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

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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.

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 microcontinents 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

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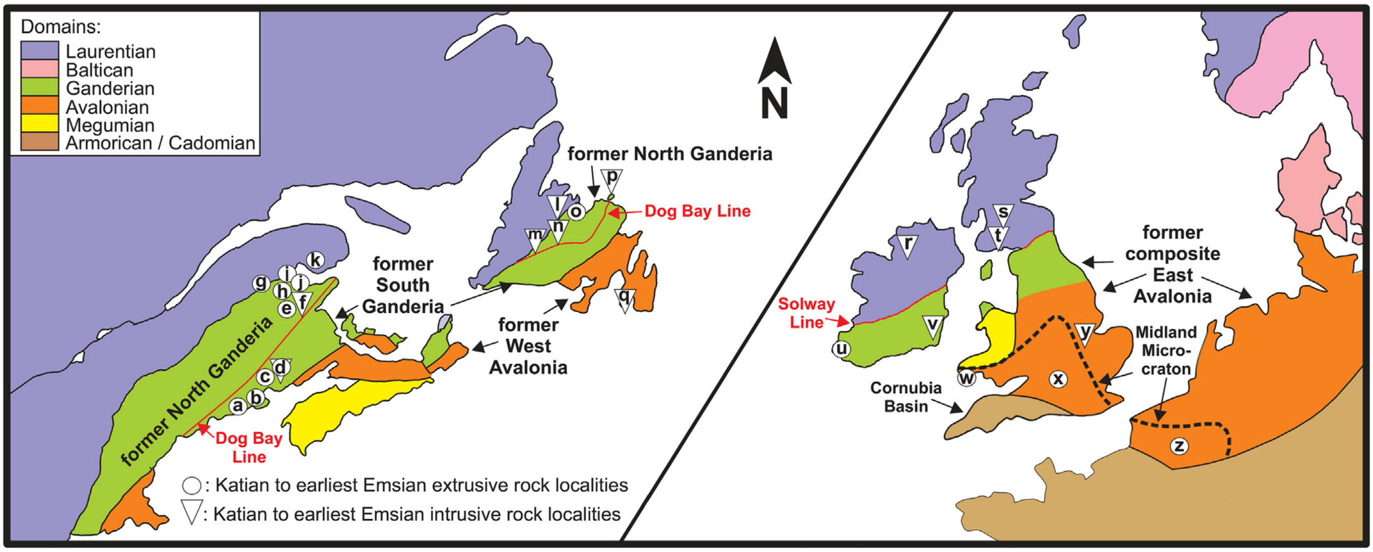

Fig. 1. Map of northeastern North America and Europe showing the main continental terrane assemblages that were involved in the formation of the Appalachian–Caledonian Belt. Details on the lettered localities are included in the text and compiled in Table 1.

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, 2019; 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".

3. 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

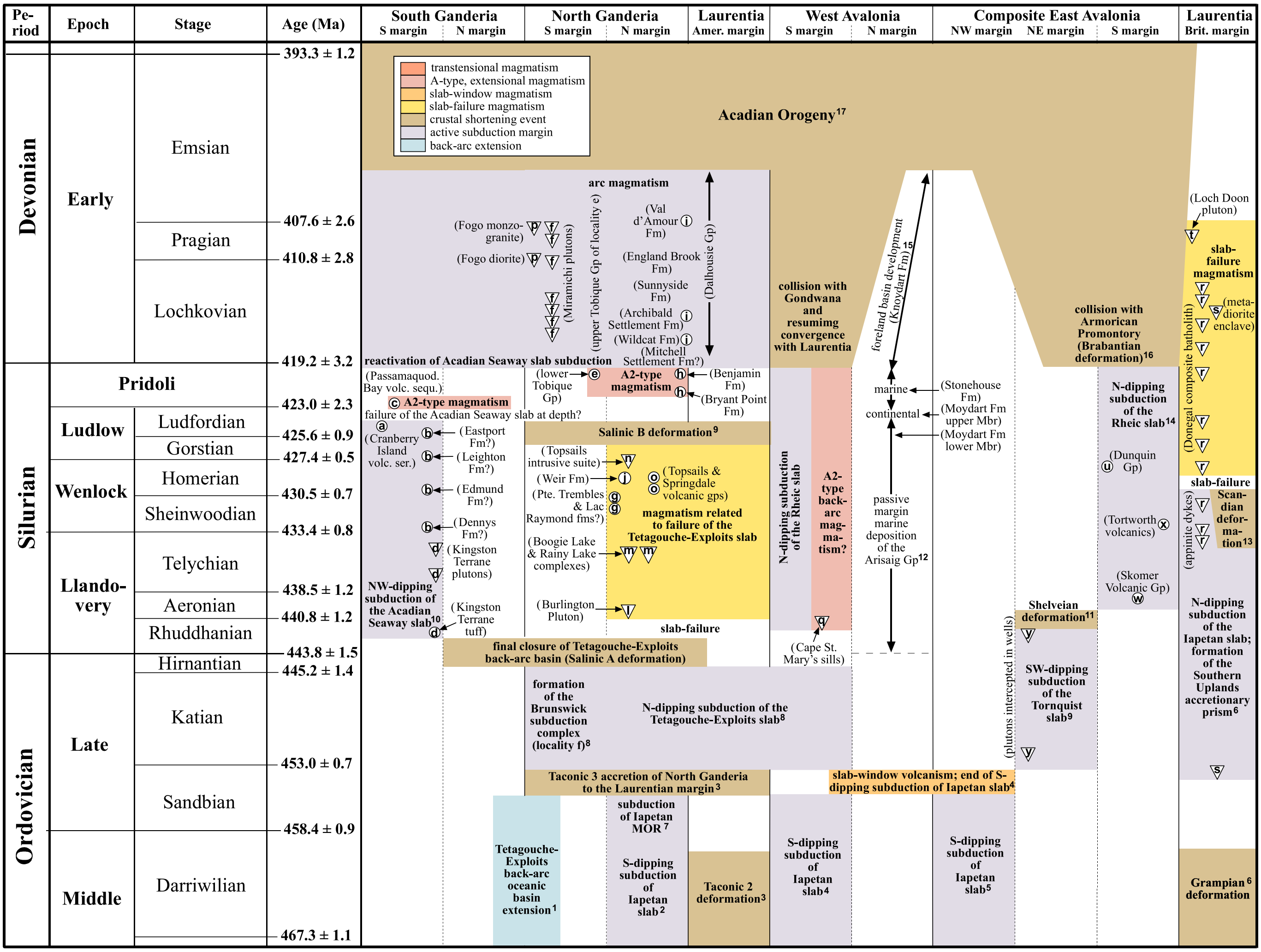

Fig. 2. Main tectono-magmatic events recorded in the study area. Ordovician, Silurian and Devonian subdivisions are respectively from Bergström et al. (2009), Melchin et al. (2020), and Becker et al. (2020). Letters in triangles and circles correspond respectively to intrusive and extrusive rocks at 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).

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).

4. 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).

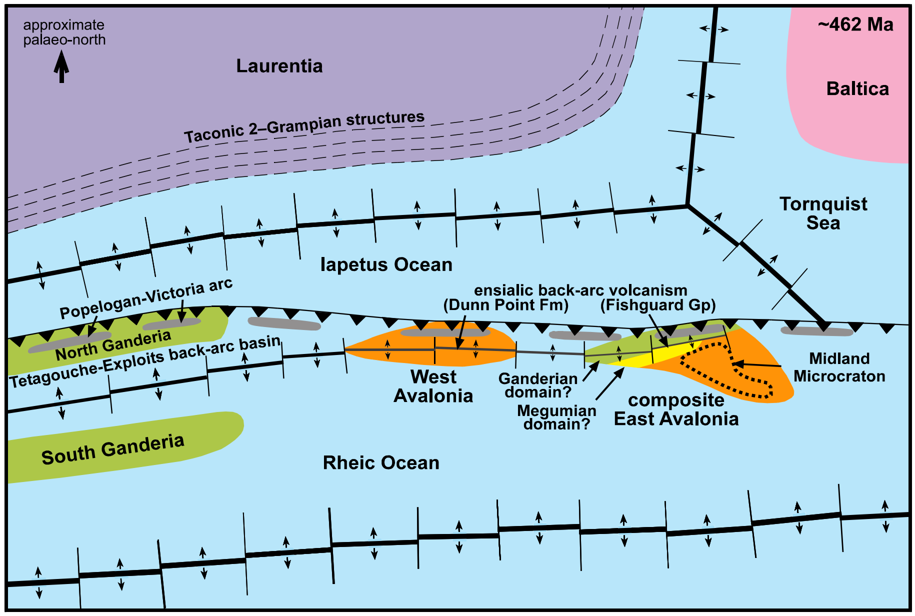

Fig. 3. Palaeocontinental reconstruction at ∼ 462 Ma based on Woodcock (2012a), Zagorevski et al. (2010), Murphy et al. (2008. 2012), Waldron et al. (2014), Phillips et al. (2016), van Staal et al. (2016), Wilson et al. (2017), and Jutras et al. (2020).

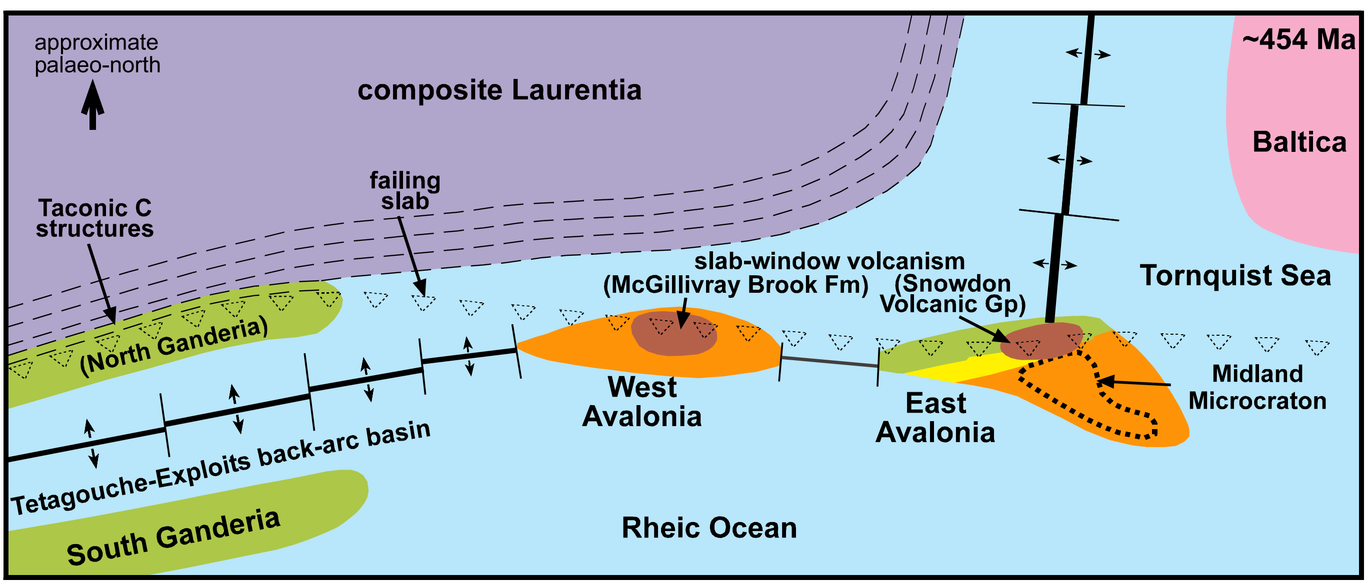

Fig. 4. Accretion of North Ganderia to composite Laurentia near 455 Ma (Taconic phase C of van Staal et al., 2007) followed by slab-window volcanism *circa* 454 Ma in the McGillivray Brook Formation of Nova Scotia (Jutras et al., 2020) and the Snowdon Group of Wales (Woodcock, 2012a; Lusty et al., 2017)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

5. 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 % SiO2 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;

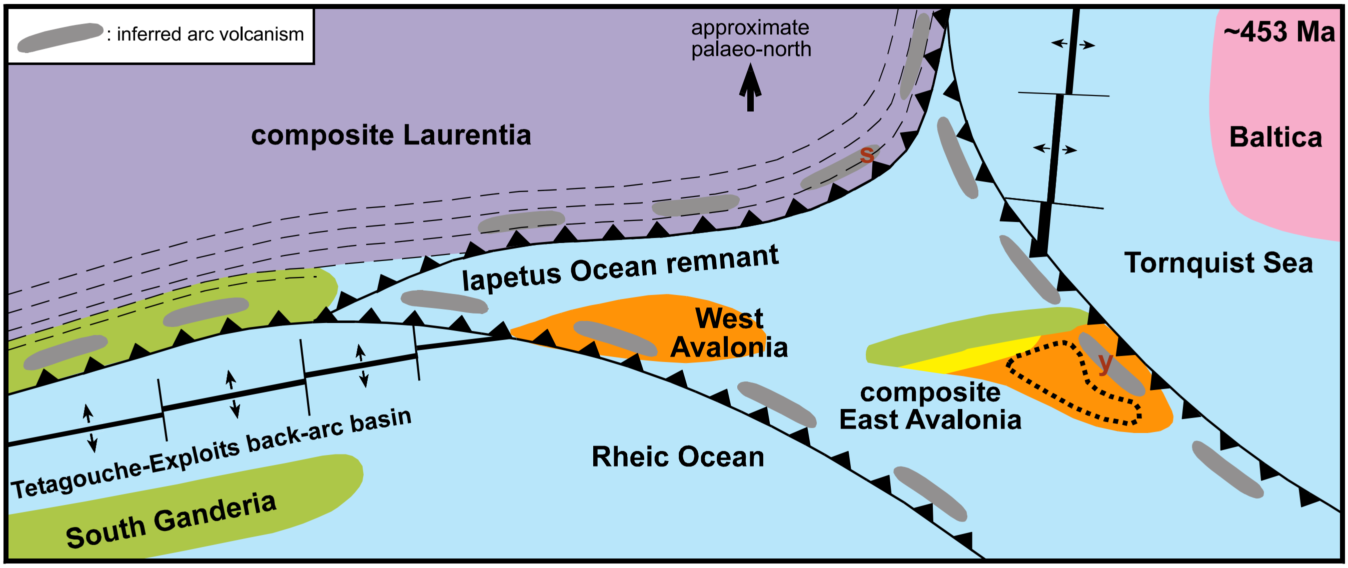

Fig. 5. Development of new, post–Taconic–Grampian subduction zones *circa* 453 Ma based on Pharaoh et al., (1991, 1993), Noble et al. (1993) and Torsvik and Rehnström (2003), Woodcock (2012a), and Wilson et al. (2017). Intrusive rocks from localities s and y are described in Table 1.

