic data (McKerrow et al., 1977; Ziegler et al., 1977; Landing and Murphy, 1991; Landing, 1996, 2007: Landing et al., 2008, 2022). However, where recorded along the composite Laurentian margin and the inferred Thor Suture of composite East Avalonia, those igneous rocks are geochemically consistent with an arc environment (Figs. 10 and 11). According to Pharaoh et al. (1995) and Torsvik and Rehnström (2003), Baltica and composite East Avalonia had already collided by early Silurian times in association with the poorly recorded Shelveian tectonic event in northeast England (Woodcock, 2012b) (Figs. 2 and 12, Table 2).

5.3. The Llandovery to Ludlow interval (~444–424 Ma)

5.3.1. Composite Laurentian margin north of the Dog Bay Line in northeastern North America

A clear slab-failure signature in Llandovery to Wenlock (~444–428 Ma) igneous rocks within North Ganderian and southeasternmost Laurentian terranes in northeastern North America (Fig. 8c,d) suggests that, although final closure of the Tetagouche–Exploits back-arc basin was previously associated with the Wenlock to Ludlow Salinic B unconformity (Wilson et al., 2017), it most likely occurred in association with the latest Ordovician to early Llandovery Salinic A deformation event (Figs. 2 and Fig. 12), which is characterized by an unconformity separating the Ordovician Brunswick subduction complex from overlying Silurian sedimentary and volcanic rocks (Wilson and Kamo, 2012). A similar timing for the closure is suggested by reports of Laurentian detrital zircons in the Llandovery Hayes Brook Formation (Dokken, 2017) to the south of the Dog Bay Line. Hence, closure of the Tetagouche–Exploits basin must have been constrained within the ~453–440 Ma interval, for which a record of arc volcanic rocks is currently lacking. It should be noted that the Tetagouche–Exploits slab was composed of young oceanic crust that was unlikely to subduct steeply and produce abundant arc volcanism.

5.3.2. Laurentian margin in the British Isles

Based on available data from the Donegal composite batholith of northwest Ireland, the Iapetan slab had failed beneath Laurentian rocks of the British Isles by ~428 Ma (Archibald and Murphy, 2021; Archibald et al., 2021, 2022) (Fig. 10c,d). This event was most likely linked to the *circa* 430 Ma culmination of the Scandian Orogeny, which was the result of the collision between Laurentia and Baltica, and which affected rocks of Scotland, east Greenland and

Scandinavia (Strachan, 2012b; Hollocher et al., 2016; Chew and Strachan, 2014; Bender et al., 2019; Jakob et al., 2022) (Fig. 13).

5.3.3. South Ganderia

Based on data from the Kingston terrane of southern New Brunswick (Fig. 6c,d), northwest-dipping subduction beneath South Ganderian terranes was already ongoing by ~442 Ma (earliest Llandovery) (Barr et al., 2002), and two closely spaced northwest dipping subduction zones may therefore have coexisted for a while along the two parts of Ganderia (*sensu* van Staal et al., 2009, Tremblay and Pinet, 2016, and Wilson et al., 2017). Based on radiometric and stratigraphic constraints (Wilson et al., 2017), it is also possible that the onset of Acadian Seaway slab subduction accompanied the Salinic A deformation and final closure of the Tetagouche–Exploits back-arc basin (Figs. 2 and 12). The tendency for relatively high Nb/Y and Nb+Y in these inferred Silurian arc igneous rocks in South Ganderian terranes suggests shallow subduction, which can result in poorly hydrated arc magmatism as much of the well-hydrated uppermost part of the subducting slab is left behind in the accretionary prism in such settings.

5.3.4. West and composite East Avalonia

Inferred subduction of the Rheic Ocean slab beneath composite East Avalonia during the Silurian (Woodcock et al., 2007; Woodcock, 2012b) is supported by the geochemistry of Silurian igneous rocks distributed along an east-west trend at the south end of the British Isles (Fig. 11c,d). Based on the available record, onset of this subduction occurred near the beginning of the Silurian (Figs. 2 and 12). In this context, the 441 ± 2 Ma Cape Saint Mary's sills of Newfoundland (Greenough et al., 1993), which show geochemical evidence for anhydrous volcanism (Fig. 11c), are pictured as probable products of back-arc extension or transtension. Associated arc volcanic rocks in West Avalonia are possibly buried beneath continental shelf strata along the northwest Atlantic margin.

5.4. The Pridoli interval (~423–420 Ma)

5.4.1. Ganderian and West Avalonian terranes

As no coeval deformation is recorded in West Avalonia, which had not yet accreted with composite Laurentia, no continental collision is inferred to have caused the minor pre–Pridoli orogenic phase responsible for the Salinic B unconformity (*sensu* Wilson et al., 2017) in Ganderian terranes, which was most likely caused by a shallowing of Acadian Seaway slab subduction in Wenlock to Ludlow times (Figs. 2 and 13). To explain the rapid switch from arc volcanism in the ~424 Ma Cranberry Island volcanic series to anhydrous, extensional volcanism in the ~423 Ma Passamaquoddy Bay volcanic sequence on South Ganderian terranes (Fig. 6c,d), we propose that the warm and slowly sinking Tetagouche–Exploits slab may have interfered with the neighbouring shallow subduction of the Acadian Seaway slab, causing chain failure at depth (Fig. 14, cross-section A-B, ~423 Ma). Because the second tear would have occurred deep below the asthenosphere-lithosphere boundary, the associated volcanism would not have developed a clear slab failure signature, but it would have generated sufficient stress release to cause significant extensional magmatism at the level of the composite Laurentian margin (Figs. 2 and 14).

Failure of the Acadian Seaway slab at the onset of the Pridoli is consistent with the contemporaneous record of a very rapid and short-lived sea regression in the Silurian Arisaig Group on West Avalonia (Boucot et al., 1974) (Fig. 2, and Fig. 14, cross-section C-D), which had drifted very close to the composite Laurentian margin by then based on palaeomagnetic studies (Cocks and Torsvik, 2002) and detrital zircon data (Murphy et al., 2004). The Arisaig Group displays an undisturbed marine succession that spans the entire Silurian with the exception of a thin interval of continental red beds in the upper member of the Moydart Formation (Fig. 15A), which were deposited near the Ludlow–Pridoli boundary (Boucot et al., 1974). Within a ~2 m interval, the succession conformably passes upward from green mudrock with coquina lenses and hummocky cross-stratified siltstone intervals deposited below the mean fairweather wave base (late Ludlow Lower Member of the Moydart Formation) to mottled red mudrock with pedogenic calcretes deposited in the supratidal zone (undated Upper Member of the Moydart Formation), the two facies being separated by rhythmic alternations of red mudrock and green biosparudite presumably deposited in the intertidal zone (Fig. 15b,c). Considering the high sedimentation rate of tidal rhythmites, this section seems to have experienced several metres of base-level lowering in a matter of months. Such rapid regression would be difficult to explain without invoking a sudden event of tectonic relaxation, which could be related to retrogressive movement of the remnant Acadian Seaway oceanic lithosphere following failure, as the latter was still attached to West Avalonia (Fig. 14). Shallow marine sedimentation resumed a few metres higher in the succession from a recrudescence of basin subsidence recorded in the Pridoli Stonehouse Formation (Waldron et al., 1996) (Figs. 2 and 15c), which is also consistent with the short-lived nature of slab-failure-related uplift.

On the Ganderian side, post–Salinic relaxation associated with the inferred failure of the Acadian Seaway slab seemingly migrated landward during the Pridoli, generating profuse volcanism recorded in the ~422 Ma Bryant Point Formation at the base of the Dickie Cove Group, which still marginally plots within the arc failure range, but which shows a significant offset towards the A-type ranges (Fig. 7c,d). Because the significant increase in Nb+Y does not show a corresponding decrease in Nb/Y, we attribute the former to the onset of A-type extensional tectonics rather than to a fading contribution of the sinking Tetagouche–Exploits slab; the latter having been most likely too deep by then to be part of the magmatic source, as both numerical models and the geological record suggest that slab-failure-related magmatism is a short-lived event of a few million years (eg. Zhu et al., 2015; Freeburn et al., 2017; Kant et al., 2018; Dostal and Jutras, 2021). We therefore attribute the relatively low HFSE contents of the Bryant Point Formation to inheritance from a previous history of hydrated arc volcanism at the base of the sub-continental lithospheric mantle (SCLM), and we associate this unit to the onset of an increasingly anhydrous extensional tectonic regime during the Pridoli in North Ganderian terranes in relation to failure of the Acadian Seaway slab at depth (Fig. 14, cross-section A-B, ~422 Ma).

The possibility of two distinct Silurian tectono-magmatic events in the area is supported by the identification of a large time gap separating the original Llandovery to early Ludlow pulse of slab-failure-related volcanic rocks (Lac Raymond, Pointe aux Trembles, and Weir formations) from bimodal magmatism associated with the Pridoli Bryant Point Formation; the latter corresponding to a significant magmatic pulse that left a ~2000 m thick succession dominated by volcanic rocks (Wilson, 2017). An increase in extensional rates may have generated the coarse, fault-controlled deposits of the overlying New Mills Formation (Bourque et al., 2000; Tremblay and Pinet, 2016), which are overlain by thick, bimodal volcanic rocks with a clear A2-type composition that form the bulk of the ~421–420 Ma Benjamin Formation (Figs. 7c,d, and 14, cross-section A-B, ~421 Ma). A similar setting is inferred for Pridoli felsic volcanic rocks in

Newfoundland based on scarce geochemical data that suggest an A-type affinity (Sandeman and Malpas, 1995; Currie, 2003).

5.4. Lochkovian to earliest Emsian interval (~419–405 Ma)

5.4.1. The Brabantian event in composite East Avalonia

The Siluro-Devonian boundary approximately marked the onset of Brabantian deformation in easternmost portions of the Avalonian domain (Dewaele et al., 2002; Debacker et al., 2005; Sintubin et al., 2009; Linnemann et al., 2012; Pharaoh, 2018). There is still much debate regarding what caused this Early Devonian event and the subsequent and partly overprinting Middle Devonian Acadian Orogeny in Europe. The Midlands Microcraton seemingly acted as a rigid internal indenter that rotated counter-clockwise with respect to the rest of composite East Avalonia during the Brabantian and Acadian events (Sintubin et al., 2009; partly based on palaeomagnetic data from Piper, 2007). This rotation implies that the region experienced shortening concentrated over a discrete area due to the docking of an external indenter. According to Soper et al. (1987, 1992) and Martinez Catalan et al. (2007), this external indenter was a peri–Gondwanan terrane associated with Armorica (or Cadomia, *sensu* Nance et al., 2012), which, according to Kroner and Romer (2013), was in the form of a promontory (the Armorican Spur) attached to Gondwana (Fig. 16). Resistance of the Scandinavian Shield to this rotation generated the Brabantian belt in the area of the inferred Thor Suture to the northeast of the Midland Microcraton, whereas rocks to the northwest of the microcraton experienced sinistral transpression evolving towards sinistral transtension to the southeast (Sintubin et al., 2009; Pharaoh, 2018).

5.4.2. Early Devonian foreland basin development in West Avalonia

In West Avalonian terranes of northern Nova Scotia, the Siluro-Devonian boundary is marked by a transition from passive-margin marine sedimentation in the Pridoli Stonehouse Formation to coarsening-upward foreland basin deposits of the Lochkovian to Pragian Knoydart Formation, which bear palaeocurrent vectors that indicate a source to the southwest (Boucot et al., 1974; Murphy, 1987; Waldron et al., 1996). This suggests that collision between Gondwana and West Avalonia was already occurring in earliest Devonian times (Fig. 16, cross-section C-D). In contrast, the now juxtaposed Meguma Belt of southern Nova Scotia was then accommodating quiet marine sediments (Jensen, 1975) that were hosting brachiopods with Rhenish affinities (Boucot, 1960). This suggests that rocks of the Meguma Terrane were proximal to Armorica/Cadomia, which is consistent with provenance data from the Silurian (White et al., 2018), but uninvolved in the early Devonian collisions that affected both West and composite East Avalonia (Fig. 16).

5.4.3. Final closure of the Acadian Seaway

One of the most challenging tectono-magmatic events to explain in the Appalachian–Caledonian is the onset of andesite-rich Early Devonian volcanism in the Matapedia cover sequence of northeastern North America, unconformably above Pridoli bimodal volcanic rocks that are clearly associated with extension or transtension (Wilson et al., 2017). The progressive depletion in HFSEs within these rocks (Fig. 8c,d) suggests a gradual reintroduction of hydrous conditions at the source. We propose that this volcanic succession may be the record of a reactivation of Acadian Seaway slab subduction beneath composite Laurentia (including the accreted Ganderian terranes) due to the Early Devonian docking of a Gondwanan promontory against West Avalonia to the southwest, which forced convergence to resume between the latter and composite Laurentia (Figs. 2 and 16, Cross-section A-B). Hence, the previously aborted subduction zone beneath the South Ganderian margin of composite Laurentia would have provided a weak zone that could have partly accommodated the shortening generated by the convergence of Gondwana against West Avalonia (Fig. 16), which was still separated from composite Laurentia by a small remnant of the Acadian Seaway at the Siluro-Devonian boundary (Fig. 14).

Final closure of the Acadian Seaway and accretion of West Avalonia to composite Laurentia occurred in late Emsian to Middle Devonian times and caused the Acadian Orogeny in northeastern North America (Figs. 2 and 17). A synchronous episode of shortening to the northwest of the Midland Microcraton in the British Isles has also been attributed to the Acadian Orogeny (eg. Soper et al., 1987; Woodcock et al., 2007) (Fig. 17). At the time, the Cornubian Basin of southern England (Fig. 1) was located outside of the collision zone, to the east (Woodcock, 2012c). Its post–Acadian westward migration may have been associated with the same east-west fault system that caused the Meguma Terrane of Atlantic Canada to migrate westward by ~900-1000 km in relation to Avalonian domains along a large Middle Devonian to Carboniferous dextral strike-slip fault corridor (Keppie, 1982; Murphy et al., 2011).

6. Conclusions

Katian to earliest Emsian igneous rocks in the Appalachian–Caledonian Belt all share characteristics of plate-margin magmatism (Figs. 6a,b–11a,b). However, differentiation between arc, slab-failure and plate-margin A2-type magmatism (Figs. 6c,d–11c,d) allowed us to draw a clearer picture on the series of tectono-magmatic events that took place in terranes of that belt during the interval separating the Taconic–Grampian and Acadian orogenies. Furthermore, relatively well constrained ages for these rocks allowed the identification of evolutionary trends in the geochemical data. Based on the latter as well as palaeomagnetic, palaeontologic, structural, stratigraphic and sedimentologic constraints, the following nuances can be added to the closure history of the Iapetus and Rheic oceans as well as their associated segments (Tornquist Sea, Tetagouche–Exploits back-arc basin, and Acadian Seaway):

- Based on the slab-failure signature of early to mid-Silurian igneous rocks to the north of the Dog Bay Line in the North Ganderian and Laurentian margin terranes of northeastern North America (Fig. 7c,d), closure of the Tetagouche–Exploits back-arc basin took place earlier than previously thought (eg. Wilson et al., 2017), and in association with the early Silurian Salinic A unconformity rather than the late Silurian Salinic B unconformity.
- In Ireland, slab failure occurred in mid-Silurian times (*circa* 428 Ma) prior to final closure of Iapetus, with no associated local deformation. However, Iapetus closure was already completed by then farther to the northeast, as recorded by Scandian deformation in terranes of northern Scotland and Greenland, which may have generated post-collisional slab failure (Fig. 13).
- Based on geochronological constraints, igneous rocks produced in association with failure of the Iapetus and Tetagouche–Exploits slabs show a gradual increase in HFSE contents with time (Figs. 7c,d and 10c,d), which we associate with a gradual dehydration of the mantle source due to the abortion of subduction. This trend is paired with a corresponding decrease in Nb/Y and La/Yb ratios with time, which we

attribute to a fading contribution of the failed slab at the source as it sinks to greater depths.

- A switch from shallow subduction and arc magmatism to extensional, A2-type bimodal magmatism occurred at the Ludlow–Pridoli boundary in South Ganderian terranes of coastal Maine and southwest New Brunswick (Fig. 7c,d)). This may have been caused by chain failure of the Acadian Seaway slab deep within the asthenosphere due to its interaction with the slowly sinking Tetagouche–Exploits slab (Fig. 14, transect A-B), which had previously failed at a short distance inboard near the beginning of the Silurian (Fig. 12, transect A-B). Such conclusion is supported by the synchronous record of a rapid and short-lived regression along the north margin of West Avalonia (Fig. 15), which was nearby at the time and attached to the Acadian Seaway slab (Fig. 14, transect C-D).
- Extensional tectonics associated with failure of the Acadian Seaway slab at depth seemingly migrated towards north Ganderian terranes during the Pridoli and produced extensional, A2-type bimodal volcanic rocks and coarse clastic deposits of the Dickie Cove Group (Fig. 14, sections A-B and A’-B’). Evidence for more hydrated volcanism at the base of the group than at the top (Fig. 7c,d) suggests an inheritance from the preceding subduction and slab failure settings and an associated delay in the development of a complete A2-type signature.
- The Early Devonian Dalhousie Group, which overlaps the North Ganderian–Laurentian suture in northern New Brunswick and eastern Quebec (locality i in Fig. 1), records a gradual return to hydrated, andesite-rich arc magmatism (Fig. 8c,d), which is synchronous with foreland basin development in West Avalonia (Table 2). It

is here proposed that these igneous rocks were produced by a reactivation of Acadian Seaway slab subduction beneath composite Laurentia forced by the prograding collision of Gondwana into West Avalonia, which was still attached to that remnant of oceanic lithosphere (Fig. 16). Final closure of the Acadian Seaway generated the laterally extensive Acadian Orogeny (Fig. 17 and Table 2).

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Figure and Table captions

Table 1. Katian to early Emsian igneous rock units at the localities featuring in Figure 1. Abbreviations: badd.: baddeleyite; biostrat.: biostratigraphic; constr.: constraints; Ems.: Emsian; Fm: Formation; Gp: Group; Lland.: Llandovery; Loch.: Lochkovian; Mon.: monazite; Ord.: Ordovician; Settl.: Settlement; strat.: stratigraphic; tit.: titanium; zirc.: zircon.

~~**Table 1.** Igneous rock units at the localities featuring in Figure 1. Abbreviations: volcs: volcanics; ig.: igneous; Fm : Formation; Gp : Group; C.: Cove; Dal.: Dalhousie; Settl.: Settlement; lampr.: lamprophyre; inter.: intermediate; Lland.: Llandovery; Lochk: Lochkovian; Ems.: Emsian; Ord.: Ordovician; strat.: stratigraphic; biostrat.: biostratigraphic.~~

Fig. 1. Map of northeastern North America and Europe showing the main continental terrane assemblages that were involved in the formation of the Appalachian–Caledonian Belt. Details on the lettered localities are included in the text and compiled in Table 1.

Fig. 2. Main tectono-magmatic events recorded in the study area. Ordovician, Silurian and Devonian subdivisions are respectively from Bergström et al. (2008), Melchin et al. (2020), and Becker et a. (2020). Letters in triangles and circles correspond respectively to intrusive and

extrusive rocks at localities indicated in Fig. 1, with references for estimated ages indicated in Table 1. Previous work and references therein include, 1: van Staal et al. (2016); 2: van Staal et al. (2012); 3: van Staal et al. (2009); 4: Jutras et al. (2020); 5: Woodcock (2012a); 6: Chew and Strachan (2014); 7: Rogers and van Staal, 2003; 8: Wilson et al. (2017); 9: Pharaoh et al. (1993); 10: Piñán-Llamas and Hepburn (2013); 11: Woodcock (2012b); 12: Boucot et al. (1974); 13: Jakob et al. (2022); 14: Woodcock et al. (2007); 15: Murphy et al. (2004); 16: Kroner and Romer (2013); 17: Tremblay and Pinet (2016), and Woodcock (2012c).

Fig. 3. Palaeocontinental reconstruction at ~462 Ma based on Woodcock (2012a), Zagorevski et al. (2010), Murphy et al. (2008. 2012), Waldron et al. (2014), Phillips et al. (2016), van Staal et al. (2016), Wilson et al. (2017), and Jutras et al. (2020).

Fig. 4. Accretion of North Ganderia to composite Laurentia near 455 Ma (Taconic phase C of van Staal et al., 2007) followed by slab-window volcanism *circa* 454 Ma in the McGillivray Brook Formation of Nova Scotia (Jutras et al., 2020) and the Snowdon Group of Wales (Woodcock, 2012a; Lusty et al., 2017) due to the incomplete subduction of the Iapetan ridge beneath Avalonia.

Fig. 5. Development of new, post–Taconic–Grampian subduction zones *circa* 453 Ma based on Pharaoh et al., (1991, 1993), Noble et al. (1993) and Torsvik and Rehnström (2003), Woodcock (2012a), and Wilson et al. (2017). Intrusive rocks from localities s and y are described in Table 1.

Fig. 6. Late Ordovician to Early Devonian igneous rocks in South Ganderian terranes of coastal Maine and southern New Brunswick (data from Seaman et al., 1999; Barr et al., 2002; van Wagoner et al., 2002; Llamas and Hepburn, 2013) plotted in (a) the Hf/3–Ta–Th diagram of

Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 7. Late Ordovician to Silurian igneous rocks in North Ganderian and Laurentian margin terranes of northeastern North America (data from Whalen, 1989; David and Gariépy, 1990; Giggie, 1999; Whalen et al., 2006; Wilson and Kamo, 2008; Wilson et al., 1995; Wilson, 2017) plotted in (a) the Hf/3‒Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 8. Lower Devonian igneous rocks in North Ganderian and Laurentian margin terranes of northern New Brunswick and eastern Quebec (data from Murphy, 1989; Whalen et al., 1996; Wilson et al., 2005; Walker, 2010; Wilson, 2017) plotted in (a) the Hf/3‒Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 9. Lower Devonian igneous rocks in North Ganderian terranes of northern Newfoundland (data from Aydin, 1995; Currie, 2003) plotted in (a) the Hf/3‒Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 10. Late Ordovician to Early Devonian igneous rocks along the Laurentian margin in the British Isles (data from Tindle and Pearce, 1981; Badenszki et al., 2019; Murphy et al., 2019; Archibald and Murphy, 2021) plotted in (a) the Hf/3‒Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 11. Late Ordovician to Early Devonian igneous rocks (data from van de Kamp, 1969; Greenough, 1984; Sloan and Bennett, 1990; Pharaoh et al., 1991, 1993) in the former micro-continents of West and composite East Avalonia plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb+Y vs Nb/Y and (d) Ta+Yb vs La/Yb diagrams of Whalen and Hildebrand (2019).

Fig. 12. Proposed model for tectono-magmatic events that occurred during the ~441-429 Ma interval (Llandovery to Wenlock) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, black letters indicating the record of extrusive rocks, and red-and-black letters indicating the record of both. Igneous rock units from that interval include the Dennys Formation at locality b (Piñán-Llamas and Hepburn, 2013), intrusive and extrusive rocks from the Kingston terrane at locality d (Barr et al., 2002), the Lac Raymond and Pointe aux Trembles formations at locality g (David and Gariépy, 1990), the Weir Formation at locality j (Wilson et al., 2008), various plutons at localities m and l (Whalen et al. (2006), the Topsails volcanic group at locality o (Whalen, 1989), the Cape St. Mary's sills at locality q (Greenough et al., 1993), the Skomer Volcanic Group at locality w (Thorpe et al., 1989), and the Tortworth volcanics at locality x (van de Kamp, 1969; Pharaoh et al., 1991).

Fig. 13. Proposed model for tectono-magmatic events that occurred during the ~428-424 Ma interval (latest Wenlock to Ludlow) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, and black letters indicating the record of extrusive rocks. Igneous rock units from that interval include the Cranberry Islands volcanic series at locality a (Seaman et al., 1999), the Edmunds Formation, and possibly the Leighton and Eastport formations at locality b (Piñán-

Llamas and Hepburn, 2013), the Topsails intrusive suite at locality n (Whalen, 1989), early intrusions in the Donegal composite pluton at locality r (Archibald and Murphy, 2021), the Dunquin Group at locality u (Sloan and Bennett, 1990), and possibly the Tortworth volcanics at locality x (van de Kamp, 1969; Pharaoh et al., 1991).

Fig. 14. Proposed model for tectono-magmatic events that occurred during the 423–421 Ma interval (Pridoli) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, and black or white letters indicating the record of extrusive rocks. Igneous rock units from that interval include the Passamaquoddy Bay volcanic sequence at locality c (van Wagoner et al., 2002), the Dickie Cove and lower Tobique groups at localities h and e, respectively (Dostal et al., 2020, 2021), and intrusive rocks in the Donegal composite pluton at locality r (Archibald and Murphy, 2021).

Fig. 15. (a) Thin interval of early Pridoli continental red beds (Upper Member of the Moydart Formation) between thick intervals of green marine mudrock in the Arisaig Group of northern Nova Scotia (West Avalonia); (b) intertidal rhythmites in the gradational, but rapid transition from subtidal to supratidal deposits near the Ludlow–Pridoli boundary; (c) calcretes within the barren Upper Member of the Moydart Formation, which is latest Ludlow to earliest Pridoli based on biostratigraphic constraints.

Fig. 16. Proposed model for tectono-magmatic events that occurred during the ~417-407 Ma interval (Lochkovian to earliest Emsian) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, and black letters indicating the record of extrusive rocks. Igneous rock units from that interval include the Dalhousie and upper Tobique groups at localities i and e,

respectively (Wilson, 2017), the Lyall and Baldwin volcanics at locality k (Doyon and Dalpé, 1993), various plutons in the Miramichi Highlands of northern New Brunswick (locality f; Whalen et al., 1996), the Fogo Island Batholith at locality p (Aydin, 1995; Currie, 2003), intrusive rocks in the Donegal composite pluton at locality r (Archibald and Murphy, 2021), the Loch Doon Pluton at locality s (Tindle and, 1981), and a xenolith within upper Palaeozoic intrusive rocks at locality t (Badenszki et al., 2019).

Fig. 17. Proposed model for the Middle Devonian Acadian Orogeny.

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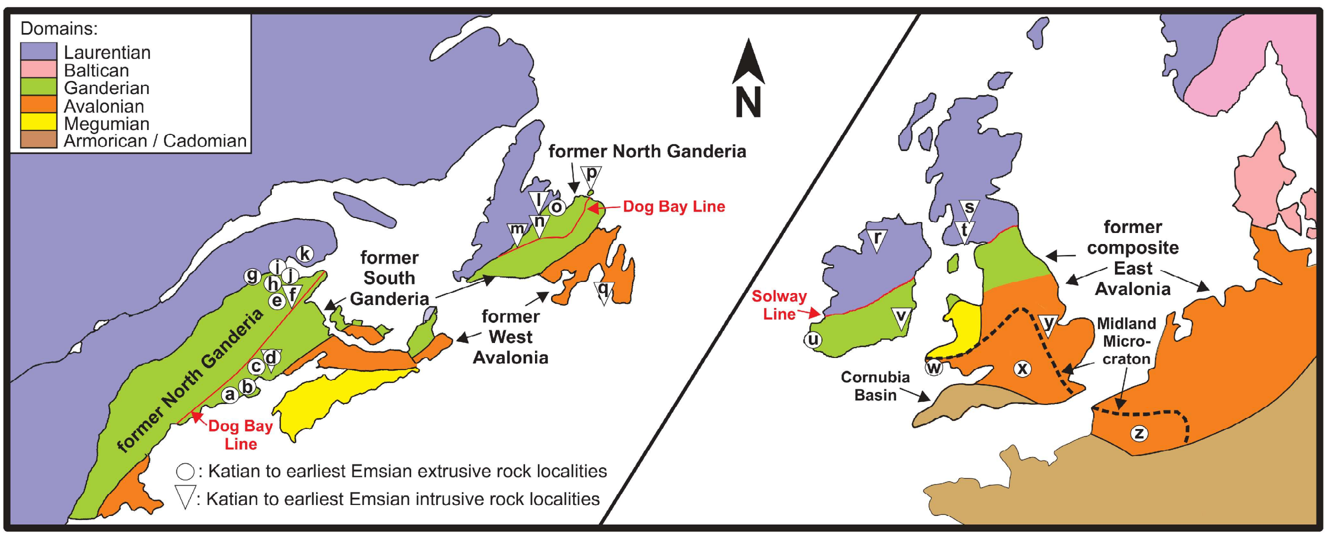