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) (Fig. 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) (Fig. 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 (Fig. 6c–11c) and (4) Ta + Yb vs La/Yb (Fig. 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 Figs. 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 (Fig. 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 (Fig. 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).

5.1. 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

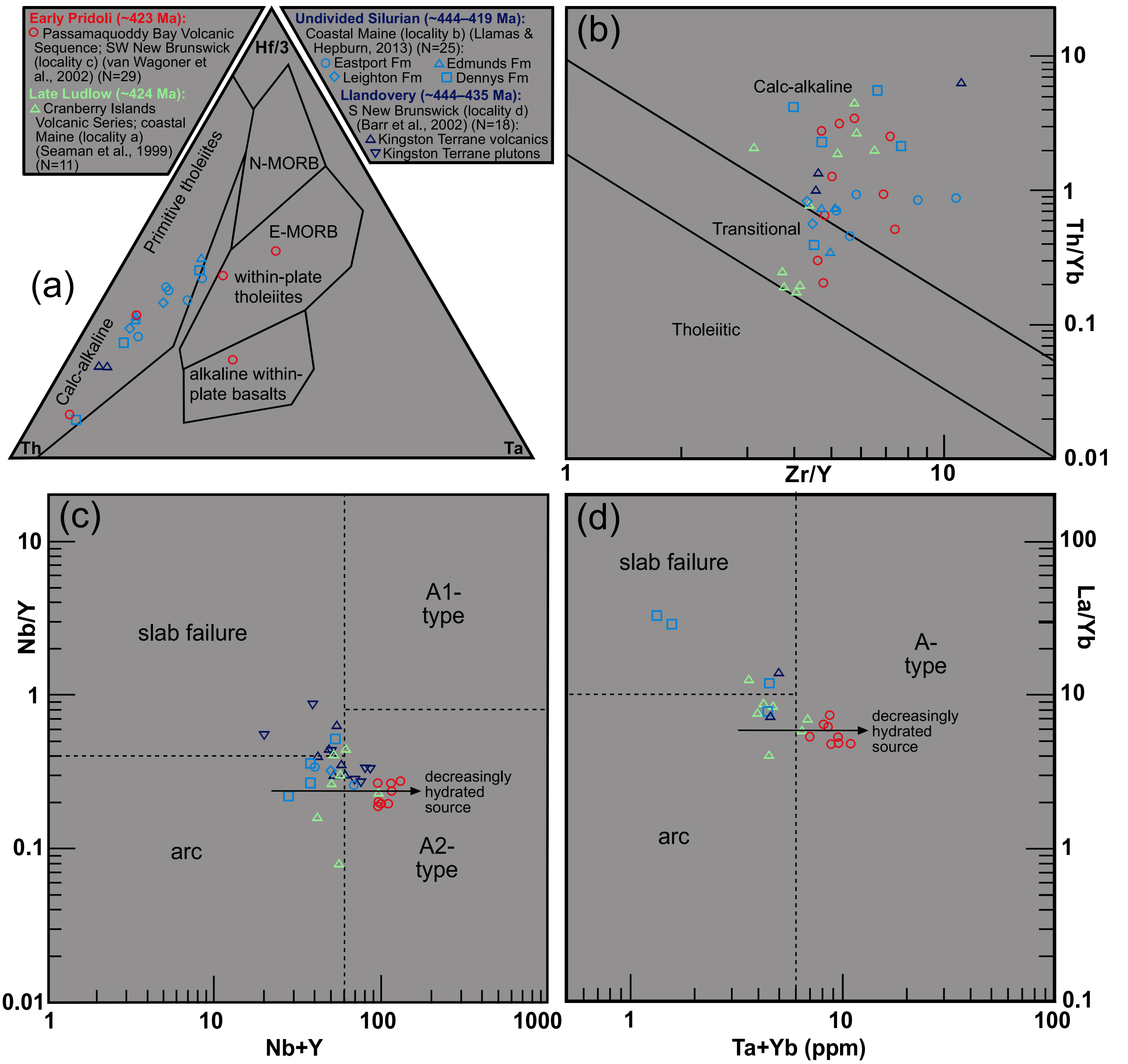

Fig. 6. Late Ordovician to Early Devonian igneous rocks in South Ganderian terranes of coastal Maine and southern New Brunswick (data from Seaman et al., 1999; Barr et al., 2002; van Wagoner et al., 2002; Llamas and Hepburn, 2013) plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs 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).

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.

5.1.1. 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 vol-

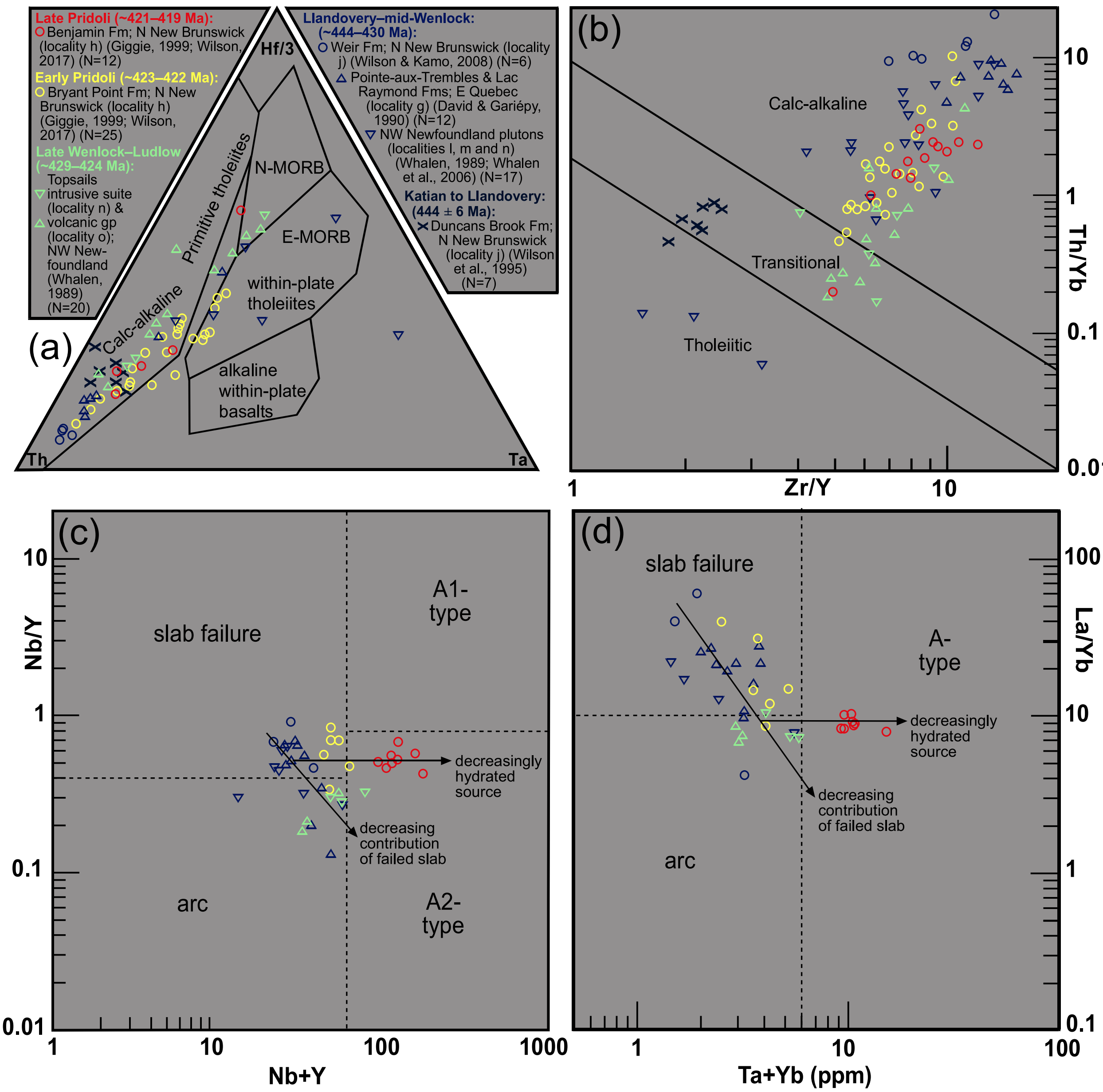

Fig. 7. Late Ordovician to Silurian igneous rocks in North Ganderian and Laurentian margin terranes of northeastern North America (data from Whalen, 1989; David and Gariépy, 1990; Giggie, 1999; Whalen et al., 2006; Wilson and Kamo, 2008; Wilson et al., 1995; Wilson, 2017) plotted in (a) the Hf/3–Ta–Th 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).

canic 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.

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

5.2.1. 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

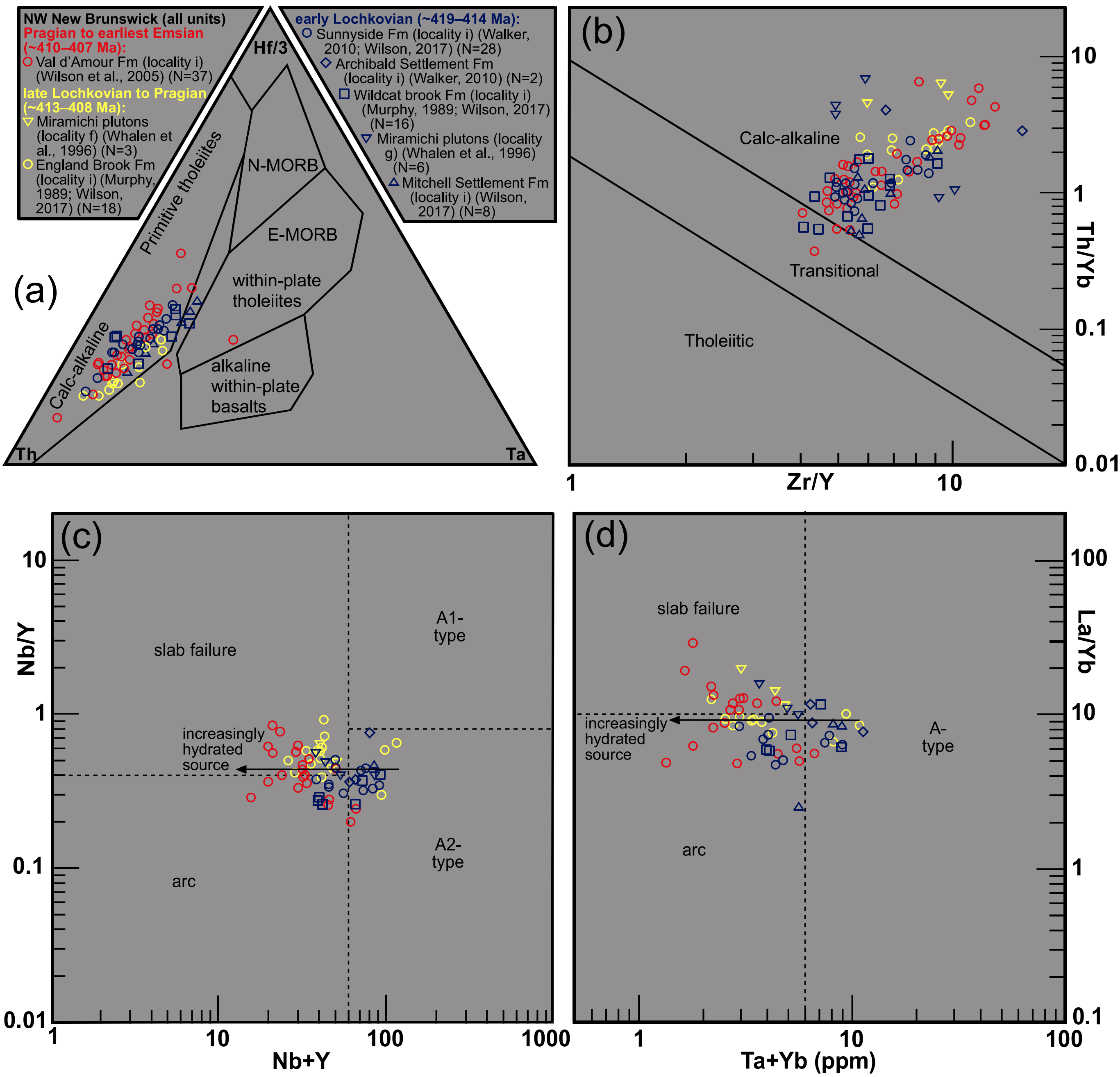

Fig. 8. Lower Devonian igneous rocks in North Ganderian and Laurentian margin terranes of northern New Brunswick and eastern Quebec (data from Murphy, 1989; Whalen et al., 1996; Wilson et al., 2005; Walker, 2010; Wilson, 2017) plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb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