Domains:
Laurentian
Baltican
Ganderian
Avalonian
Megumian
Armorican / Cadomian
N
former North Ganderia
Dog Bay Line
former South Ganderia
former West Avalonia
former North Ganderia
Dog Bay Line
Solway Line
former composite East Avalonia
Midland Micro-craton
Cornubia Basin
a
b
c
d
e
f
g
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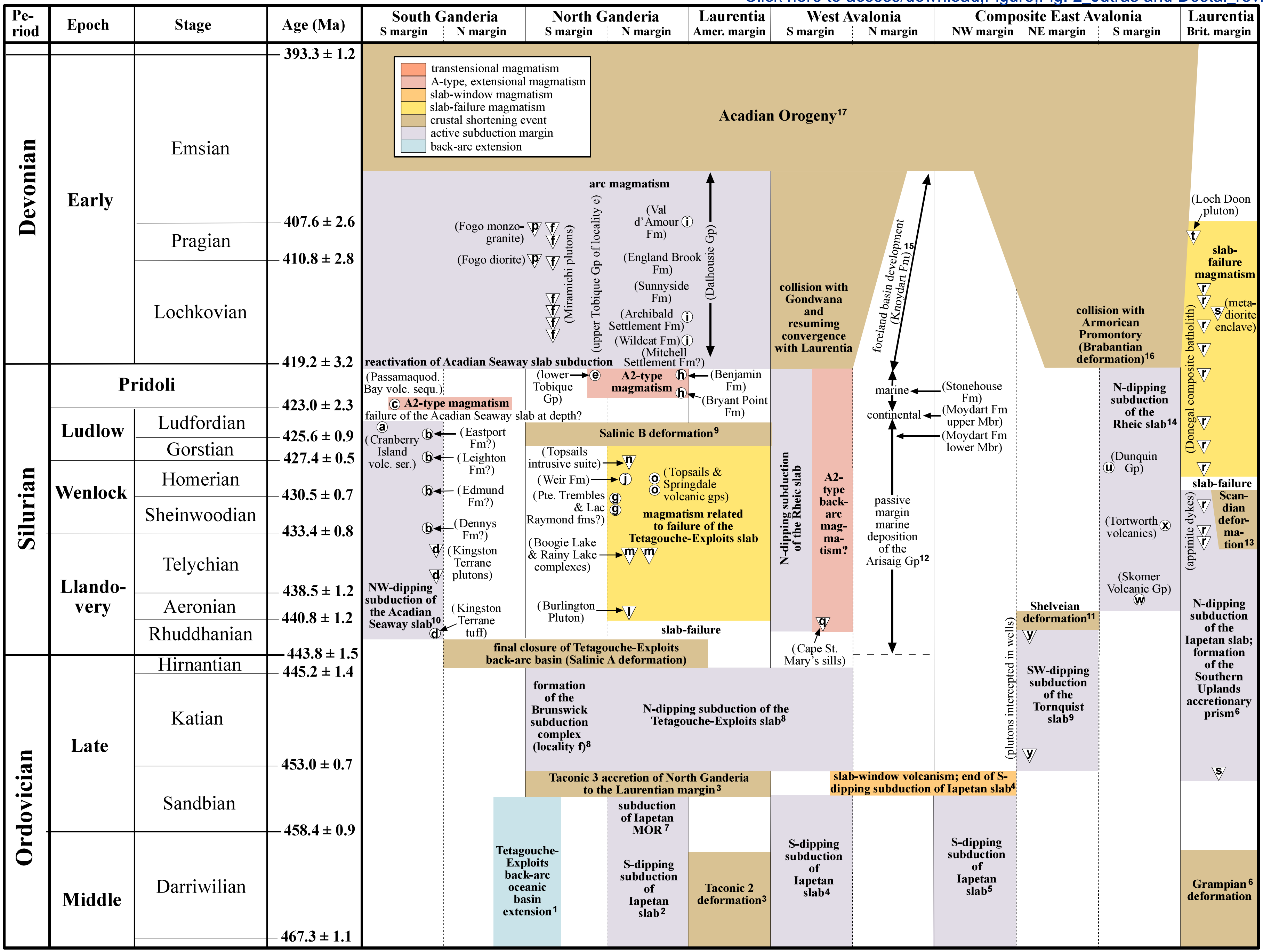
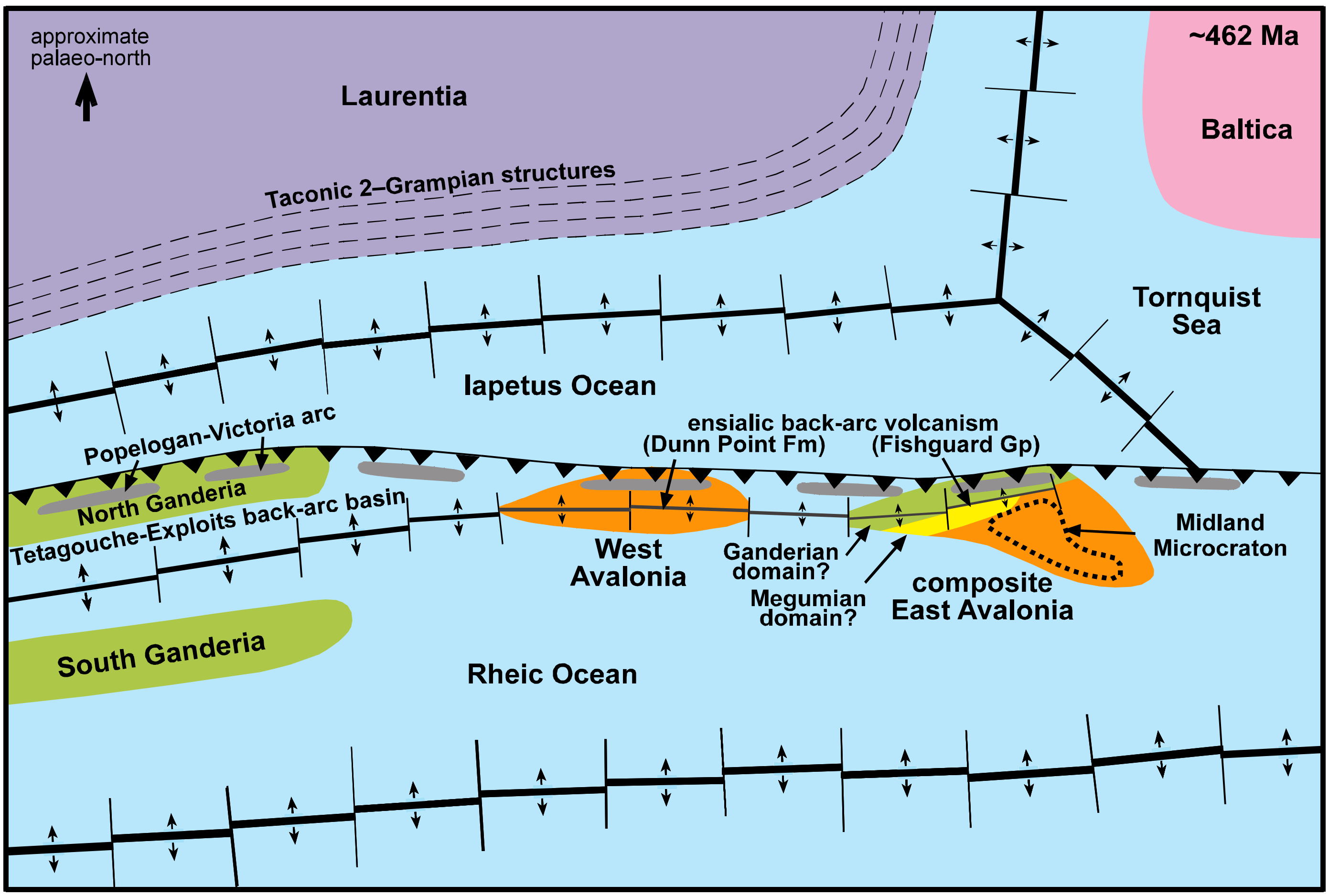
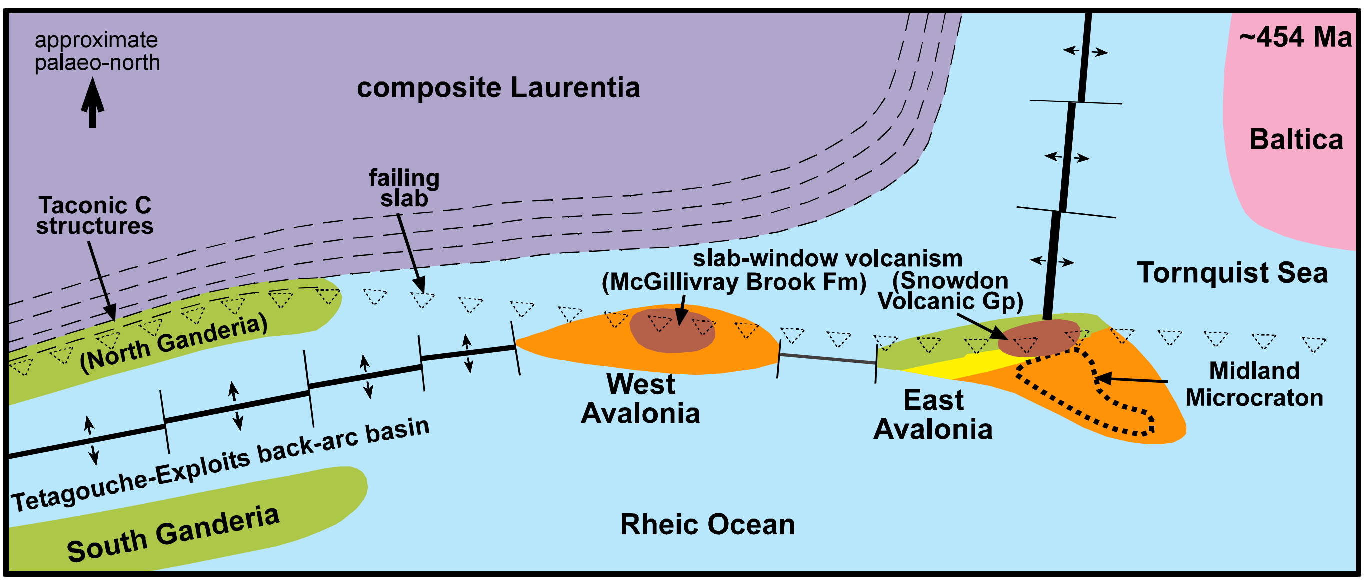
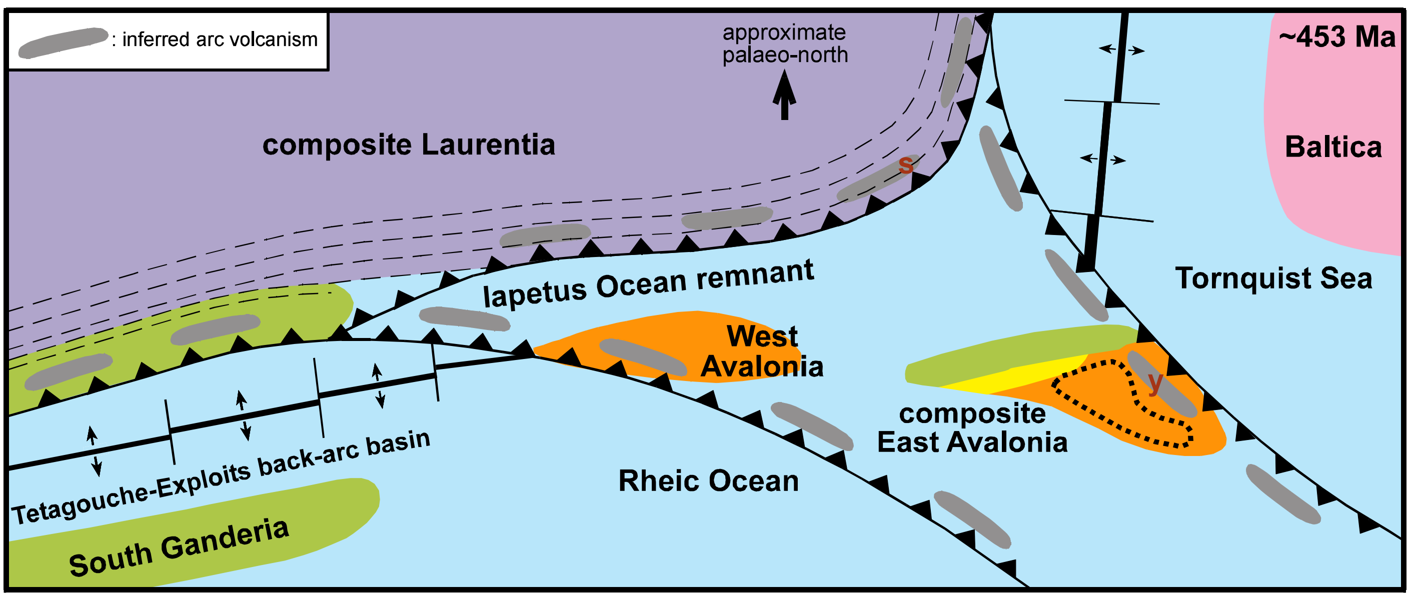
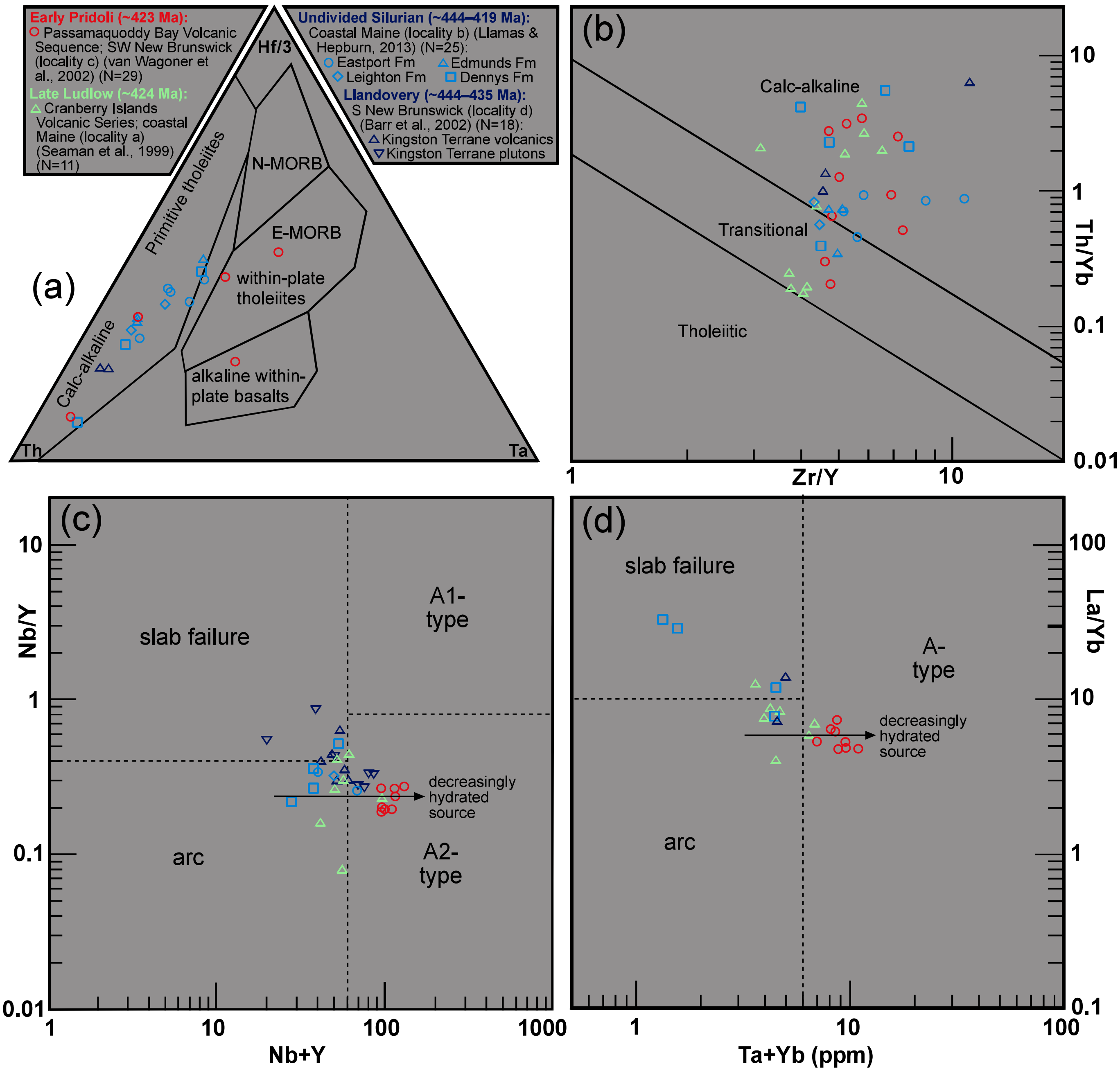
: Katian to earliest Emsian extrusive rock localities
: Katian to earliest Emsian intrusive rock localities