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 M a (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

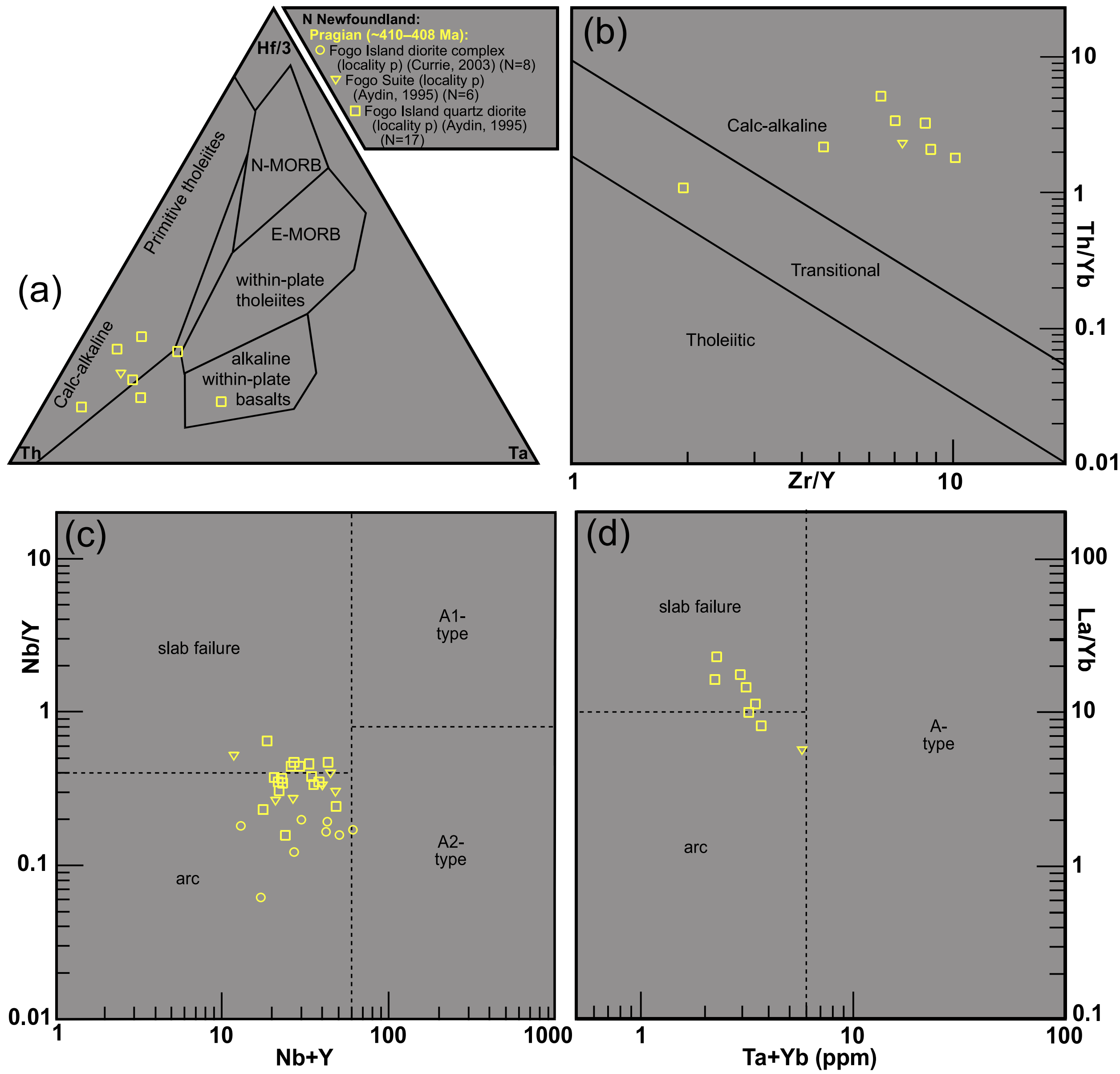

Fig. 9. Lower Devonian igneous rocks in North Ganderian terranes of northern Newfoundland (data from Aydin, 1995; Currie, 2003) plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of Ross and Bédard (2009), and (c) the Nb + Y vs Nb/Y and (d) Ta + Yb vs La/Yb diagrams of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

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).

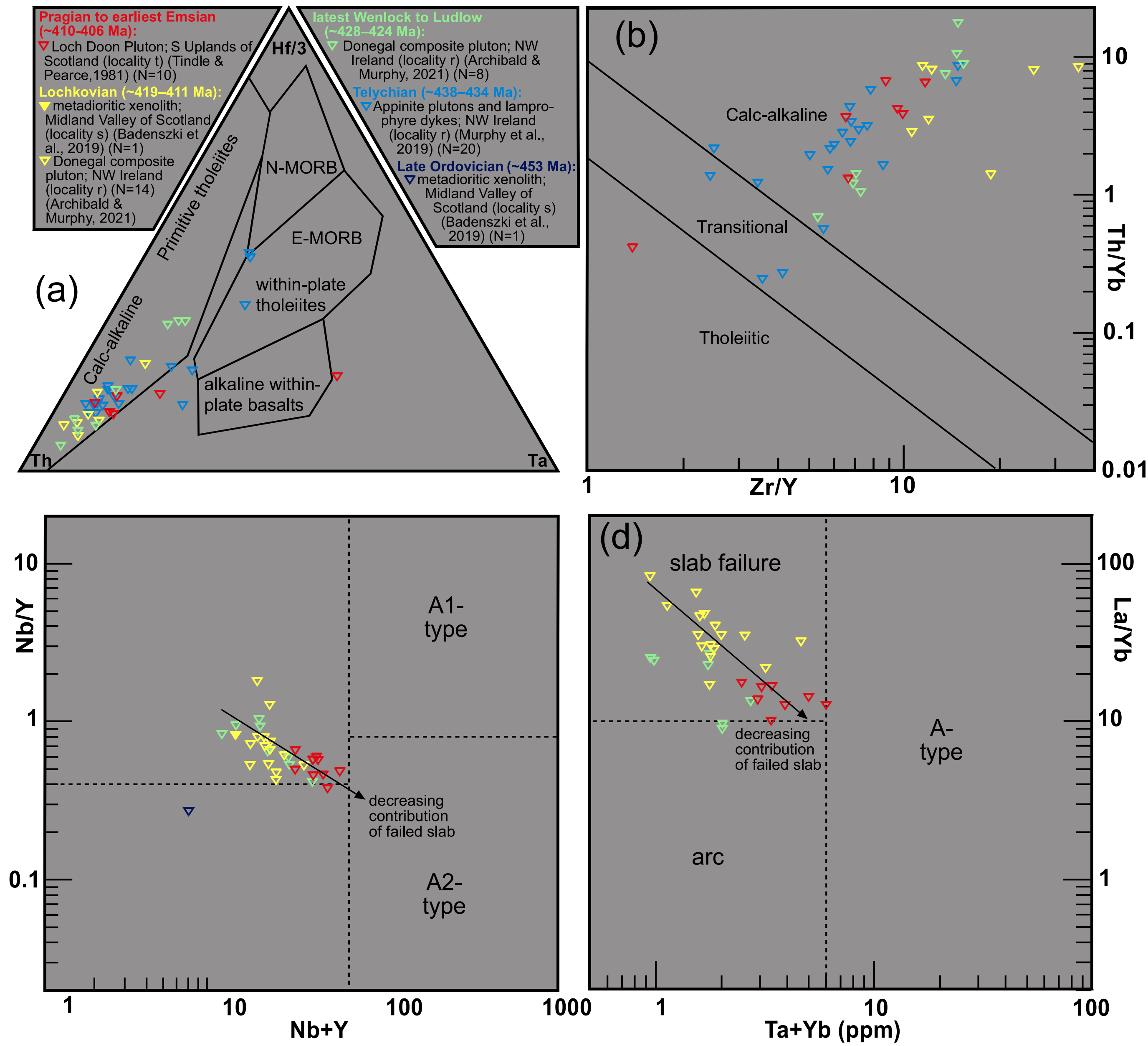

Fig. 10. Late Ordovician to Early Devonian igneous rocks along the Laurentian margin in the British Isles (data from Tindle and Pearce, 1981; Badenszki et al., 2019; Murphy et al., 2019; Archibald and Murphy, 2021) plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram of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

5.2.1.1. 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).

5.2.2. 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

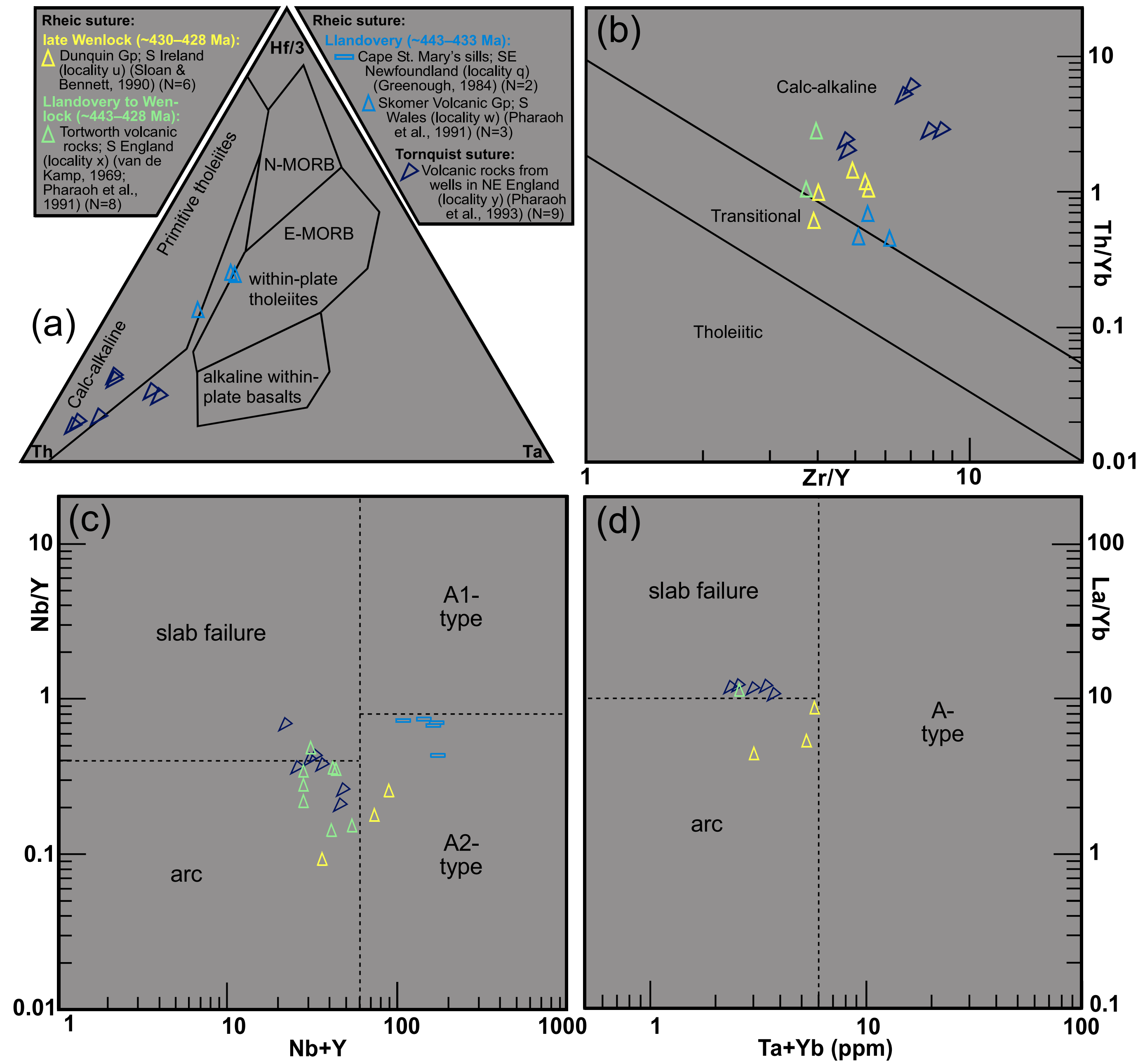

Fig. 11. Late Ordovician to Early Devonian igneous rocks (data from van de Kamp, 1969; Greenough, 1984; Sloan and Bennett, 1990; Pharaoh et al., 1991, 1993) in the former micro-continents of West and composite East Avalonia plotted in (a) the Hf/3–Ta–Th diagram of Wood (1980), (b) the Zr/Y vs Th/Yb diagram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

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.