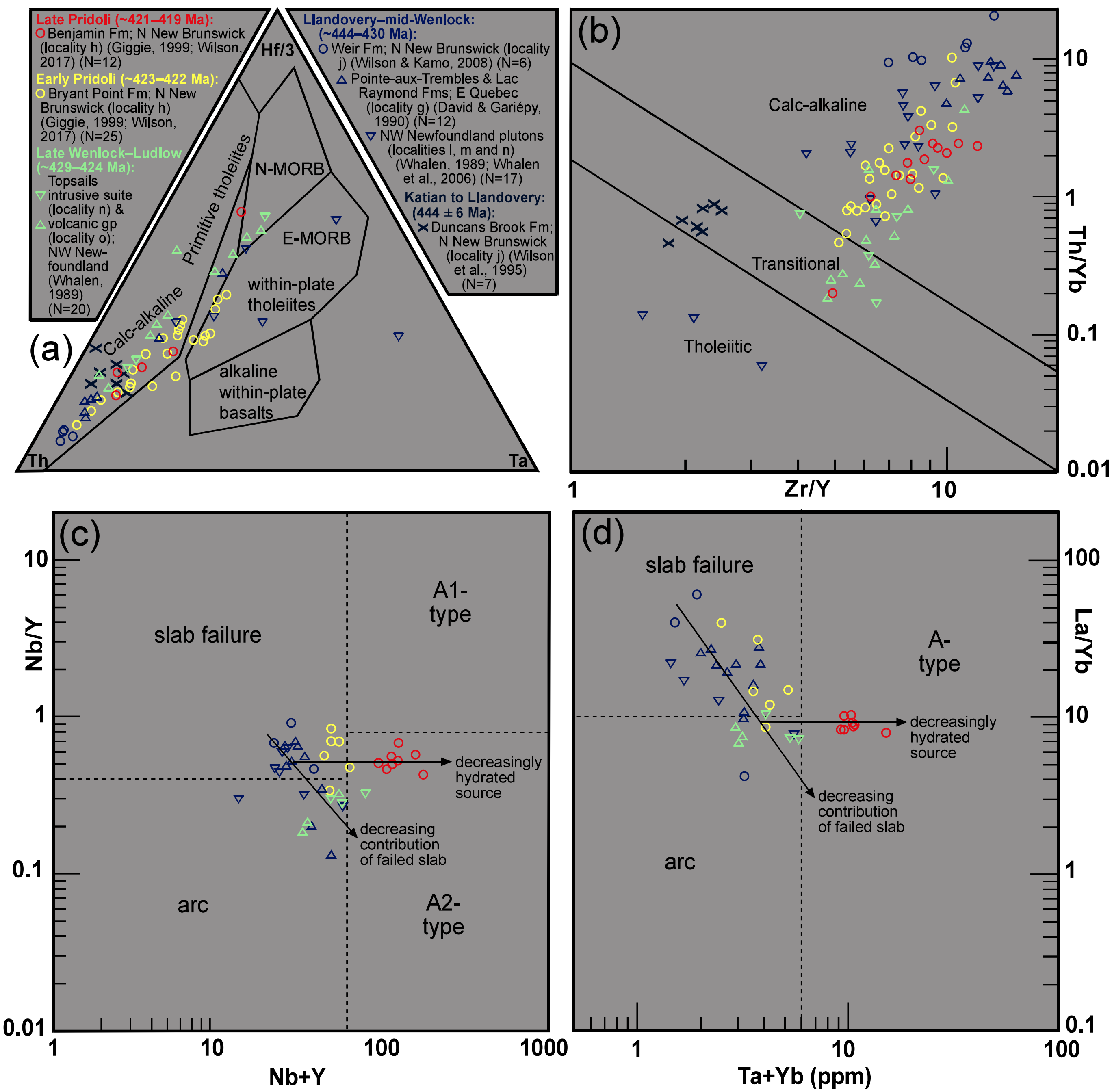

Pe-riod
Epoch
Stage
Age (Ma)
South Ganderia
S margin
N margin
North Ganderia
S margin
N margin
Laurentia
Amer. margin
West Avalonia
S margin
N margin
Composite East Avalonia
NW margin
NE margin
S margin
Laurentia
Brit. margin
Devonian
Silurian
Ordovician
Early
Pridoli
Ludlow
Wenlock
Llando-very
Late
Middle
Emsian
Pragian
Lochkovian
Ludfordian
Gorstian
Homerian
Sheinwoodian
Telychian
Aeronian
Rhuddhanian
Hirnantian
Katian
Sandbian
Darriwilian
393.3 ± 1.2
407.6 ± 2.6
410.8 ± 2.8
419.2 ± 3.2
423.0 ± 2.3
425.6 ± 0.9
427.4 ± 0.5
430.5 ± 0.7
433.4 ± 0.8
438.5 ± 1.2
440.8 ± 1.2
443.8 ± 1.5
445.2 ± 1.4
453.0 ± 0.7
458.4 ± 0.9
467.3 ± 1.1
transtensional magmatism
A-type, extensional magmatism
slab-window magmatism
slab-failure magmatism
crustal shortening event
active subduction margin
back-arc extension
Acadian Orogeny[17]
arc magmatism
(Fogo monzo-granite)
(Fogo diorite)
(Miramichi plutons)
(upper Tobique Gp of locality e)
(Val d'Amour Fm)
(England Brook Fm)
(Sunnyside Fm)
(Archibald Settlement Fm)
(Wildcat Fm)
(Mitchell Settlement Fm?)
(Dalhousie Gp)
collision with Gondwana and resumimg convergence with Laurentia
foreland basin development (Knoydart Fm)[15]
collision with Armorican Promontory (Brabantian deformation)[16]
(Loch Doon pluton)
slab-failure magmatism
(meta-diorite enclave)
(Donegal composite batholith)
reactivation of Acadian Seaway slab subduction
(Passamaquod. Bay volc. sequ.)
A2-type magmatism
failure of the Acadian Seaway slab at depth?
(lower Tobique Gp)
A2-type magmatism
(Benjamin Fm)
(Bryant Point Fm)
marine
continental
(Stonehouse Fm)
(Moydart Fm upper Mbr)
(Moydart Fm lower Mbr)
N-dipping subduction of the Rheic slab[14]
(Cranberry Island volc. ser.)
(Eastport Fm?)
(Leighton Fm?)
(Edmund Fm?)
(Dennys Fm?)
(Kingston Terrane plutons)
Salinic B deformation[9]
(Topsails intrusive suite)
(Weir Fm)
(Pte. Trembles & Lac Raymond fms?)
(Topsails & Springdale volcanic gps)
magmatism related to failure of the Tetagouche-Exploits slab
(Boogie Lake & Rainy Lake complexes)
N-dipping subduction of the Rheic slab
A2-type back-arc mag-ma-tism?
passive margin marine deposition of the Arisaig Gp[12]
(Dunquin Gp)
(Tortworth volcanics)
(Skomer Volcanic Gp)
slab-failure
Scan-dian defor-ma-tion[13]
(appinite dykes)
NW-dipping subduction of the Acadian Seaway slab[10]
(Kingston Terrane tuff)
(Burlington Pluton)
slab-failure
(Cape St. Mary's sills)
Shelveian deformation[11]
(plutons intercepted in wells)
N-dipping subduction of the Iapetan slab; formation of the Southern Uplands accretionary prism[6]
final closure of Tetagouche-Exploits back-arc basin (Salinic A deformation)
formation of the Brunswick subduction complex (locality f)[8]
N-dipping subduction of the Tetagouche-Exploits slab[8]
SW-dipping subduction of the Tornquist slab[9]
Taconic 3 accretion of North Ganderia to the Laurentian margin[3]
slab-window volcanism; end of S-dipping subduction of Iapetan slab[4]
Tetagouche-Exploits back-arc oceanic basin extension[1]
subduction of Iapetan MOR[7]
S-dipping subduction of Iapetan slab[2]
Taconic 2 deformation[3]
S-dipping subduction of Iapetan slab[4]
S-dipping subduction of Iapetan slab[5]
Grampian[6] deformation

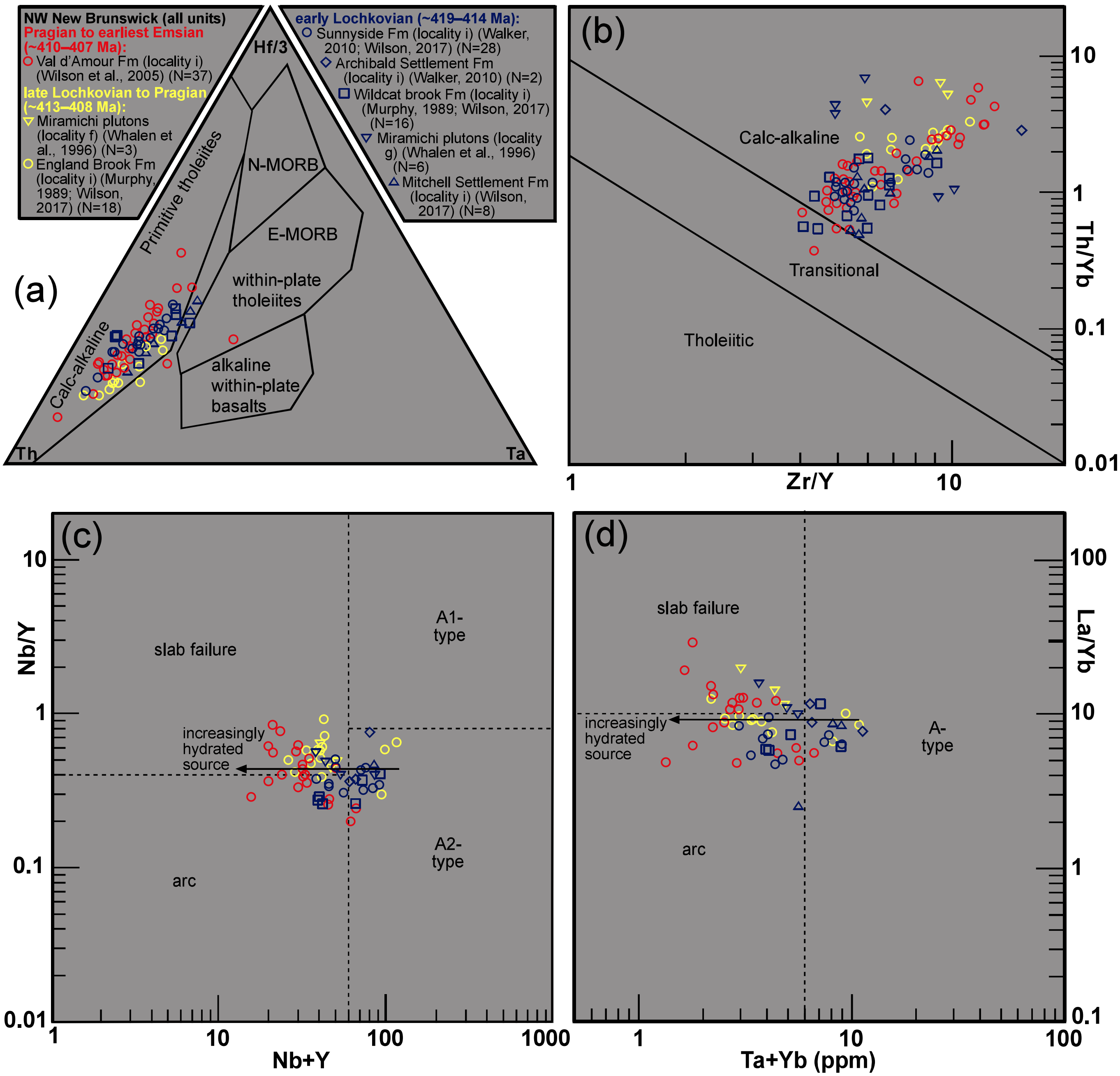

approximate
palaeo-north
Laurentia
~462 Ma
Baltica
Taconic 2–Grampian structures
Tornquist
Sea
Iapetus Ocean
Popelogan-Victoria arc
ensialic back-arc volcanism
(Dunn Point Fm)
(Fishguard Gp)
North Ganderia
Tetagouche-Exploits back-arc basin
West
Avalonia
Ganderian
domain?
Megumian
domain?
composite
East Avalonia
Midland
Microcraton
South Ganderia
Rheic Ocean