5.2.2.1. 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.

Table 1
Katian to early Emsian igneous rock units at the localities featuring in Fig. 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	Edmunds Fm	Pridoli?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
b	Coastal Maine	Leighton Fm	Pridoli?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
b	Coastal Maine	Edmunds Fm	Ludlow?	biostrat. constraints	Gates & Moench, 1981	Llamas & Hepburn, 2013
	Coastal Maine	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
d	S New Brunswick	Kingston terrane igneous suite	435 ± 1.5 Ma	U-Pb zircon	Doig et al., 1990	Barr et al., 2002
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
g	E Quebec	Lac Raymond Fm	late Llandovery	ostracods	David & Gariépy, 1990	David & Gariépy, 1990
g	E Quebec	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 & 420.8 ± 0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008, 2012	Giggie, 1989; Wilson, 2017
h	NW New Brunswick	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 Lochkovian to early Emsian;	Fossil assemblages & strat. constraints	Wilson et al., 2004, 2005 Wilson 2017	Wislon et al. 2005; Wilson, 2017
i	NW New Brunswick	Val d'Amour Fm (Dalhousie Gp)	407.4 ± 0.8 Ma	U-Pb zircon	Wilson et al., 2004	Wislon et al. 2005; Wilson, 2017
i	NW New Brunswick	England Brook Fm (Dalhousie Gp)	mid-Lochkovian	biostrat. constraints;	Wilson, 2017	Murphy, 1989; Wilson, 2017
i	NW New Brunswick	Sunnyside Fm (Dalhousie Gp)	early mid-Loch	biostrat. constraints	Greiner, 1970; Irrinki, 1990;	Walker, 2010; Wilson, 2017
i	NW New Brunswick	Archibald Settlement Fm (Dalhousie Gp)	415.6 ± 0.4 Ma	U-Pb zircon	Wilson & Kamo, 2008;	Walker, 2010; Wilson, 2017
i	NW New Brunswick	Wildcat Brook Fm (Dalhousie Gp)	417.5 ± 0.4 Ma	U-Pb zircon	Wilson, 2017	McGregor, 1992; Wilson, 2017
i		Mitchell Settlement Fm (Dalhousie Gp)	early Lochkovian	spores & strat. constraints	Wilson, 2017	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 volcanics	Lochkovian to early Emsian?	biostrat. constraints	Doyon & Dalpé, 1993	Doyon & Dalpé, 1993
k		Ristigouche Volcanics	Wenlock to Pridoli?	biostrat. constraints	Bourque et al., 2000	Bourque et al., 2000
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
m	NW Newfoundland	Main Gut complex	431 ± 2 Ma	U-Pb zircon	Dunning et al., 1990	Whalen et al., 2006
m	NW Newfoundland	Rainy Lake complex	435 ± 1 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
m	NW Newfoundland	Silver Pond complex	431.6 ± 4 Ma	U-Pb zircon	Whalen et al., 2006	Whalen et al., 2006
m	NW Newfoundland	Puddle Pond complex	432.4 ± 1 Ma	U-Pb zircon	Lissenberg et al., 2005	Whalen et al., 2006
m	NW Newfoundland	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
n	NW Newfoundland	Topsails intrusive suite	425 ± 4 Ma	U-Pb zircon	van Staal et al., 2014	Whalen, 1989
o	NW Newfoundland	Topsails volcanic gp	429 ± 4 Ma	U-Pb zircon	Whalen et al., 1987	Whalen, 1989
o	NW Newfoundland	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
p	N Newfoundland	Patch Valley rhyolite	423 ± 3.5 Ma	U-Pb zircon	McNicoll et al., 2008	
p	N Newfoundland	Stony Lake Volcanics	423 + 3–2 Ma	U-Pb zircon	Dunning et al., 1990	
p	N Newfoundland	Port Albert dykes	422 ± 2 Ma	U-Pb zircon	Elliott et al., 1991	
p	N Newfoundland	Lawrenceton Fm	421 ± 4 Ma	U-Pb zircon	van Staal et al., 2014	
p	N Newfoundland	Port Albert Fm	418.5 ± 4 Ma	U-Pb zircon	van Staal et al., 2014	
p	N Newfoundland	Fogo Island quartz diorite	410 ± 2 Ma	U-Pb titanite	Aydin, 1995	Aydin, 1995
p	N Newfoundland	Fogo Island quartz diorite	420 ± 2 Ma	U-Pb zircon	Aydin, 1995	Aydin, 1995
p		Fogo Island diorite complex	408 ± 0.8 Ma	U-Pb zircon	Aydin, 1995;	Aydin, 1995; Currie, 2003

(*continued on next page*)

Table 1 (*continued*)

Locality	Region	Unit	Age	Dating method	Age data	Geochemical data
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
r	NW Ireland	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 of Scotland	xenolith	453.6 ± 8 &	U-Pb zircon	Badenszki et al., 2019	Badenszki et al., 2019
s	Midland Valley of Scotland	xenolith	415 ± 3 Ma	U-Pb zircon	Badenszki et al., 2019	Badenszki et al., 2019
t	S Uplands of Scotland	Loch Doon pluton	408 ± 1.5 Ma;	Rb/Sr	Piper, 2007	Tindle & Pearce, 1981
t	S Uplands of Scotland	Loch Doon pluton	410 ± 1 & 406 ± 2 Ma	U-Pb zircon	Stone et al., 2012	Tindle & Pearce, 1981
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 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
y	NE England	igneous rocks in wells	452 + 8–5 Ma	U-Pb zircon	Pidgeon & Aftalion, 1978	Pharaoh et al., 1993
z	Brabant Massif, of Belgium	NW province suite	Late Ordovician 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.

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).

5.3. 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).

5.3.1. 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.

5.4. 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 M a 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).

5.4.1. 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).

6. Discussion

6.1. 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 (Fig. 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.

6.2. 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, 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).

6.3. The Llandovery to Ludlow interval (∼444–424 Ma)

6.3.1. 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 (Fig. 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.

6.3.2. 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).

6.3.3. 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

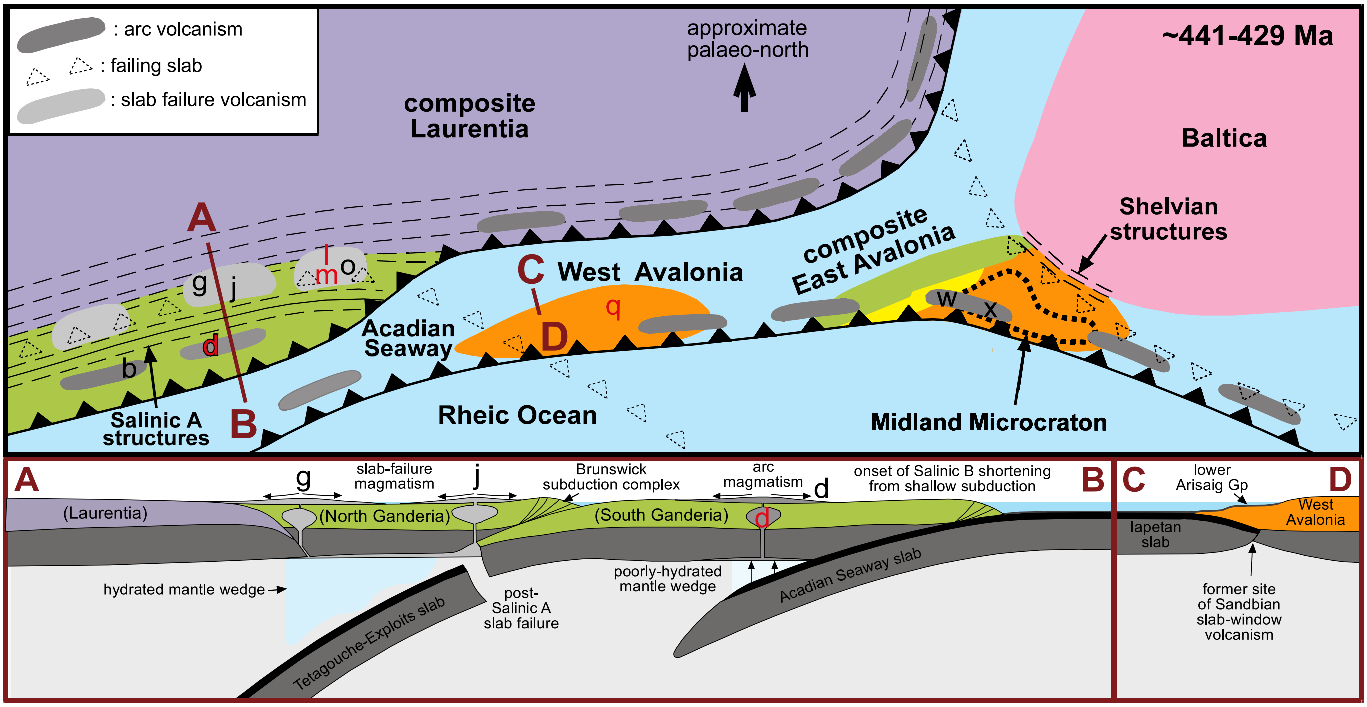

Fig. 12. Proposed model for tectono-magmatic events that occurred during the ~ 441–429 Ma interval (Llandovery to Wenlock) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, 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).

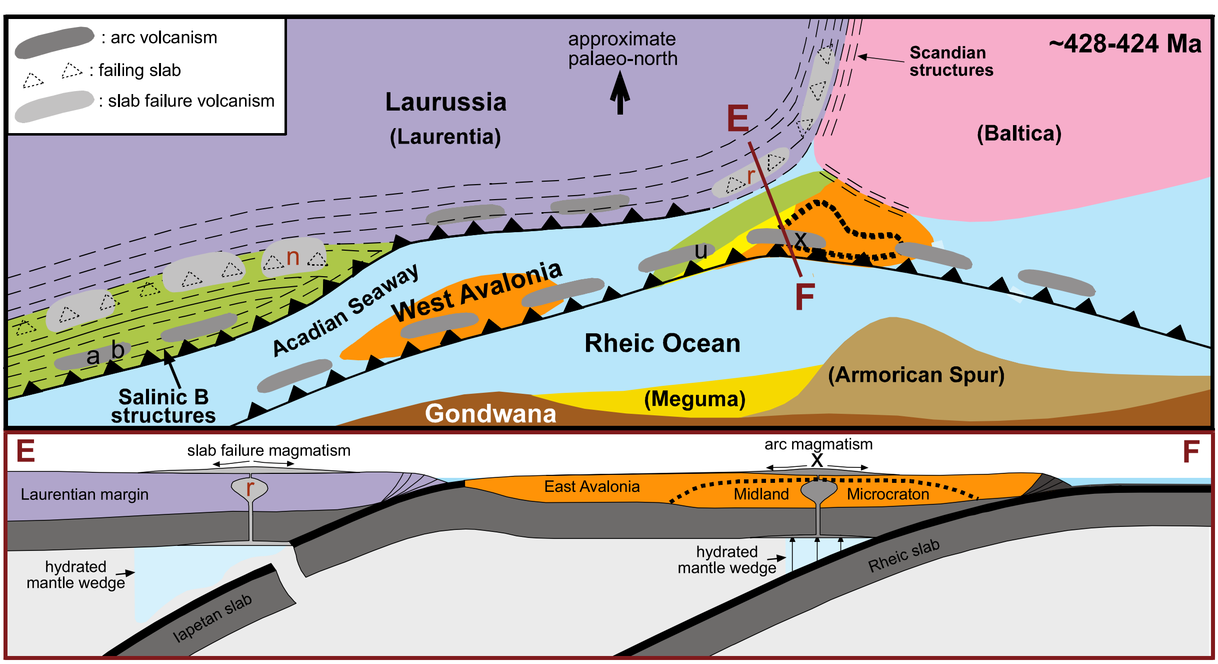

Fig. 13. Proposed model for tectono-magmatic events that occurred during the ~ 428–424 Ma interval (latest Wenlock to Ludlow) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, 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).

much of the well-hydrated uppermost part of the subducting slab is left behind in the accretionary prism in such settings.