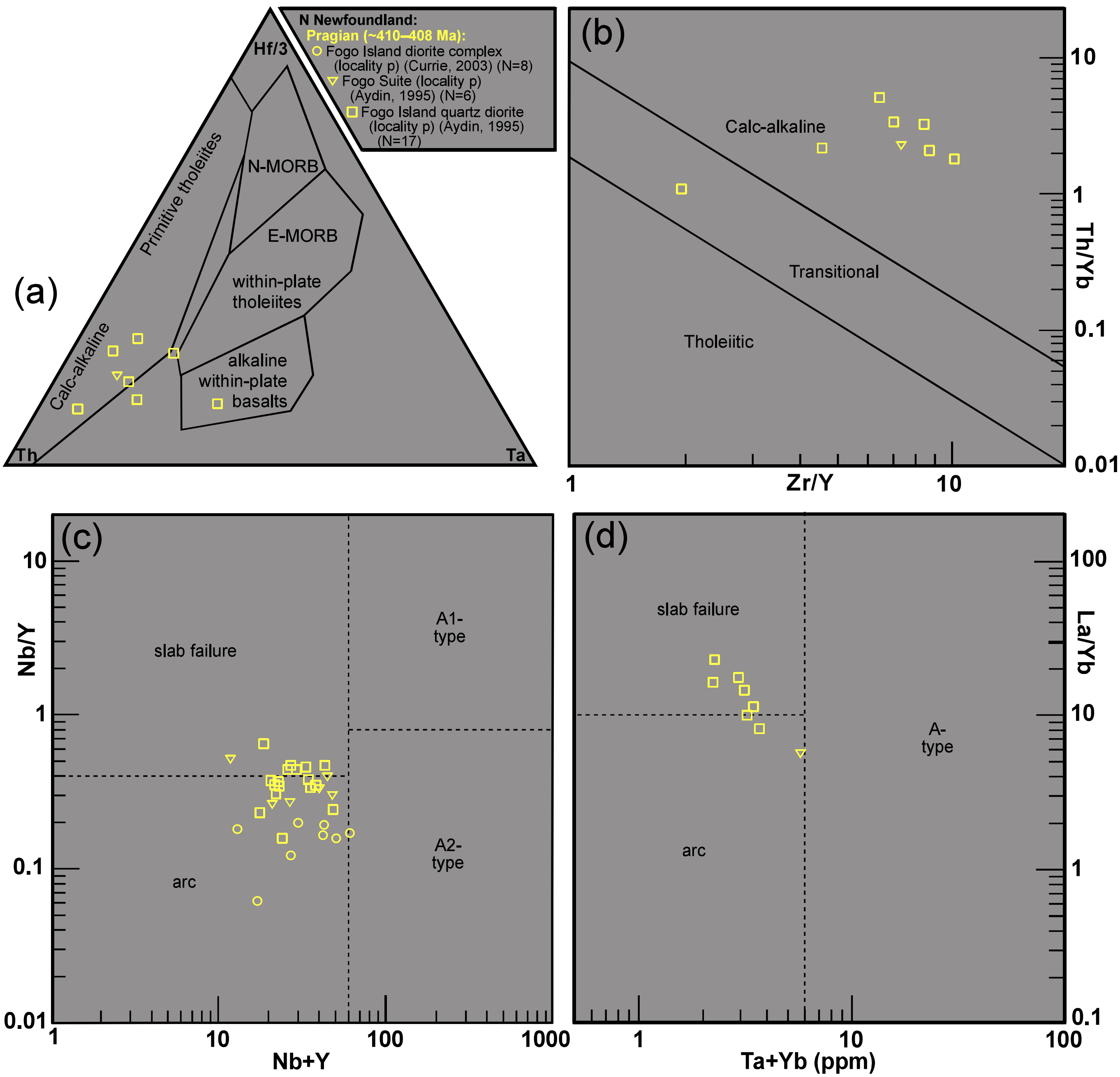

approximate
palaeo-north
composite Laurentia
~454 Ma
Baltica
Taconic C
structures
failing
slab
slab-window volcanism
(McGillivray Brook Fm)
(Snowdon
Volcanic Gp)
Tornquist Sea
(North Ganderia)
West
Avalonia
East
Avalonia
Midland
Microcraton
Tetagouche-Exploits back-arc basin
South Ganderia
Rheic Ocean

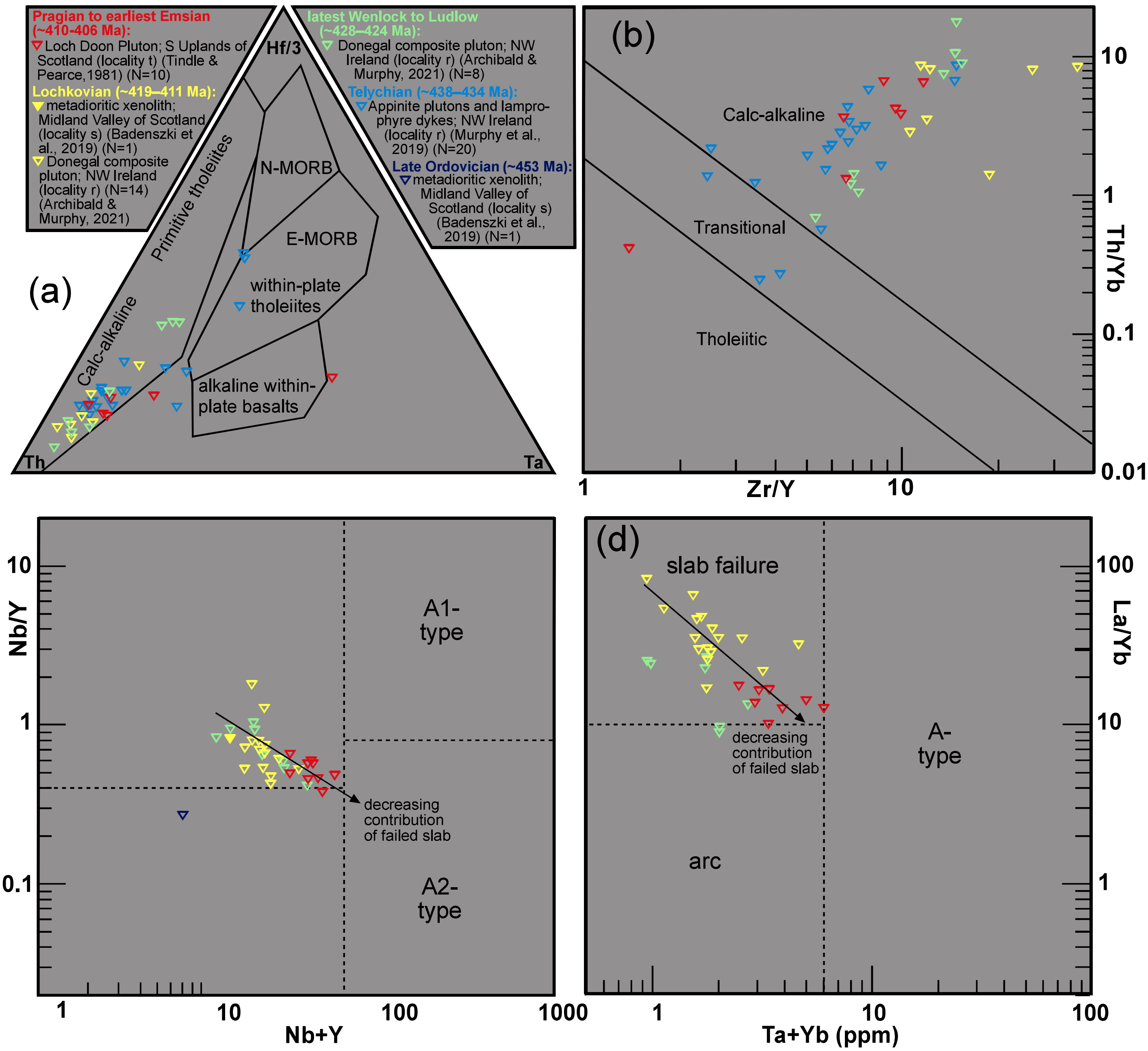

: inferred arc volcanism
approximate palaeo-north
~453 Ma
composite Laurentia
Baltica
s
Iapetus Ocean remnant
Tornquist Sea
West Avalonia
y
composite East Avalonia
Tetagouche-Exploits back-arc basin
Rheic Ocean
South Ganderia

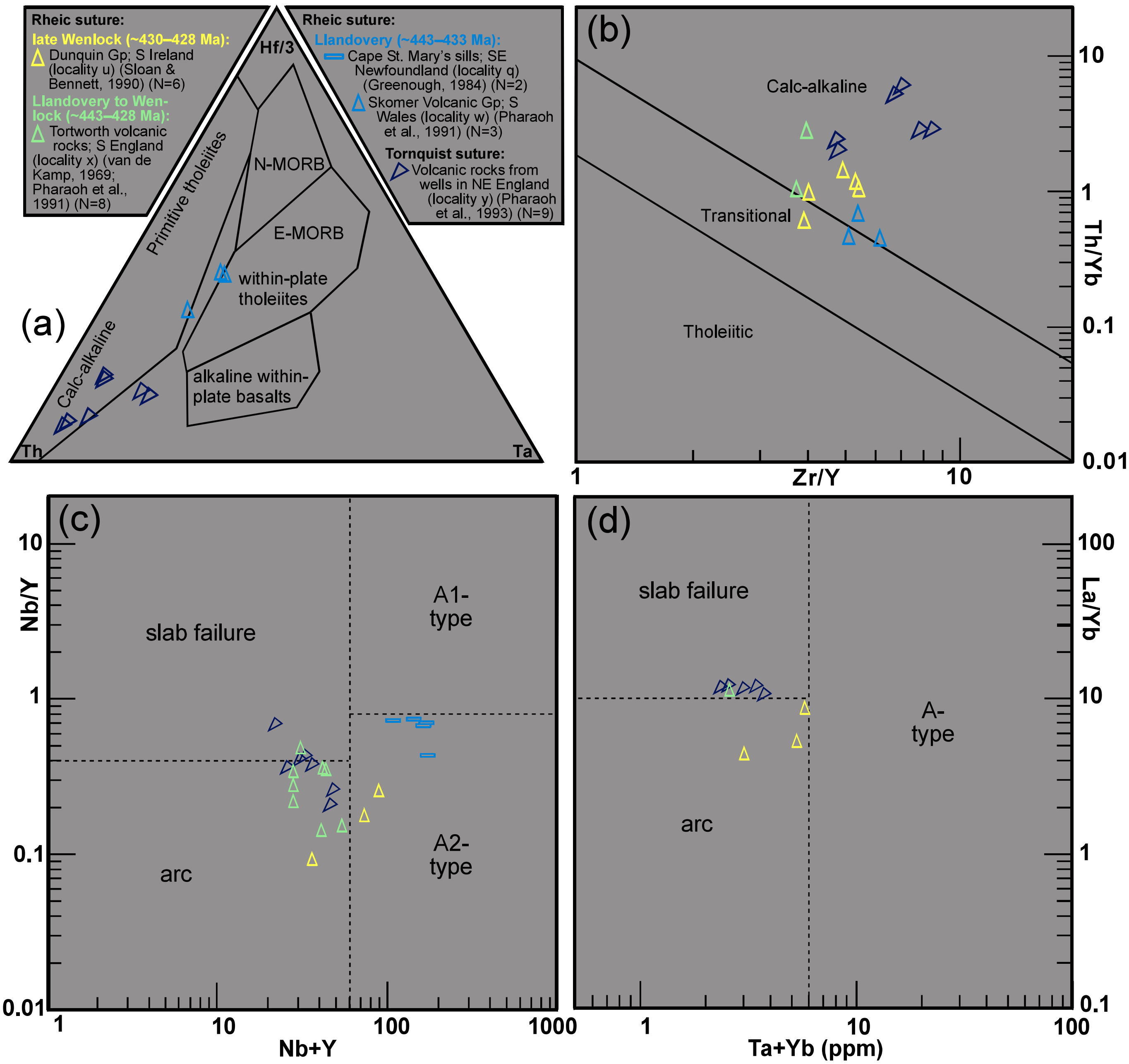

Early Pridoli (~423 Ma):
Passamaquoddy Bay Volcanic Sequence; SW New Brunswick (locality c) (van Wagoner et al., 2002) (N=29)
Late Ludlow (~424 Ma):
Cranberry Islands Volcanic Series; coastal Maine (locality a) (Seaman et al., 1999) (N=11)
Undivided Silurian (~444–419 Ma):
Coastal Maine (locality b) (Llamas & Hepburn, 2013) (N=25):
Eastport Fm
Edmunds Fm
Leighton Fm
Dennys Fm
Llandovery (~444–435 Ma):
S New Brunswick (locality d) (Barr et al., 2002) (N=18):
Kingston Terrane volcanics
Kingston Terrane plutons
(a)
Hf/3
Th
Ta
Primitive tholeiites
N-MORB
E-MORB
within-plate tholeiites
Calc-alkaline
alkaline within-plate basalts
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
1
10
0.1
0.01
(c)
slab failure
A1-type
arc
A2-type
decreasingly hydrated source
Nb/Y
Nb+Y
0.01
1000
100
(d)
slab failure
A-type
arc
decreasingly hydrated source
La/Yb
Ta+Yb (ppm)