6.3.4. 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.

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

6.4.1. 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 (Boucat 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 (Boucat 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 (Fig. 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).

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

6.5.1. 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 counterclockwise 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,

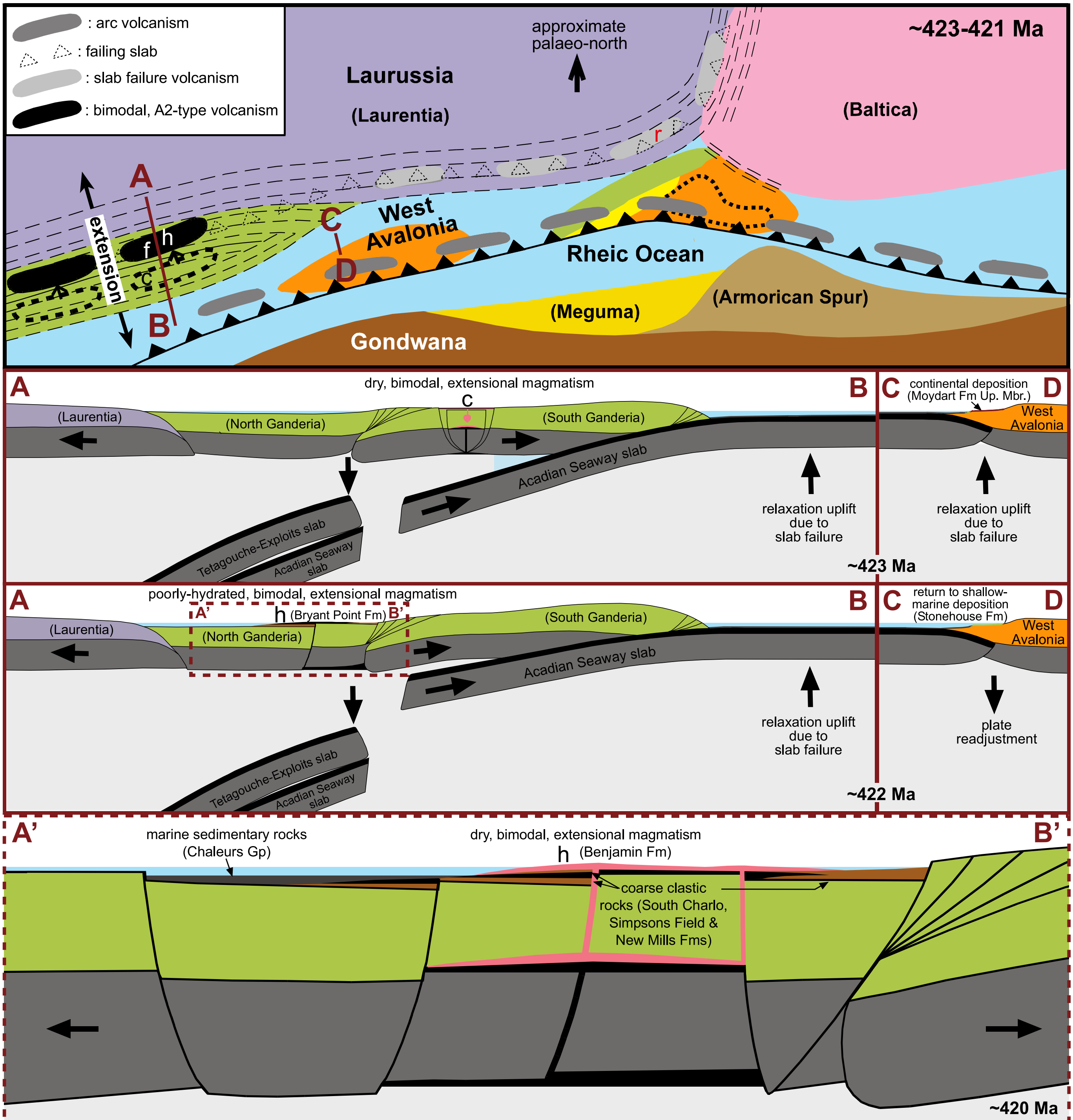

Fig. 14. Proposed model for tectono-magmatic events that occurred during the 423–421 Ma interval (Pridoli) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive rocks, and black or white 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).

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).

6.5.2. 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 (Boucat et al., 1974; Murphy, 1987; Waldron et al., 1996). This suggests that collision

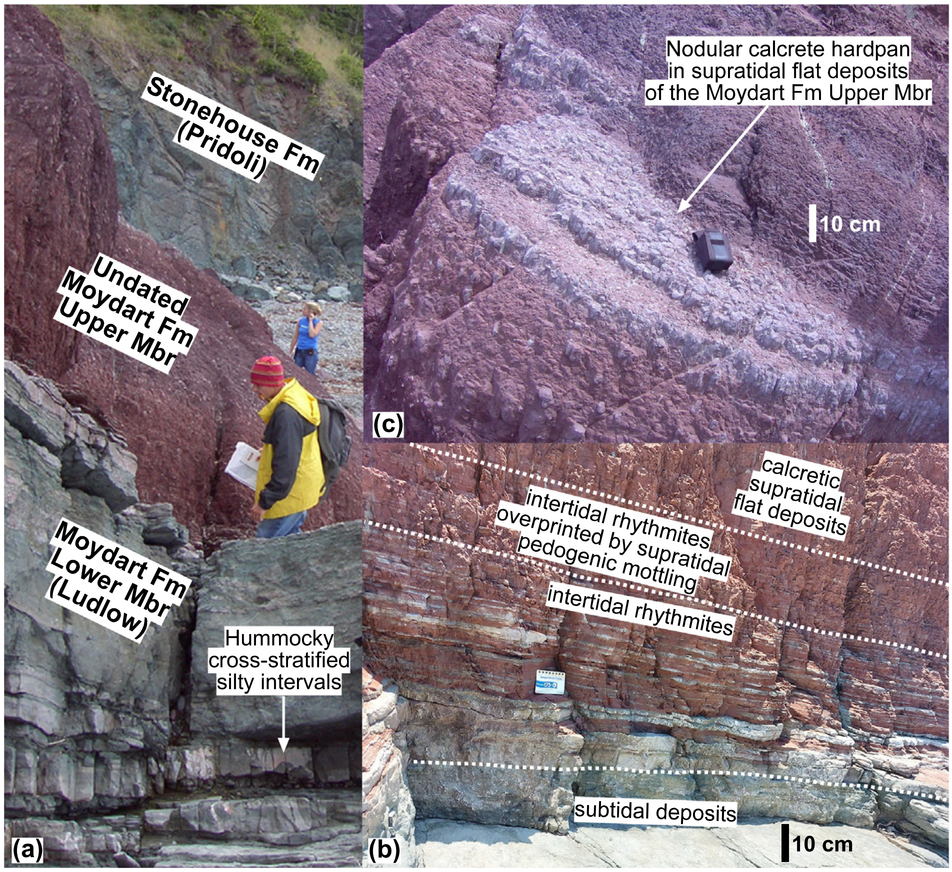

Fig. 15. (a) Thin interval of early Pridoli continental red beds (Upper Member of the Moydart Formation) between thick intervals of green marine mudrock in the Arisaig Group of northern Nova Scotia (West Avalonia); (b) intertidal rhythmites in the gradational, but rapid transition from subtidal to supratidal 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.

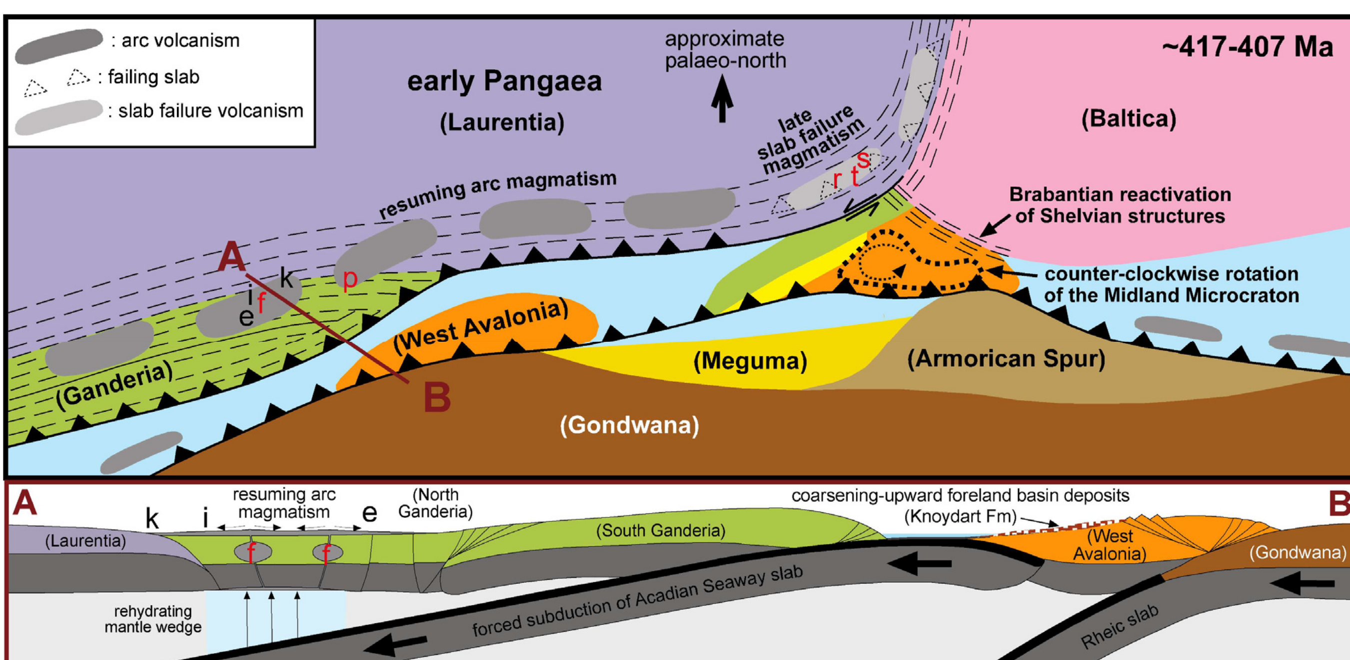

Fig. 16. Proposed model for tectono-magmatic events that occurred during the ∼ 417–407 Ma interval (Lochkovian to earliest Emsian) in rocks of the Appalachian–Caledonian Belt. Isolated letters correspond to localities on Fig. 1 described in Table 1, with red letters indicating the record of intrusive 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).

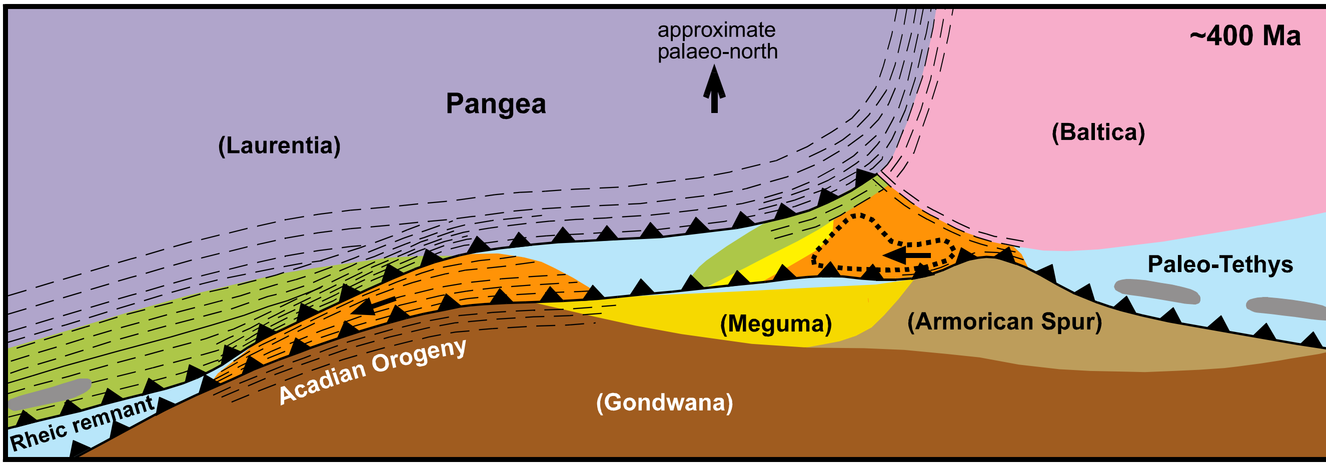

Fig. 17. Proposed model for the Middle Devonian Acadian Orogeny.