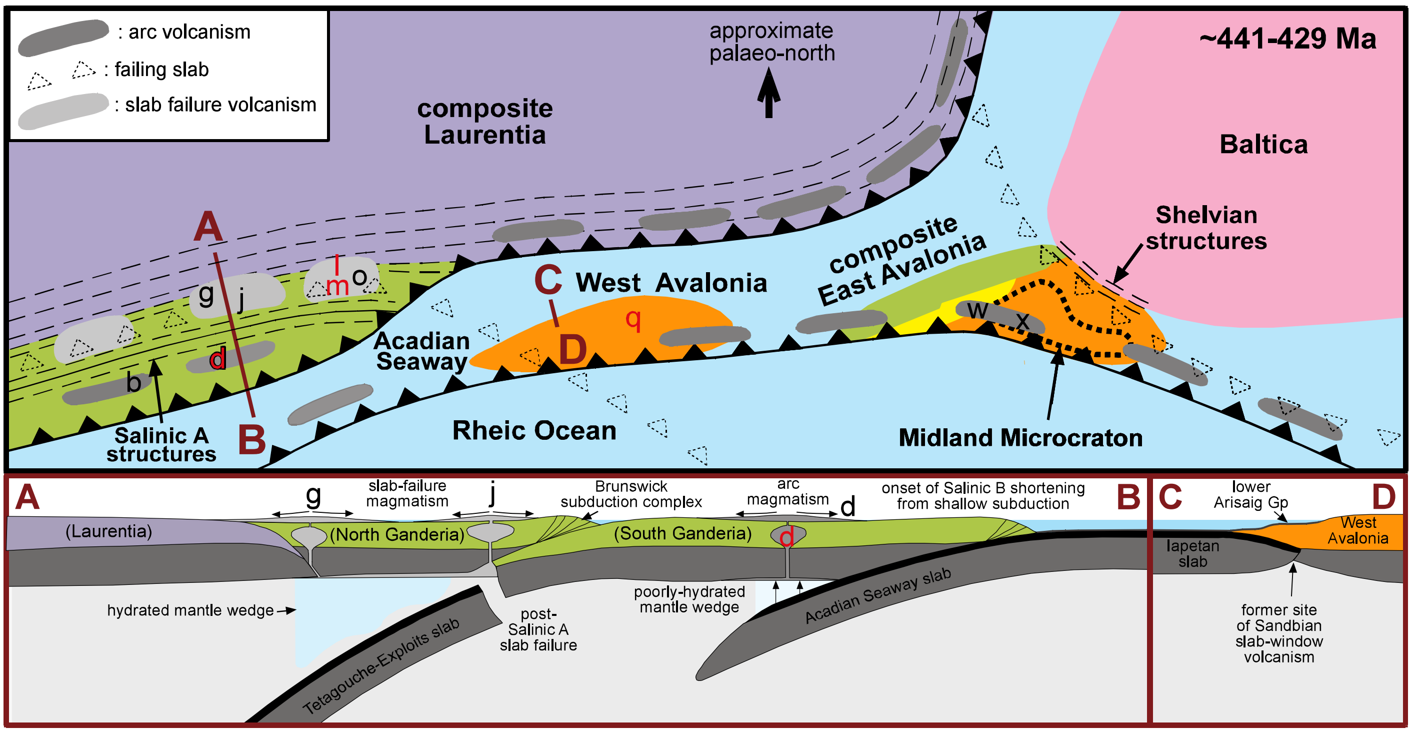

Late Pridoli (~421–419 Ma):
Benjamin Fm; N New Brunswick (locality h) (Giggie, 1999; Wilson, 2017) (N=12)
Early Pridoli (~423–422 Ma):
Bryant Point Fm; N New Brunswick (locality h) (Giggie, 1999; Wilson, 2017) (N=25)
Late Wenlock–Ludlow (~429–424 Ma):
Topsails intrusive suite (locality n) & volcanic gp (locality o); NW New-foundland (Whalen, 1989) (N=20)
Llandovery–mid-Wenlock: (~444–430 Ma):
Weir Fm; N New Brunswick (locality j) (Wilson & Kamo, 2008) (N=6)
Pointe-aux-Trembles & Lac Raymond Fms; E Quebec (locality g) (David & Gariépy, 1990) (N=12)
NW Newfoundland plutons (localities l, m and n) (Whalen, 1989; Whalen et al., 2006) (N=17)
Katian to Llandovery: (444 ± 6 Ma):
Duncans Brook Fm; N New Brunswick (locality j) (Wilson et al., 1995) (N=7)
(a)
Hf/3
Th
Ta
N-MORB
E-MORB
Primitive tholeiites
Calc-alkaline
within-plate tholeiites
alkaline within-plate basalts
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
(c)
slab failure
A1-type
arc
A2-type
decreasingly hydrated source
decreasing contribution of failed slab
Nb/Y
Nb+Y
(d)
slab failure
A-type
arc
decreasingly hydrated source
decreasing contribution of failed slab
La/Yb
Ta+Yb (ppm)


NW New Brunswick (all units)
Pragian to earliest Emsian (~410–407 Ma):
Val d'Amour Fm (locality i) (Wilson et al., 2005) (N=37)
late Lochkovian to Pragian (~413–408 Ma):
Miramichi plutons (locality f) (Whalen et al., 1996) (N=3)
England Brook Fm (locality i) (Murphy, 1989; Wilson, 2017) (N=18)
early Lochkovian (~419–414 Ma):
Sunnyside Fm (locality i) (Walker, 2010; Wilson, 2017) (N=28)
Archibald Settlement Fm (locality i) (Walker, 2010) (N=2)
Wildcat brook Fm (locality i) (Murphy, 1989; Wilson, 2017) (N=16)
Miramichi plutons (locality g) (Whalen et al., 1996) (N=6)
Mitchell Settlement Fm (locality i) (Wilson, 2017) (N=8)
(a)
Hf/3
Th
Ta
Primitive tholeiites
Calc-alkaline
N-MORB
E-MORB
within-plate tholeiites
alkaline within-plate basalts
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
1
10
0.01
0.1
1
10
(c)
slab failure
A1-type
A2-type
arc
increasingly hydrated source
Nb/Y
Nb+Y
0.01
0.1
1
10
1
10
100
1000
(d)
slab failure
A-type
arc
increasingly hydrated source
La/Yb
Ta+Yb (ppm)
0.1
1
10
100
1
10
100

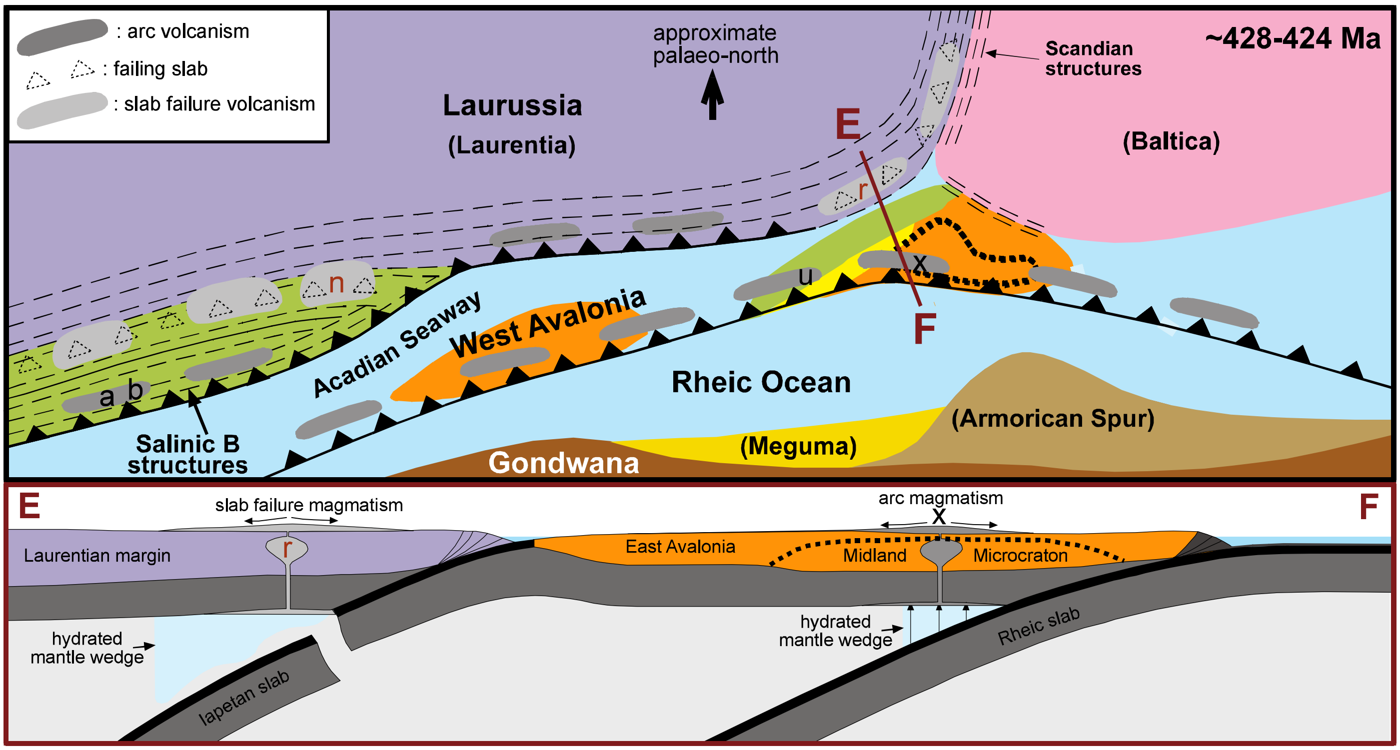

N Newfoundland:
Pragian (~410–408 Ma):
Fogo Island diorite complex (locality p) (Currie, 2003) (N=8)
Fogo Suite (locality p) (Aydin, 1995) (N=6)
Fogo Island quartz diorite (locality p) (Aydin, 1995) (N=17)
(a)
Hf/3
Th
Ta
N-MORB
E-MORB
within-plate tholeiites
alkaline within-plate basalts
Primitive tholeiites
Calc-alkaline
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
1
10
0.1
0.01
(c)
slab failure
arc
A1-type
A2-type
Nb/Y
Nb+Y
1
10
100
1000
0.1
0.01
(d)
slab failure
arc
A-type
La/Yb
Ta+Yb (ppm)
100


Pragian to earliest Emsian (~410-406 Ma):
Loch Doon Pluton; S Uplands of Scotland (locality t) (Tindle & Pearce,1981) (N=10)
Lochkovian (~419–411 Ma):
metadioritic xenolith; Midland Valley of Scotland (locality s) (Badenszki et al., 2019) (N=1)
Donegal composite pluton; NW Ireland (locality r) (N=14) (Archibald & Murphy, 2021)
latest Wenlock to Ludlow (~428–424 Ma):
Donegal composite pluton; NW Ireland (locality r) (Archibald & Murphy, 2021) (N=8)
Telychian (~438–434 Ma):
Appinite plutons and lamprophyre dykes; NW Ireland (locality r) (Murphy et al., 2019) (N=20)
Late Ordovician (~453 Ma):
metadioritic xenolith; Midland Valley of Scotland (locality s) (Badenszki et al., 2019) (N=1)
(a)
Hf/3
Th
Ta
Primitive tholeiites
Calc-alkaline
N-MORB
E-MORB
within-plate tholeiites
alkaline within-plate basalts
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
1
10
0.01
0.1
1
10
Nb/Y
Nb+Y
A1-type
A2-type
decreasing contribution of failed slab
0.1
1
10
1
10
100
1000
(d)
slab failure
arc
A-type
decreasing contribution of failed slab
Ta+Yb (ppm)
La/Yb
1
10
100

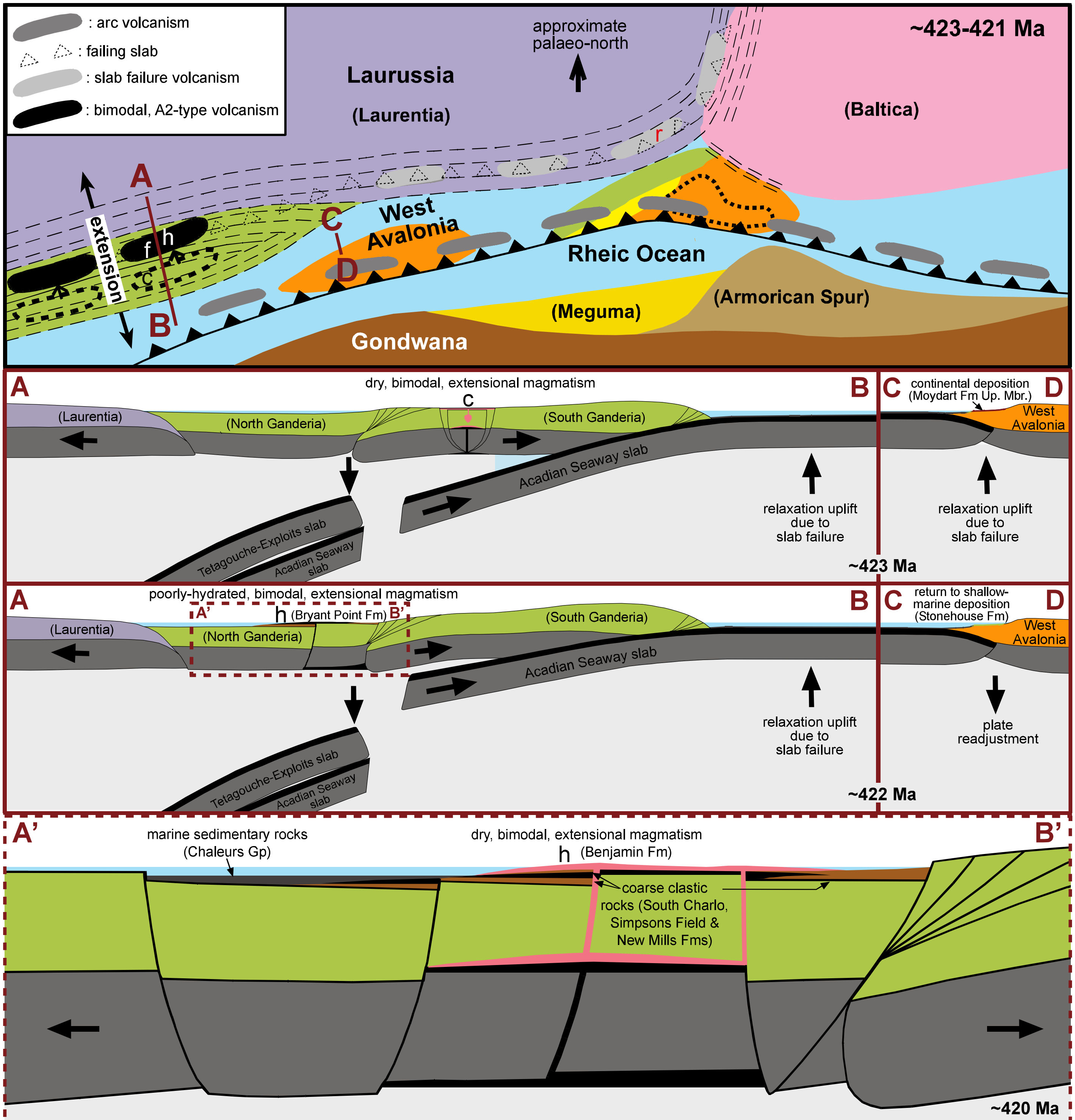

Rheic suture:
late Wenlock (~430–428 Ma):
Dunquin Gp; S Ireland (locality u) (Sloan & Bennett, 1990) (N=6)
Llandovery to Wenlock (~443–428 Ma):
Tortworth volcanic rocks; S England (locality x) (van de Kamp, 1969; Pharaoh et al., 1991) (N=8)
Rheic suture:
Llandovery (~443–433 Ma):
Cape St. Mary's sills; SE Newfoundland (locality q) (Greenough, 1984) (N=2)
Skomer Volcanic Gp; S Wales (locality w) (Pharaoh et al., 1991) (N=3)
Tornquist suture:
Volcanic rocks from wells in NE England (locality y) (Pharaoh et al., 1993) (N=9)
(a)
Hf/3
Th
Ta
Primitive tholeiites
Calc-alkaline
N-MORB
E-MORB
within-plate tholeiites
alkaline within-plate basalts
(b)
Calc-alkaline
Transitional
Tholeiitic
Zr/Y
Th/Yb
(c)
Nb/Y
Nb+Y
slab failure
arc
A1-type
A2-type
(d)
slab failure
arc
A-type
Ta+Yb (ppm)
La/Yb

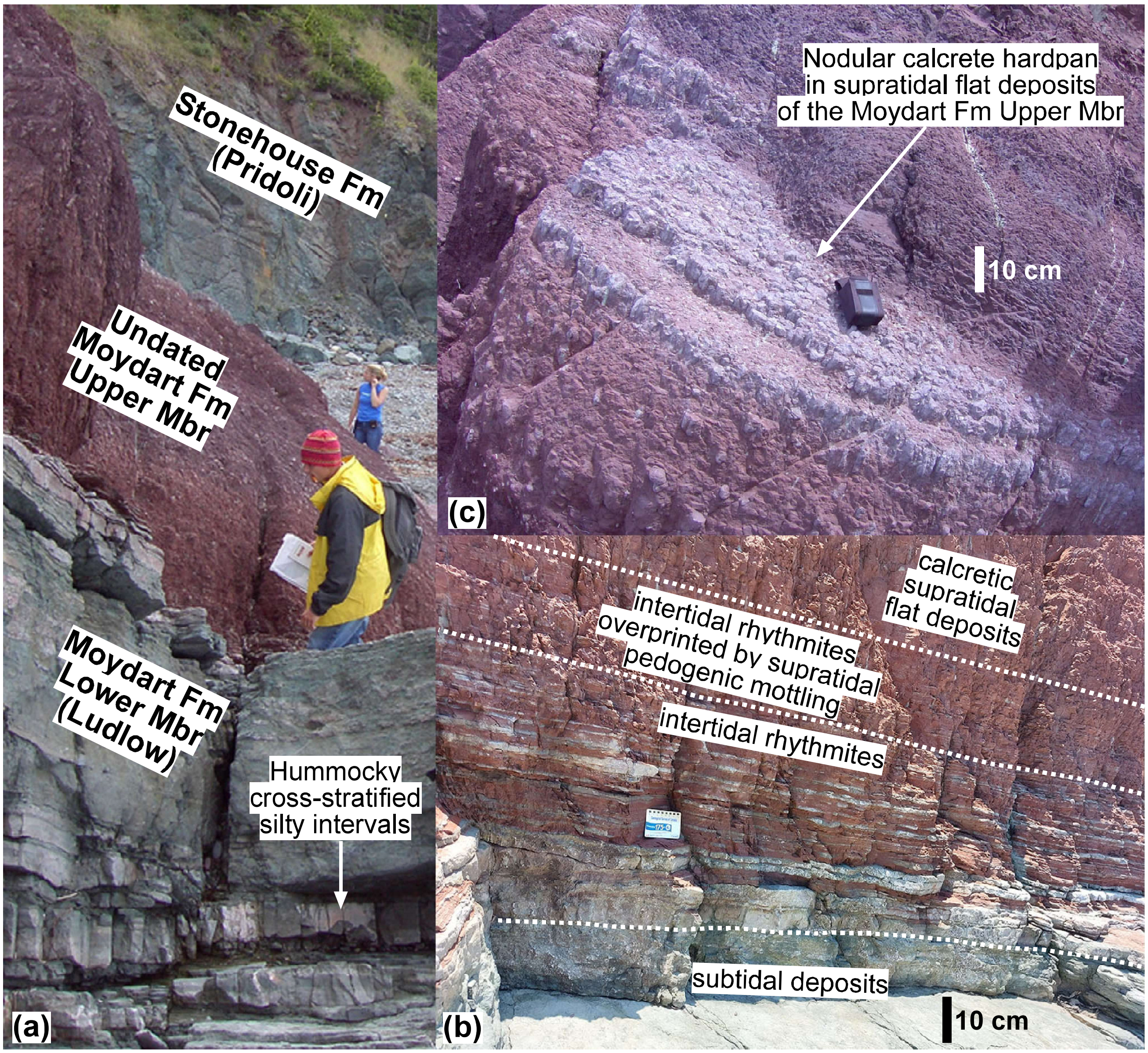


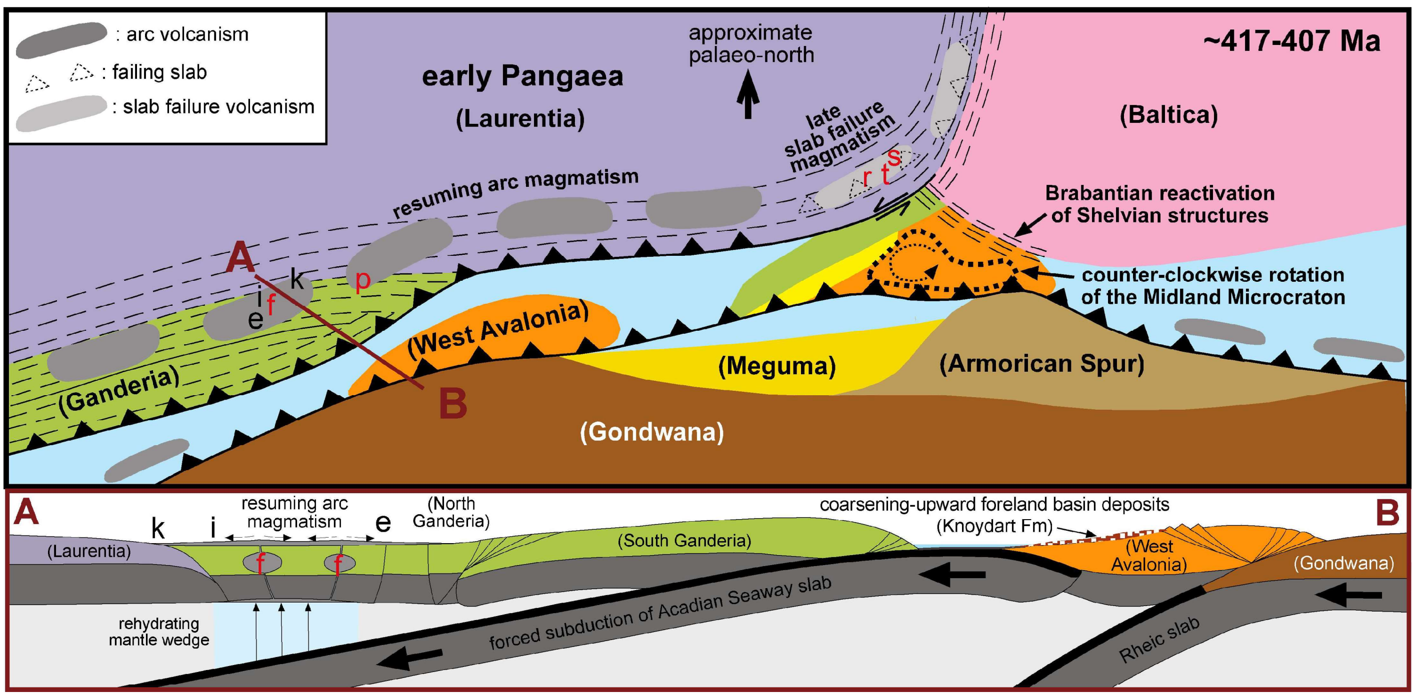
: arc volcanism
: failing slab
: slab failure volcanism
approximate palaeo-north
composite Laurentia
~441-429 Ma
Baltica
Shelvian structures
composite East Avalonia
West Avalonia
Acadian Seaway
Rheic Ocean
Midland Microcraton
Salinic A structures
A
B
C
D
g
j
l
m
o
d
b
q
w
x
slab-failure magmatism
Brunswick subduction complex
arc magmatism
onset of Salinic B shortening from shallow subduction
(Laurentia)
(North Ganderia)
(South Ganderia)
hydrated mantle wedge
post-Salinic A slab failure
poorly-hydrated mantle wedge
Tetagouche-Exploits slab
Acadian Seaway slab
lower Arisaig Gp
West Avalonia
Iapetan slab
former site of Sandbian slab-window volcanism


: arc volcanism
: failing slab
: slab failure volcanism
approximate palaeo-north
Laurussia
(Laurentia)
Scandian structures
~428-424 Ma
(Baltica)
E
F
r
n
u
x
a b
Acadian Seaway
West Avalonia
Rheic Ocean
Salinic B structures
(Armorican Spur)
(Meguma)
Gondwana
slab failure magmatism
arc magmatism
Laurentian margin
East Avalonia
Midland
Microcraton
hydrated mantle wedge
Iapetan slab
Rheic slab

Click here to access/download;Figure;Fig. 14_Jutras and Dostal_revised.pdf




Stonehouse Fm
(Pridoli)
Undated
Moydart Fm
Upper Mbr
Moydart Fm
Lower Mbr
(Ludlow)
Hummocky
cross-stratified
silty intervals
(a)
Nodular calcrete hardpan
in supratidal flat deposits
of the Moydart Fm Upper Mbr
10 cm
(c)
calcretic
supratidal
flat deposits
intertidal rhythmites
overprinted by supratidal
pedogenic mottling
intertidal rhythmites
subtidal deposits
10 cm
(b)


: arc volcanism
: failing slab
: slab failure volcanism
early Pangaea
(Laurentia)
approximate palaeo-north
~417-407 Ma
(Baltica)
late slab failure magmatism
resuming arc magmatism
Brabantian reactivation of Shelvian structures
counter-clockwise rotation of the Midland Microcraton
A
B
k
i
e
f
p
r
t
s
(Ganderia)
(West Avalonia)
(Meguma)
(Armorican Spur)
(Gondwana)
A
B
resuming arc magmatism
(North Ganderia)
coarsening-upward foreland basin deposits
(Knoydart Fm)
(Laurentia)
(South Ganderia)
(West Avalonia)
(Gondwana)
rehydrating mantle wedge
forced subduction of Acadian Seaway slab
Rheic slab

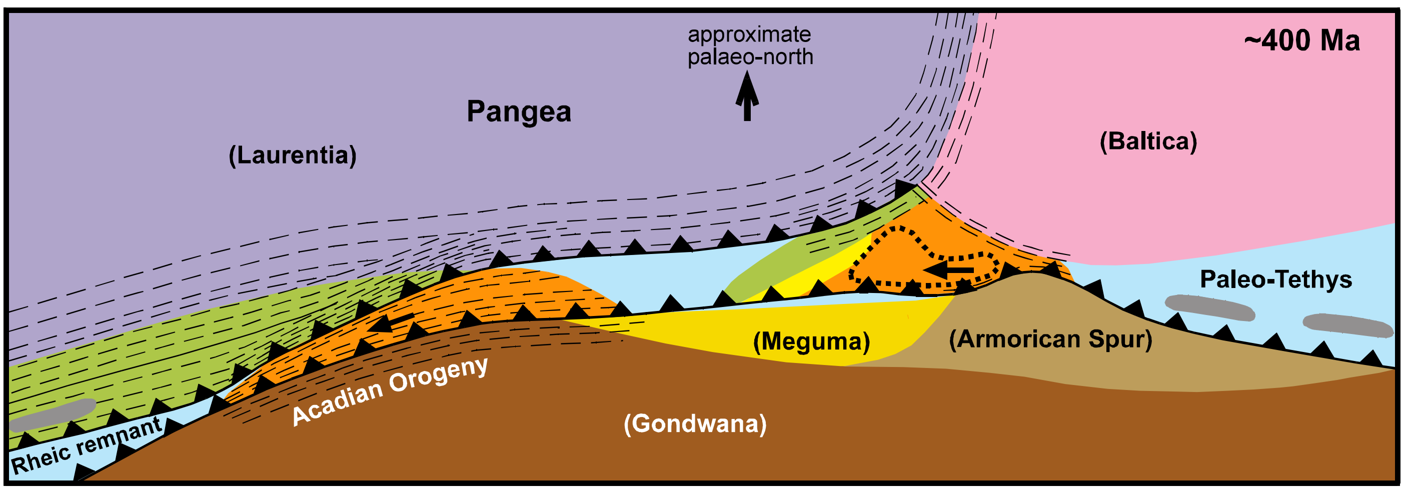

~400 Ma
approximate
palaeo-north
Pangea
(Laurentia)
(Baltica)
Paleo-Tethys
(Meguma)
(Armorican Spur)
Acadian Orogeny
Rheic remnant
(Gondwana)

Table 1.

Katian to early Emsian igneous rock units at the localities featuring in Figure 1.