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).

6.5.3. 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).

7. Conclusions

Katian to earliest Emsian igneous rocks in the Appalachian–Caledonian Belt all share characteristics of plate-margin magmatism (Fig. 6a,b–11a,b). However, differentiation between arc, slab-failure and plate-margin A2-type magmatism (Fig. 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 (Fig. 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).

CRediT authorship contribution statement

Pierre Jutras: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft. **Jaroslav Dostal:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2023.08.002.

References

André, L., Hertogen, J., Deutsch, S., 1986. Ordovician-Silurian magmatic provinces in Belgium and the Caledonian orogeny in middle Europe. Geology 14 (10), 879–882.

Archibald, D.B., Murphy, J.B., Fowler, M., Strachan, R.A., Hildebrand, R.S., 2022. Testing petrogenetic models for contemporaneous mafic and felsic to intermediate magmatism within the 'Newer Granite'suite of the Scottish and Irish Caledonides, *in* Kuiper, Y., Murphy, J.B., Nance, R.D., Strachan, R.S., Thompson, M.D., eds., New Developments in the Appalachian–Caledonian–Variscan Orogen. Geological Society of America - Special Paper, vol. 554, pp. 375–400.

Archibald, D.B., Murphy, J.B., 2021. A slab failure origin for the Donegal composite batholith, Ireland as indicated by trace-element geochemistry. Geol. Soc. Lond. Spec. Publ. 503, 347–370.

Archibald, D.B., Macquarrie, L.M., Murphy, J.B., Strachan, R.A., McFarlane, C.R., Button, M., Larson, K.P., Dunlop, J., 2021. The construction of the Donegal composite batholith, Irish Caledonides: Temporal constraints from U-Pb dating of zircon and titanite. Geol. Soc. Am. Bull. 133 (11–12), 2335–2354.

Aydin, N.S., 1995. Petrology of the composite mafic-felsic rocks of the Fogo Island batholith: A window to mafic magma chamber processes and the role of mantle in the petrogenesis of granitoid rocks. Unpublished PhD thesis, Memorial University of Newfoundland, St. John's, NL, 191 p.

Badenszki, E., Daly, J.S., Whitehouse, M.J., Kronz, A., Upton, B.G., Horstwood, M.S., 2019. Age and origin of deep crustal meta-igneous xenoliths from the Scottish Midland Valley: vestiges of an early Palaeozoic arc and 'Newer Granite' magmatism. J. Petrol. 60 (8), 1543–1574.

Barr, S.M., White, C.E., Miller, B.V., 2002. The Kingston terrane, southern New Brunswick, Canada: evidence for an Early Silurian volcanic arc. Geol. Soc. Am. Bull. 8, 964–982.

Becker, R.T., Marshall, J.E.A., Da Silva, A.-C., 2020. Chapter 22—The Devonian Period, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., eds., The Geologic Time Scale 2020, Volume 2. Elsevier: Boston, MA, USA, pp. 733–810. ISBN: 978-0-128-24361-9.

Bender, H., Glodny, J., Ring, U., 2019. Absolute timing of Caledonian orogenic wedge assembly, Central Sweden, constrained by Rb–Sr multi-mineral isochron data. Lithos 344, 339–359.

Bergström, S.M., Chen, X., Gutiérrez-Marco, J.C., Dronov, A., 2009. The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and to δ13C chemostratigraphy. Lethaia 42 (1), 97–107. https://doi.org/10.1111/j.1502-3931.2008.00136.x.

Boucot, A.J., Dewey, J.F., Dineley, D.L., Fletcher, R., Fyson, W.K., Griffin, J.G., Hickox, C.F., Mckerrow, W.S., Ziegler, A.M., 1974. Geology of the Arisaig area, Antigonish County, Nova Scotia. Geological Society of America - Special Paper, vol. 139, 191 p.

Boucot, A.J., 1960. A New Lower Devonian Stropheodontid Brachiopod. J. Paleo. 34 (3), 483–485.

Bourque, P.A., Lachambre, G., 1980. Stratigraphie du Silurien et du Dévonien basal du sud de la Gaspésie. Québec Ministry of Energy and Ressources, Special Paper ES–30, 123 p.

Bourque, P.A., Malo, M., Kirkwood, D., 2000. Paleogeography and tectono-sedimentary history at the margin of Laurentia during Silurian to earliest Devonian time: The Gaspé Belt. Québec. Geol. Soc. Am. Bull. 112 (1), 4–20.

Brem, A.G., Lin, S., Van Staal, C.R., Davis, D.W., McNicoll, V.J., 2007. The Middle Ordovician to Early Silurian voyage of the Dashwoods microcontinent, West Newfoundland; based on new U/Pb and 40Ar/39Ar geochronological, and kinematic constraints. Am. J. Sci. 307, 311–338.

Cawood, P.A., Dunning, G.R., 1993. Silurian age for movement on the Baie Verte Line: implications for accretionary tectonics in the northern Appalachians. In Geological Society of America, Abstracts with Programs 25, p. A422.

Cawood, P.A., van Gool, J.A.M., Dunning, G.R., 1996. Geological development of eastern Humber and western Dunnage zones: Corner Brook-Glover Island region. Newfoundland. Can. J. Earth Sci. 33, 182–198.

Chew, D.M., Strachan, R.A., 2014. The Laurentian Caledonides of Scotland and Ireland. Geol. Soc. Lond. Spec. Publ. 390, 45–91.

Churchill-Dickson, L., 2004. A Late Silurian (Pridolian) age for the Eastport Formation, Maine: A review of the fossil, stratigraphic, and radiometric-age data. Atl. Geol. 40, 189–195.

Cocks, L.R.M., Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago; a faunal and palaeomagnetic review. J. Geol. Soc. 159, 631–644.

Currie, K.L., 2003. Emplacement of the Fogo Island Batholith. Newfoundland. Atl. Geol. 39, 79–96.

Daly, R.A., 1925. The geology of Ascension Island. Proc. Am. Acad. Arts Sci. 60, 3–80.

David, J., Gariépy, C., 1990. Early Silurian orogenic andesites from the central Quebec Appalachians. Can. J. Earth Sci. 27 (5), 632–643.

Debacker, T.N., Dewaele, S., Sintubin, M., Verniers, J., Muchez, P., Boven, A., 2005. Timing and duration of the progressive deformation of the Brabant Massif, Belgium. Geol. Belg. 8 (4), 20–34.

Dewaele, S., Boven, A., Muchez, P.H., 2002. $^{40}Ar/^{39}Ar$ dating of mesothermal, orogenic mineralization in a low-angle reverse shear zone in the Lower Palaeozoic of the Anglo-Brabant fold belt, Belgium. Appl. Earth Sci. 111 (3), 215–220.

Dewey, J.F., Dalziel, I.W., Reavy, R.J., Strachan, R.A., 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. Scott. J. Geol. 51, 5–30.

Doig, R., Nance, R.D., Murphy, J.B., Casseday, R.P., 1990. Evidence for Silurian sinistral accretion of Avalon composite terrane in Canada. J. Geol. Soc. 147 (6), 927–930.

Dokken, R., 2017. Detrital zircon studies in Silurian basins of southern New Brunswick. University of Alberta. MSc thesis.

Dostal, J., Wilson, R., Jutras, P., 2021. Petrogenesis of Siluro-Devonian rhyolites of the Tobique Group in the northwestern Appalachians (northern New Brunswick, Canada): Tectonic implications for the accretion history of peri–Gondwanan terranes along the Laurentian margin, *in* Quesada, C., Strachan, R., Murphy, B., eds., Pannotia to Pangea: Neoproterozoic and Paleozoic orogenic cycles in the circum–North Atlantic region. Geological Society, London, Special Publications, vol. 503, pp. 391–407.
Dostal, J., Jutras, P., Wilson, R., 2022. Geochemical and Nd isotopic constraints on the origin of Upper Silurian rhyolitic rocks in the northern Appalachians (northern New Brunswick): tectonic implications, *in* Kuiper, Y., Murphy, J.B., Nance, R.D., Strachan, R.S., Thompson, M.D., eds., New Developments in the Appalachian–Caledonian–Variscan Orogen. Geological Society of America - Special Paper, vol. 554, pp. 121–134.
Dostal, J., Jutras, P., 2021. Tectonic and petrogenetic settings of the Eocene Challis-Kamloops volcanic belt of western Canada and the northwestern United States. Int. Geol. Rev. 64 (18), 2565–2583. https://doi.org/10.1080/00206814.2021.1992800.
Dostal, J., Wilson, R.A., Keppie, J.D., 1989. Geochemistry of Siluro-Devonian Tobique volcanic belt in northern and central New Brunswick (Canada): tectonic implications. Can. J. Earth Sci. 26, 1282–1296.
Dostal, J., Laurent, R., Keppie, J.D., 1993. Late Silurian-Early Devonian rifting during dextral transpression in the southern Gaspé Peninsula (Quebec): petrogenesis of volcanic rocks. Can. J. Earth Sci. 30, 2283–2294.
Dostal, J., Keppie, J.D., Wilson, R.A., 2016. Nd isotopic and trace element constraints on the source of Silurian-Devonian mafic lavas in the Chaleur Bay Synclinorium of New Brunswick (Canada): Tectonic implications. Tectonophyics 681, 364–375.
Doyon, M., Dalpé, C., 1993. Roches magmatiques siluro-dévoniennes de la Gaspésie. Québec Ministry of Energy and Resources, MB 93–16, 128 p.
Dunning, G.R., O'brien, S.J., Colman-Sadd, S.P., Blackwood, R.F., Dickson, W.L., O'neill, P.P., Krogh, T.E., 1990. Silurian orogeny in the Newfoundland Appalachians. The J. Geol. 98 (6), 895–913.
Dunning, G.R., 1992, U–Pb geochronological research agreement final report for the Newfoundland Department of Mines and Energy. Unpublished report (results published in van Staal et al., 2014).
Eby, N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. Geology 20, 641–644.
Elliott, C.G., Dunning, G.R., Williams, P.F., 1991. New U/Pb zircon age constraints on the timing of deformation in north-central Newfoundland and implications for early Paleozoic Appalachian orogenesis. Geol. Soc. Am. Bull. 103, 125–135.
Freeburn, R., Bouilhol, P., Maunder, B., Magni, V., van Hunen, J., 2017. Numerical models of the magmatic processes induced by slab breakoff. Earth Planet. Sci. Lett. 478, 203–213.
Fritschle, T., Daly, J.S., Whitehouse, M.J., McConnell, B., Buhre, S., 2018a. Multiple intrusive phases in the Leinster Batholith, Ireland: geochronology, isotope geochemistry and constraints on the deformation history. J. Geol. Soc. 175 (2), 229–246.
Fritschle, T., Daly, J.S., McConnell, B., Whitehouse, M.J., Menuge, J.F., Buhre, S., Mertz-Kraus, R., Döpke, D., 2018b. Peri-Gondwanan Ordovician arc magmatism in southeastern Ireland and the Isle of Man: Constraints on the timing of Caledonian deformation in Ganderia. Geol. Soc. Am. Bull. 130 (11-12), 1918-1939.
Fyffe, L., Fricker, A., 1987. Tectonostratigraphic terrane analysis of New Brunswick. Atl. Geol. 23 (3), 113–122.
Giggie, K.V., 1999. Ground follow-up to the multi-sensor airborne geophysical survey in central Restigouche County, New Brunswick: results and interpretation. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Open File Report, vol. 99–9, 41 p.
Greenough, J.D., Kamo, S.L., Krogh, T.E., 1993. A Silurian U-Pb age for the Cape St Mary's sills, Avalon Peninsula, Newfoundland, Canada: implications for Silurian orogenesis in the Avalon Zone. Can. J. Earth Sci. 30, 1607–1612.
Greenough, J.D. 1984. Petrology and geochemistry of Cambrian volcanic rocks from the Avalon Zone in Newfoundland and New Brunswick. Ph.D. thesis, Memorial University of Newfoundland, St. John's.
Greiner, H.R., 1970. Geology of the Charlo area, 21O/16, Restigouche County, New Brunswick. New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Series 70–2, 18 p.
Hamilton, M.A., Kerr, A., 2016. New U-Pb dates from Silurian rocks on Fogo Island: Preliminary stratigraphic and tectonic implications. Newfoundland and Labrador Department of Natural Resources Geological Survey. Current Research 16, 123–132.
Heaman, L.M., Erdmer, P., Owen, J.V., 2002. U-Pb geochronologic constraints on the crustal evolution of the Long Range Inlier, Newfoundland. Can. J. Earth Sci. 39, 845–865.
Hildebrand, R.S., Whalen, J.B., 2017. The Tectonic Setting and Origin of Cretaceous Batholiths Within the North American Cordillera: The Case for Slab Failure Magmatism and Its Significance for Crustal Growth. Geol. Soc. Am. - Special Paper 532, 113 p.
Holland, C.H., 1988. The fossiliferous Silurian rocks of the Dunquin inlier, Dingle peninsula, County Kerry, Ireland. Trans. R. Soc. Edinb. Earth Sci. l9, 347–360.
Hollocher, K., Robinson, P., Seaman, K., Walsh, E., 2016. Ordovician–early Silurian intrusive rocks in the northwest part of the Upper Allochthon, mid-Norway: Plutons of an Iapetan volcanic arc complex. Am. J. Sci. 316 (10), 925–980.
Irrinki, R.R., 1990. Geology of the Charlo area, Restigouche County, New Brunswick. New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Report of Investigation 24, 118 p.
Jakob, J., Andersen, T.B., Mohn, G., Kjøll, H.J., Beyssac, O., 2022. A Revised Tectono-Stratigraphic Scheme for the Scandinavian Caledonides and Its Implications for Our Understanding of the Scandian Orogeny, *in* Kuiper, Y., Murphy, J.B., Nance, R.D., Strachan, R.S., Thompson, M.D., eds., New Developments in the Appalachian–Caledonian–Variscan Orogen. Geological Society of America - Special Paper, vol. pp. 554, 335–374.
Jensen, L.R., 1975. The Torbrook Formation. Atl. Geol. 11 (3), 107–118.
Johnson, R.J.E., Van der Voo, R., 1985. Middle Cambrian paleomagnetism of the Avalon Terrane in Cape Breton Island, Nova Scotia. Tectonics 4, 629–651. https://doi.org/10.1029/TC004i007p00629.
Johnson, R.J.E., Van der Voo, R., 1990. Pre-folding magnetization reconfirmed for theLate Ordovician-Early Silurian Dunn Point volcanics, Nova Scotia. Tectonophysics 178, 193–205. https://doi.org/10.1016/0040-1951(90)90146-Y.
Jutras, P., Murphy, J.B., Quick, D., Dostal, J., 2020. Evolution of subduction dynamics beneath West Avalonia in Middle to Late Ordovician times. Lithosphere, Article 8837633, 22 p., https://doi.org/10.2113/2020/8837633.
Kant, L.B., Tepper, J.H., Eddy, M.P., Nelson, B.K., 2018. Eocene basalt of Summit Creek: slab breakoff magmatism in the central Washington Cascades, USA. Lithosphere 10 (6), 792–805.
Karabinos, P., Macdonald, F.A., Crowley, J., 2017. Bridging the gap between the foreland and hinterland 1: geochronology and plate tectonic geometry of Ordovician magmatism and terrane accretion on the Laurentian margin of New England. Am. J. Sci. 317, 515–554.
Keppie, J.D., 1982. The Minas Geofracture. In St-Julien, Pierre (editor); Beland, J (editor). Geol. Assoc. Canada - Special Paper 24, 263–280.
Kirkland, C.L., Alsop, G.I., Daly, J.S., Whitehouse, M.J., Lam, R., Clark, C., 2013. Constraints on the timing of Scandian deformation and the nature of a buried Grampian terrane under the Caledonides of northwestern Ireland. J. Geol. Soc. 170 (4), 615–625.
Kroner, U., Romer, R.L., 2013. Two plates—many subduction zones: the Variscan orogeny reconsidered. Gondw. Res. 24 (1), 298–329.
Landing, E., Murphy, J.B., 1991. Uppermost Precambrian(?)–Lower Cambrian of mainland Nova Scotia; faunas, depositional environments, and stratigraphic revision. J. Paleo. 65, 382–396.
Landing, E., Johnson, S.C., Geyer, G., 2008. Faunas and Cambrian volcanism on the Avalonian marginal platform, southern New Brunswick. J. Paleo. 82, 884–905. https://doi.org/10.1666/07-007.1.
Landing, E., Keppie, J.D., Keppie, D.F., Geyer, G., Westrop, S.R., 2022. Greater Avalonia—latest Ediacaran-Ordovician "peribaltic" terrane bounded by continental margin prisms ("Gander", Harlech Dome, Meguma): review, tectonic implications, and paleogeography. Earth Sci. Rev. 224,. https://doi.org/10.1016/j.earscirev.2021.103863 103863.
Landing, E., 1996. Avalon; insular continent by the latest Precambrian, *in* Nance, R. D., Thompson, M.D., eds., Avalonian and Related Peri–Gondwanan Terranes of the Circum–North Atlantic. Geological Society of America - Special Paper, vol. 304, pp. 29–63.
Landing, E., 2007. Ediacaran–Ordovician of East Laurentia. S. W. Ford Memorial Volume, Bulletin 510 - New York State Museum, University of The State of New York, Albany, NY, United States.
Leggett, J.K., McKerrow, W.S., Eales, M.H., 1979. The Southern Uplands of Scotland: a Lower Palaeozoic accretionary prism. J. Geol. Soc. 136, 755–770.
Linnemann, U., Herbosch, A., Liégeois, J.P., Pin, C., Gärtner, A., Hofmann, M., 2012. The Cambrian to Devonian odyssey of the Brabant Massif within Avalonia: a review with new zircon ages, geochemistry, Sm–Nd isotopes, stratigraphy and palaeogeography. Earth Sci. Rev. 112 (3–4), 126–154.
Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R., Whalen, J.B., 2005. Assembly of the Annieopsquotch Accretionary Tract, Newfoundland Appalachians: age and geodynamic constraints from syn-kinematic Intrusions. J. Geol. 113, 553–570.
Lusty, P.A.J., Lacinska, A.M., Millar, I.L., Barrie, C.D., Boyce, A.J., 2017. Wales, UK; a failed volcanogenic massive sulfide system in the Avalon Zone of the British Caledonides. Ore Geol. Rev. 89, 557–586.
Mac Niocaill, C., 2000. A new Silurian paleolatitude for eastern Avalonia and evidencefor crustal rotations in the Avalonian margin of southwestern Ireland. Geophys. J. Int. 141 (3), 661–671. https://doi.org/10.1046/j.1365-246x.2000.00101.x.
Macdonald, F.A., Ryan-Davis, J., Coish, R.A., Crowley, J.L., Karabinos, P., 2014. A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean. Geology 42 (6), 539–542.
Martinez Catalan, J.R., Arenas, R., García, F.D., Cuadra, P.G., Gómez-Barreiro, J., Abati, J., Castiñeiras, P., Fernández-Suárez, J., Martínez, S.S., Andonaegui, P., Clavijo, E. G., 2007. Space and time in the tectonic evolution of the northwestern Iberian Massif: Implications for the Variscan belt, *in* Hatcher, R.D. Jr, Carlson, M.P., McBride, J.H., Martinez Catalan, J.R., eds., 4-D framework of continental crust. Geological Society of America Memoir, vol. 200, pp. 403–423. doi:10.1130/2007.1200(21).
McConnell, B., Riggs, N., Fritschle, T., 2021. Tectonic history across the Iapetus suture zone in Ireland. Geol. Soc. Lond. Spec. Publ. 503 (1), 333–345.
McGregor, D.C., 1992. Palynology of Upper Silurian/Lower Devonian rock samples from the western margin of the Elmtree inlier of northern New Brunswick (NTS 21 P/13). In: Geological Survey of Canada, unpublished paleontological report F1–1–1992–DCM, p. 2 p..
McKerrow, W.S., Leggett, J.K., Eales, M.H., 1977. Imbricate thrust model of the Southern Uplands of Scotland. Nature 267, 237–239.