Locality	Region	Unit	Age	Dating method	Age data	Geochemical data
a	Coastal Maine	Cranberry Island volcanics	424±1 Ma	U-Pb zircon	Seaman et al., 1995	Seaman et al., 1999
b	Coastal Maine	Eastport Fm	Pridoli?	biostrat. Constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Leighton Fm	Pridoli?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Edmunds Fm	Ludlow?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Dennys Fm	late Lland. to Wenlock?	biostrat. Constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
c	S New Brunswick	Passamaquoddy Bay volcanics	423±1 Ma	U-Pb zircon	van Wagoner et al., 2001	van Wagoner et al., 2002
d	S New Brunswick	Kingston terrane igneous suite	442±6 & 437±10 Ma	U-Pb zircon	Barr et al., 2002	Barr et al., 2002
			435±1.5 Ma	U-Pb zircon	Doig et al., 1990	
e	W New Brunswick	Tobique Gp	Pridoli to Lochkovian	biostrat. constraints	Dostal et al., 2021	Dostal et al., 2021
f	N New Brunswick	Miramichi plutons	~418 to ~402 Ma	U-Pb zirc., tit. & mon.	Whalen et al., 1996	Whalen et al., 1996
g	E Quebec	Lac Raymond Fm	late Llandovery	ostracods	David & Gariépy, 1990	David & Gariépy, 1990
		Pointe aux Trembles Fm	late Llandovery	ostracods	David & Gariépy, 1990	David & Gariépy, 1990
h	NW New Brunswick	Benjamin Fm (Dickie Cove Gp)	419.7±0.3 &	U-Pb zircon	Wilson & Kamo, 2012	Giggie, 1989; Wilson, 2017
			420.8±0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008	
		Bryant Point Fm (Dickie Cove Gp)	422.3±0.3 Ma	U-Pb zircon	Wilson & Kamo, 2012	Giggie, 1989; Wilson, 2017
i	NW New Brunswick	Val d'Amour Fm (Dalhousie Gp)	late Loch. to early Ems.	biostrat. constraints &	Wilson, 2017	Wilson et al., 2005
			407.4±0.8 Ma	U-Pb zircon	Wilson et al., 2004	
		England Brook Fm (Dalhousie Gp)	mid-Lochkovian	biostrat. constraints	Wilson, 2017	Murphy, 1989; Wilson, 2017
		Sunnyside Fm (Dalhousie Gp)	early mid-Lochkovian	biostrat. constraints	Greiner, 1970; Irrinki, 1990	Walker, 2010; Wilson, 2017
		Archibald Settl. Fm (Dalhousie Gp)	415.6±0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008	Walker, 2010; Wilson, 2017
		Wildcat Brook Fm (Dalhousie Gp)	417.5±0.4 Ma	U-Pb zircon	Wilson et al., 2017	Wilson, 2017
		Mitchell Settl. Fm (Dalhousie Gp)	early Lochkovian	spores & strat. constr.	McGregor, 1992;	Wilson, 2017
j	NW New Brunswick	Weir Fm (Chaleurs Gp)	429.2±0.5 Ma	U-Pb zircon	Wilson et al., 2008	Wilson et al., 2008
k	E Quebec	Baldwin & Lyall volcanics	Loch. to early Emsian	biostrat. constraints	Doyon & Dalpé, 1993	Doyon & Dalpé, 1993
		Ristigouche Volcanics	Wenlock to Pridoli	biostrat. constraints	Bourque et al., 2000	Doyon & Dalpé, 1993
l	NW Newfoundland	Burlington pluton	440±2 Ma	U-Pb monazite	Cawood & Dunning, 1993	Whalen et al., 2006
m	NW Newfoundland	Boogie Lake complex	435±6 Ma	U-Pb zircon	Dunning et al., 1990	Whalen et al., 2006
		Main Gut complex	431±2 Ma	U-Pb zircon	Dunning et al., 1990	Whalen et al., 2006
		Rainy Lake complex	435±1 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
		Silver Pond complex	431.6±4 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
		Puddle Pond complex	432.4±1 Ma	U-Pb zircon	Lissenberg et al., 2005	Whalen et al., 2006
		Taylor Brook complex	430.5±2 Ma	U-Pb zircon	Heaman et al., 2002	Whalen et al., 2006
n	NW Newfoundland	Topsails intrusive suite	427±1 Ma	U-Pb zircon	Whalen et al., 2006	Whalen, 1989
				425 ± 4 Ma	U-Pb zircon	van Staal et al., 2014
o	NW Newfoundland	Topsails volcanic gp	429±4 Ma	U-Pb zircon	Whalen et al., 1987	Whalen, 1989
		Springdale volcanic gp	430±5 Ma	U-Pb zircon	Chandler et al., 1987	Whalen et al., 2006
p	N Newfoundland	Mount Peyton Batholith	424±2 Ma	U-Pb zircon	Dunning, 1992	Strong & Dupuy, 1982
		Patch Valley rhyolite	423±3.5 Ma	U-Pb zircon	McNicoll et al., 2008	
		Stony Lake Volcanics	423+3-2 Ma	U-Pb zircon	Dunning et al., 1990	
		Port Albert dykes	422 ± 2 Ma	U-Pb zircon	Elliott et al., 1991	
		Lawrenceton Fm	421±4 Ma	U-Pb zircon	van Staal et al., 2014	
		Port Albert Fm	418.5±4 Ma	U-Pb zircon	van Staal et al., 2014	
		Fogo Island quartz diorite	410±2 Ma	U-Pb titanite	Aydin, 1995	Aydin, 1995
			420±2 Ma	U-Pb zircon	Aydin, 1995	
		Fogo Island diorite complex	408±0.8 Ma	U-Pb zircon	Aydin, 1995	Aydin, 1995; Currie, 2003
q	S Newfoundland	Cape St. Mary's sills	441±2 Ma	U-Pb baddeleyite	Greenough et al., 1993	Greenough, 1984
r	NW Ireland	Donegal composite pluton	428±4 to ~400 Ma	U-Pb zircon	Archibald et al., 2021	Archibald & Murphy, 2019
		appinite & lamprophyre suite	434.2±2.1 to 431±6 Ma	Ar/Ar hornblende	Murphy et al., 2019	Murphy et al., 2019
s	Midland Valley, Scotland	xenoliths	453.6±8 & 415±3 Ma	U-Pb zircon	Badenszki et al., 2019	Badenszki et al., 2019
t	S Uplands, Scotland	Loch Doon pluton	408±1.5 Ma;	Rb/Sr	Piper, 2007	Tindle & Pearce, 1981
			410±1 & 406±2 Ma	U-Pb zircon	Stone et al., 2012	
u	S Ireland	Dunquin Gp	late Wenlock	biostrat. constraints	Holland, 1988	Sloan & Bennett, 1990
v	SE Ireland	Leinster Batholith	405±2 Ma	U-Pb zircon	O'Connor et al., 1989	Sweetman, 1987
w	S Wales	Skomer Volcanic Gp	Llandovery	biostrat. constraints	Ziegler et al., 1969	Thorpe et al., 1989
x	S England	Tortworth volcanics	Lland. to Wenlock	biostrat. constraints	Reynolds, 1924;	van de Kamp, 1969;
						Pharaoh et al., 1991
y	NE England	igneous rocks in wells	449±13–442±3 Ma	U-Pb zircon & badd.	Noble et al., 1993	Pharaoh et al., 1993
			452+8-5 Ma	U-Pb zircon	Pidgeon & Aftalion, 1978	
z	Brabant Massif, Belgium	NW province suite	Late Ord. to Wenlock	biostrat. constraints	Martin & Richards, 1979	André et al., 1986

Abbreviations: badd.: baddeleyite; biostrat.: biostratigraphic; constr.: constraints; Ems.: Emsian; Fm: Formation; Gp: Group; Lland.: Llandovery; Loch.: Lochkovian; Mon.: monazite; Ord.: Ordovician; Settl.: Settlement; strat.: stratigraphic; tit.: titanium; zirc.: zircon.

Table 1.

Katian to early Emsian igneous rock units at the localities featuring in Figure 1.

Locality	Region	Unit	Age	Dating method	Age data	Geochemical data
a	Coastal Maine	Cranberry Island volcanics	424±1 Ma	U-Pb zircon	Seaman et al., 1995	Seaman et al., 1999
B	Coastal Maine	Eastport Fm	Pridoli?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Leighton Fm	Pridoli?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Edmunds Fm	Ludlow?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
		Dennys Fm	late Lland. to Wenlock?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
c	S New Brunswick	Passamaquoddy Bay volcanics	423±1 Ma	U-Pb zircon	van Wagoner et al., 2001	van Wagoner et al., 2002
d	S New Brunswick	Kingston terrane igneous suite	442±6 & 437±10 Ma	U-Pb zircon	Barr et al., 2002	Barr et al., 2002
			435±1.5 Ma	U-Pb zircon	Doig et al., 1990	
e	W New Brunswick	Tobique Gp	Pridoli to Lochkovian	biostrat. constraints	Dostal et al., 2021	Dostal et al., 2021
f	N New Brunswick	Miramichi plutons	~418 to ~402 Ma	U-Pb zircon tit. & mon.	Whalen et al., 1996	Whalen et al., 1996

Table 1 contd.

g	E Quebec	Lac Raymond Fm	late Llandovery	ostracods	David & Gariépy, 1990	David & Gariépy, 1990
		Pointe aux Trembles Fm	late Llandovery	ostracods	David & Gariépy, 1990	David & Gariépy, 1990
h	NW New Brunswick	Benjamin Fm	419.7±0.3 &	U-Pb zircon	Wilson & Kamo, 2012	Giggie, 1989;
		(Dickie Cove Gp)	420.8±0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008	Wilson, 2017
		Bryant Point Fm	422.3±0.3 Ma	U-Pb zircon	Wilson & Kamo, 2012	Giggie, 1989;
		(Dickie Cove Gp)				Wilson, 2017
i	NW New Brunswick	Val d'Amour Fm	late Lochkovian to	Fossil assemblages,	Wilson et al., 2004, 2005	Wilson et al., 2005;
		(Dalhousie Gp)	early Emsian;	strat. constraints &		Wilson, 2017
			407.4±0.8 Ma	U-Pb zircon	Wilson et al., 2004	
		England Brook Fm	mid-Lochkovian	biostrat. constraints	Wilson, 2017	Murphy, 1989;
		(Dalhousie Gp)				Wilson, 2017
		Sunnyside Fm	early mid-Loch.	biostrat. constraints	Greiner, 1970;	Walker, 2010;
		(Dalhousie Gp)			Irrinki, 1990	Wilson, 2017
		Archibald Settlement Fm	415.6±0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008	Walker, 2010;
		(Dalhousie Gp)				Wilson, 2017
		Wildcat Brook Fm	417.5±0.4 Ma	U-Pb zircon	Wilson et al., 2017	Wilson, 2017
		(Dalhousie Gp)				

Table 1 contd.

		Mitchell Settlement Fm	early Lochkovian	spores &	McGregor, 1992;	Wilson, 2017
		(Dalhousie Gp)		strat. constraints	Wilson, 2017	
j	NW New Brunswick	Weir Fm	429.2±0.5 Ma	U-Pb zircon	Wilson et al., 2008	Wilson et al., 2008
k	E Quebec	Baldwin & Lyall	Lochkovian to `	biostrat. constraints	Doyon & Dalpé, 1993	Doyon & Dalpé, 1993
		volcanics	early Emsian?			
		Ristigouche	Wenlock to	biostrat. constraints	Bourque et al., 2000	Doyon & Dalpé, 1993
		Volcanics	Pridoli?			
l	NW Newfoundland	Burlington pluton	440±2 Ma	U-Pb monazite	Cawood & Dunning, 1993	Whalen et al., 2006
m	NW Newfoundland	Boogie Lake complex	435±6 Ma	U-Pb zircon	Dunning et al., 1990	Whalen et al., 2006
		Main Gut complex	431±2 Ma	U-Pb zircon	Dunning et al., 1990	Whalen et al., 2006
		Rainy Lake complex	435±1 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
		Silver Pond complex	431.6±4 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
		Puddle Pond complex	432.4±1 Ma	U-Pb zircon	Lissenberg et al., 2005	Whalen et al., 2006
		Taylor Brook complex	430.5±2 Ma	U-Pb zircon	Heaman et al., 2002	Whalen et al., 2006
n	NW Newfoundland	Topsails intrusive suite	427±1 Ma	U-Pb zircon	Whalen et al., 2006	Whalen, 1989
			425 ± 4 Ma	U-Pb zircon	van Staal et al., 2014	

Table 1 contd.

o	NW Newfoundland	Topsails volcanic gp	429±4 Ma	U-Pb zircon	Whalen et al., 1987	Whalen, 1989
		Springdale volcanic gp	430±5 Ma	U-Pb zircon	Chandler et al., 1987	Whalen et al., 2006
p	N Newfoundland	Mount Peyton Batholith	424±2 Ma	U-Pb zircon	Dunning, 1992	Strong & Dupuy, 1982
		Patch Valley rhyolite	423±3.5 Ma	U-Pb zircon	McNicoll et al., 2008	
		Stony Lake Volcanics	423+3-2 Ma	U-Pb zircon	Dunning et al., 1990	
		Port Albert dykes	422 ± 2 Ma	U-Pb zircon	Elliott et al., 1991	
		Lawrenceton Fm	421±4 Ma	U-Pb zircon	van Staal et al., 2014	
		Port Albert Fm	418.5±4 Ma	U-Pb zircon	van Staal et al., 2014	
		Fogo Island Batholith	410±2 &	U-Pb titanite	Aydin, 1995	Aydin, 1995
			420±2 Ma	U-Pb zircon		
		Fogo Island Batholith	408±0.8 Ma	U-Pb zircon	Aydin, 1995	Aydin, 1995;
						Currie, 2003
q	S Newfoundland	Cape St. Mary's sills	441±2 Ma	U-Pb baddeleyite	Greenough et al., 1993	Greenough, 1984
r	NW Ireland	Donegal composite pluton	428±4 to ~400 Ma	U-Pb zircon	Archibald et al., 2021	Archibald & Murphy, 2021
		appinite & lamprophyre	434.2±2.1 to	Ar/Ar hornblende	Murphy et al., 2019	Murphy et al., 2019
		suite	431±6 Ma			

Table 1 contd.

s	Midland Valley of	xenoliths	453.6±8 &	U-Pb zircon	Badenszki et al., 2019	Badenszki et al., 2019
	Scotland		415±3 Ma	U-Pb zircon	Badenszki et al., 2019	Badenszki et al., 2019
t	S Uplands of	Loch Doon pluton	408±1.5 Ma;	Rb/Sr	Piper, 2007	Tindle & Pearce, 1981
	Scotland		410±1 & 406±2 Ma	U-Pb zircon	Stone et al., 2012	
u	S Ireland	Dunquin Gp	late Wenlock	biostrat. constraints	Holland, 1988	Sloan and Bennett, 1990
v	SE Ireland	Leinster Batholith	405±2 Ma	U-Pb zircon	O'Connor et al., 1989	Sweetman, 1987
w	S Wales	Skomer Volcanic Gp	Llandovery	biostrat. constraints	Ziegler et al., 1969	Thorpe et al., 1989
x	S England	Tortworth volcs.	Llandovery to	biostrat. constraints	Reynolds, 1924;	van de Kamp, 1969;
			Wenlock			Pharaoh et al., 1991
y	NE England	igneous rocks in wells	449±13–442±3 Ma	U-Pb zircon & badd.	Noble et al., 1993	Pharaoh et al., 1993
			452+8-5 Ma	U-Pb zircon	Pidgeon & Aftalion, 1978	
z	Brabant Massif,	NW province suite	Late Ordovician to	biostrat. constraints	Martin & Richards, 1979	André et al., 1986
	Belgium		Wenlock			

Abbreviations: badd.: baddeleyite; biostrat.: biostratigraphic; Fm: Formation; Gp: Group; Lland.: Llandovery; mon.: monazite; strat.: stratigraphic; tit.: titanium.