McNicoll, V., Squires, G.C., Kerr, A., Moore, P.J., 2008. Geological and metallogenic implications of U-Pb zircon geochronological data from the Tally Pond area, central Newfoundland. Newfoundland and Labrador Department of Natural Resources. Geol. Survey, Report 8, 173–193.
Melchin, M.J., Sadler, P.M., Cramer, B.D., 2020. The Silurian Period, *in* Geologic Time Scale 2020, Elsevier, p. 695-732.
Miller, B.V., Fyffe, L.R., 2002. Geochronology of the Letete and Waweig Formations, Mascarene Group, southwestern New Brunswick. Atl. Geol. 38, 29–36.
Murphy, J., 1987. The stratigraphy and depositional environment of upper Ordovician to lower Devonian rocks in the Antigonish Highlands, Nova Scotia. Atl. Geol. 23 (2), 63–75.
Murphy, R.B., 1989. Geochemistry of Siluro-Devonian mafic volcanic rocks and associated gabbroic intrusions, Upsalquitch Forks area, New Brunswick. Acadia University, Wolfville, Nova Scotia, p. 274 p.. Unpublished M.Sc. thesis.
Murphy, J.B., Fernández-Suárez, J., Jeffries, T.E., 2004. Lithogeochemical, Sm-Nd and U-Pb isotopic data from the Silurian-Early Devonian Arisaig Group clastic rocks, Avalon terrane, Nova Scotia: a record of terrane accretion in the Appalachian-Caledonide orogeny. Geol. Soc. Am. Bull. 116, 1183–1201.
Murphy, J.B., Dostal, J., Keppie, J.D., 2008. Neoproterozoic-Early Devonian magmatism in the Antigonish Highlands, Avalon terrane, Nova Scotia: Tracking the evolution of the mantle and crustal sources during the evolution of the Rheic Ocean. Tectonophysics 461, 181–201.
Murphy, J.B., Waldron, J.W., Kontak, D.J., Pe-Piper, G., Piper, D.J., 2011. Minas Fault Zone: Late Paleozoic history of an intra-continental orogenic transform fault in the Canadian Appalachians. J. Struct. Geol. 33 (3), 312–328.
Murphy, J.B., Hamilton, M.A., Leblanc, B., 2012. Tectonic significance of Late Ordovician silicic magmatism, Avalon terrane, northern Antigonish Highlands, Nova Scotia. Can. J. Earth Sci. 49, 346–358.
Murphy, J.B., Nance, R.D., Gabler, L.B., Martell, A., Archibald, D.A., 2019. Age, geochemistry and origin of the Ardara appinite plutons, northwest Donegal, Ireland. Geosci. Can. 46 (1), 31–48.
Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2010. Evolution of the Rheic ocean. Gondw. Res. 17, 194–222.
Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2012. A brief history of the Rheic Ocean. Geosci. Front. 3, 125–135.
Noble, J.P.A., 1976. Silurian stratigraphy and paleogeography, Pointe Verte area, New Brunswick, Canada. Can. J. Earth Sci. 13 (4), 537–546.
Noble, S.R., Tucker, R.D., Pharaoh, T.C., 1993. Lower Palaeozoic and Precambrian igneous rocks from eastern England, and their bearing on late Ordovician closure of the Tornquist Sea: constraints from U-Pb and Nd isotopes. Geol. Mag. 130 (6), 835–846.
Nowlan, G.S., 1983. Early Silurian conodonts of eastern Canada. Fossils Strata 15, 95–110.
Pharaoh, T., 2018. The Anglo-Brabant Massif: persistent but enigmatic palaeo-relief at the heart of western Europe. Proc. Geol. Assoc. 129 (3), 278–328.
Pharaoh, T.C., Merriman, R.J., Evans, J.A., Brewer, T.S., Webb, P.C., Smith, N.J.P., 1991. Early Palaeozoic arc-related volcanism in the concealed Caledonides of southern Britain. Ann. Soc. Geol. Belg. 114, 63–91.
Pharaoh, T.C., Brewer, T.S., Webb, P.C., 1993. Subduction-related magmatism of late Ordovician age in eastern England. Geol. Mag. 130, 647–656.
Pharaoh, T., England, R., Lee, M., 1995. The concealed Caledonide basement of eastern England and the southern North Sea—a review. Stud. Geophys. Geod. 39, 330–346.
Phillips, B.A., Kerr, A.C., Bevins, R., 2016. A re-appraisal of the petrogenesis and tectonic setting of the Ordovician Fishguard volcanic group, SW Wales. Geol. Mag. 153, 410–425.
Pidgeon R.T., Aftalion M., 1978. Cogenetic and Inherited Zircon U-Pb Systems in Palaeozoic granites of Scotland and England, *in* Bowes, R.D. and Leake, B.E., eds., Crustal evolution in Northwest Britain and adjacent regions. Geology Journal Special Issue 10, 183–220.
Piñán-Llamas, A., Hepburn, J.C., 2013. Geochemistry of Silurian-Devonian volcanic rocks in the Coastal Volcanic belt, Machias-Eastport area, Maine: Evidence for a pre–Acadian arc. Geol. Soc. Am. Bull. 125, 1930–1942.
Piper, J.D.A., 2007. Palaeomagnetism of the Loch Doon Granite Complex, Southern Uplands of Scotland: the Late Caledonian palaeomagnetic record and an early Devonian Episode of true polar wander. Tectonophysics 432 (1–4), 133–157.
Pothier, H.D., Waldron, J.W.F., Schofield, D.I., DuFrane, A., 2015. Peri-Gondwanan terrane interactions recorded in the Cambrian-Ordovician detrital zircon geochronology of North Wales. Gondw. Res. 28 (3), 987–1001.
Rogers, N., Van Staal, C.R., 2003. Volcanology and tectonic setting of the northern Bathurst Mining Camp: Part II. Mafic volcanic constraints on back-arc opening, *in* Goodfellow, W.D., McCutcheon, S.R., Peter , J.M., eds., Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick, and Northern Maine. Economic Geology Monograph 11, 181–201.
Ross, P.S., Bédard, J.H., 2009. Magmatic affinity of modern and ancient subalkaline volcanic rocks determined from trace-element discriminant diagrams. Can. J. Earth Sci. 46 (11), 823–839.
Ryan, P.D., Dewey, J.F., 1991. A geological and tectonic cross-section of the Caledonides of western Ireland. J. Geol. Soc. 148, 173–180.
Sandeman, H.A., Malpas, J., 1995. Epizonal I-and A-type granites and associated ash-flow tuffs, Fogo Island, northeast Newfoundland. Can. J. Earth Sci. 32, 1835–1844.
Schofield, D.I., Potter, J., Barr, S.M., Horák, J.M., Millar, I.L., Longstaffe, F.J., 2016. Reappraising the Neoproterozoic 'East Avalonian' terranes of southern Great Britain. Gondw. Res. 35, 257–271.
Seaman, S.J., Wobus, R.A., Wiebe, R.A., Lubick, N., Bowring, S.A., 1995. Volcanic expression of bimodal magmatism: the Cranberry Island-Cadillac Mountain complex, coastal Maine. J. Geol. 103 (3), 301–311.
Seaman, S.J., Scherer, E.E., Wobus, R.A., Zimmer, J.H., Sales, J.G., 1999. Late Silurian volcanism in coastal Maine: the Cranberry Island series. Geol. Soc. Am. Bull. 111 (5), 686–708.
Sintubin, M., Debacker, T.N., Van Baelen, H., 2009. Early Palaeozoic orogenic events north of the Rheic suture (Brabant, Ardenne): A review. C. R. Geosci. 341, 156–173.
Sloan, R.J., Bennett, M.C., 1990. Geochemical character of Silurian volcanism in SW Ireland. J. Geol. Soc. 147 (6), 1051–1060.
Smethurst, M.A., McEnroe, S.A., 2003. The palaeolatitude controversy in the Silurian of Newfoundland resolved: New palaeomagnetic results from the central mobile belt. Tectonophysics 362, 83–104. https://doi.org/10.1016/S0040-1951(02)00632-7.
Soper, N.J., Webb, B.C., Woodcock, N.H., 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. Proc. Yorks. Geol. Soc. 46 (3), 175–192.
Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A., Greiling, R.O., 1992. Sinistral transpression and the Silurian closure of Iapetus. J. Geol. Soc. 149 (6), 871–880.
Stone, P., McMillan, A.A., Floyd, J.D., Barnes, R.P., Phillips, E.R., 2012. British Regional Geology: South of Scotland, 4th Edition. British Geological Survey, Nottingham. 247 p. ISBN 978-085272-694-5.
Strachan, R.A., 2012a. The Grampian Orogeny: Mid-Ordovician Arc–Continent Collision along the Laurentian Margin of Iapetus, *in* Woodcock, N.H., Strachan, R., eds., Geological history of Britain and Ireland. Second Edition: Geological history of Britain and Ireland, Chapter 6, Wiley–Blackwell.
Strachan, R.A., 2012b. Mid-Ordovician to Silurian Subduction and Collision: Closure of the Iapetus Ocean, *in* Woodcock, N.H., Strachan, R., eds., Geological history of Britain and Ireland. Second Edition: Geological history of Britain and Ireland, Chapter 7, Wiley–Blackwell.
Strong, D.F., Dupuy, C., 1982. Rare earth elements in the bimodal Mount Peyton batholith: Evidence of crustal anatexis by mantle-derived magma. Can. J. Earth Sci. 19 (2), 308–315.
Sweetman, T.M., 1987. The geochemistry of the Blackstairs unit of the Leinster granite. Ireland. J. Geol. Soc. 144 (6), 971–984.
Thompson, M.D., Barr, S.M., Pollock, J.C., 2022. Evolving views of West Avalonia: Perspectives from southeastern New England, USA, *in* Kuiper, Y.D., Murphy, J.B., Nance, R.D., Strachan, R.A., Thompson, M.D., eds., New Developments in the Appalachian–Caledonian– Variscan Orogen. Geological Society of America - Special Paper, vol. 554, pp. 47-72. https://doi.org/10.1130/2022.2554(03).
Thompson, M.D., Grunow, A.M., Ramezani, J., 2010. Cambro-Ordovician paleogeography of the Southeastern New England Avalon Zone: implications for Gondwana breakup. Geol. Soc. Am. Bull. 122, 76–88. https://doi.org/10.1130/b26581.1.
Thorpe, R.S., Leat, P.T., Bevins, R.E., Hughes, D.J., 1989. Late-orogenic alkaline/subalkaline Silurian volcanism of the Skomer Volcanic Group in the Caledonides of south Wales. J. Geol. Soc. 146 (1), 125–132.
Tindle, A.G., Pearce, J.A., 1981. Petrogenetic modelling of in situ fractional crystallization in the zoned Loch Doon Pluton. Scotland. Cont. Min. Pet. 78 (2), 196–207.
Torsvik, T.H., Rehnström, E.F., 2003. The Tornquist Sea and Baltica-Avalonia docking. Tectonophysics 362, 67–82.
Tremblay, A., Pinet, N., 2016. Late Neoproterozoic to Permian tectonic evolution of the Quebec Appalachians, Canada. Earth-Sci. Rev. 160, 131–170.
van de Kamp, P.C., 1969. The silurian volcanic rocks of the Mendip hills, Somerset; and the Tortworth area, Gloucestershire, England. Geol. Mag. 106 (6), 542–553.
van Staal, C.R., 1994. Brunswick subduction complex in the Canadian Appalachians: record of the Late Ordovician to Late Silurian collision between Laurentia and the Gander margin of Avalon. Tectonics 13, 946–962.
van Staal, C.R., Ravenhurst, C.E., Roddick, J.C., Winchester, J.A., Langton, J.P., 1990. Post-Taconic blueschist suture in the northern Appalachians of northern New Brunswick, Canada. Geology 18, 1073–1077.
van Staal, C.R., Dewey, J.F., MacNiocaill, C., McKerrow, W.S., 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In: Blundell, D.J., Scott, A.C. (Eds.), Lyell: The Past Is the Key to the Present. Geological Society, vol. 143. Special Publications, London, pp. 199–242.
van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, and A., Rogers, N., 2009. Pre Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J. B., Keppie, J.D., Hynes, A.J., eds., Ancient Orogens and Modern Analogues. Geological Society, London, Special Publications, vol. 327, pp. 271–316.
van Staal, C.R., Whalen, J.B., McNicoll, V.J., Pehrsson, S., Lissenberg, C.J., Zagorevski, A., Van Breemen, O., Jenner, G.A., 2007. The Notre Dame arc and the Taconic orogeny in Newfoundland. Geol. Soc. Am. Mem. 200, 511–552.
van Staal, C.R., Barr, S.M., Murphy, J.B., 2012. Provenance and tectonic evolution of Ganderia: Constraints on the evolution of the Iapetus and Rheic Oceans. Geology 40, 987–990.
van Staal, C.R., McNicoll, V.J., Rogers, N., 2014. Time-transgressive Salinic and Acadian orogenesis, magmatism and Old Red Sandstone sedimentation in Newfoundland. Geosci. Can. 41, 138–164.

van Staal, C.R., Wilson, R.A., Kamo, S.L., McClelland, W.C., McNicoll, V., 2016. Evolution of the Early to Middle Ordovician Popelogan arc in New Brunswick, Canada, and adjacent Maine, USA: Record of arc-trench migration and multiple phases of rifting. Geol. Soc. Am. Bull. 128, 122–146. https://doi.org/10.1130/B31253.1.

van Staal, C.R., Barr, S.M., Waldron, J.W., Schofield, D.I., Zagorevski, A., White, C.E., 2021. Provenance and Paleozoic tectonic evolution of Ganderia and its relationships with Avalonia and Megumia in the Appalachian-Caledonide orogen. Gondw. Res. 98, 212–243.

van Wagoner, N.A., Leybourne, M.I., Dadd, K.A., Huskins, M.L., 2001. The Silurian (?) Passamaquoddy Bay mafic dyke swarm, New Brunswick: petrogenesis and tectonic implications. Can. J. Earth Sci. 38, 1565–1578.

van Wagoner, N.A., Leybourne, M.I., Dadd, K.A., Baldwin, D.K., McNeil, W., 2002. Late Silurian bimodal volcanism of southwestern New Brunswick, Canada: Products of continental extension. Geol. Soc. Am. Bull. 114 (4), 400–418.

Waldron, J.W., Phil J.A. McCausland, P.J.A., Barr S.M., Schofield, D.I., Reusch, D., Wu, L., 2022. Terrane history of the Iapetus Ocean as preserved in the northern Appalachians and western Caledonides. Earth-Sci. Rev. 233, 104163.

Waldron, J.W., Murphy, J.B., Melchin, M.J., Davis, G., 1996. Silurian tectonics of western Avalonia: strain-corrected subsidence history of the Arisaig Grou, Nova Scotia. J. Geol. 104 (6), 677–694.

Waldron, J.W.F., Schofield, D.I., White, C.E., Barr, S.M., 2011. Cambrian successions of the Meguma Terrane, Nova Scotia, Canada, and Harlech Dome, North Wales, UK: dispersed fragments of a peri-Gondwanan basin? J. Geol. Soc. 168, 83–98.

Waldron, J.W.F., Schofield, D.I., DuFrane, S.A., Floyd, J.D., Crowley, Q.G., Simonetti, A., Dokken, R.J., Pothier, H.D., 2014. Ganderia-Laurentia collision in the Caledonides of Great Britain and Ireland. J. Geol. Soc. 171, 555–569.

Waldron, J.W., Schofield, D.I., Murphy, J.B., 2019. Diachronous Paleozoic accretion of peri–Gondwanan terranes at the Laurentian margin. Geol. Soc. Lond. Spec. Publ. 470, 289–310.

Walker, J.A., 2010. Stratigraphy and lithogeochemistry of Early Devonian volcano-sedimentary rocks hosting the Nash Creek Zn-Pb-Ag deposit, northern New Brunswick, *in* Martin, G.L., ed., Geological Investigations in New Brunswick for 2009. New Brunswick Department of Natural Resources; Lands, Minerals and Petroleum Division. Mineral Resource Report 2010–1, 52–97.

Whalen, J.B., 1989. The Topsails igneous suite, western Newfoundland: an Early Silurian subduction-related magmatic suite? Can. J. Earth Sci. 26 (12), 2421–2434.

Whalen, J.B., Hildebrand, R.S., 2019. Trace element discrimination of arc, slab failure, and A-type granitic rocks. Lithos 348–349, 105179.

Whalen, J.B., Currie, K.L., Van Breemen, O., 1987. Episodic Ordovician-Silurian plutonism in the Topsails igneous terrane, western Newfoundland. Earth Env. Sci. Trans. R. Soc. Edinb. 78 (1), 17–28.

Whalen, J.B., Jenner, G.A., Longstaffe, F.J., Hegner, E., 1996. Nature and evolution of the eastern margin of Iapetus: geochemical and isotopic constraints from Siluro-Devonian granitoid plutons in the New Brunswick Appalachians. Can. J. Earth Sci. 33, 140–155.

Whalen, J.B., McNicoll, V.J., van Staal, C.R., Lissenberg, C.J., Longstaffe, F.J., Jenner, G. A., van Breeman, O., 2006. Spatial, temporal and geochemical characteristics of Silurian collision-zone magmatism, Newfoundland Appalachians: An example of a rapidly evolving magmatic system related to slab break-off. Lithos 89 (3–4), 377–404.

White, C.E., Barr, S.M., Linnemann, U., 2018. U-Pb (zircon) ages and provenance of the White Rock Formation of the Rockville Notch Group, Meguma terrane, Nova Scotia, Canada. evidence for the "Sardian gap" and West African origin. Can. J. Earth Sci. 55 (6), 589–603.

Whitehead, J., Reynolds, P.H., Spray, J.G., 1996. $^{40}Ar/^{39}Ar$ age constraints on Taconian and Acadian events in the Quebec Appalachians. Geology 24, 359–362.

Williams, H., 1979. Appalachian orogen in Canada. Can. J. Earth Sci. 16 (3), 792–807.

Wilson, R.A., 2017. The Middle Paleozoic rocks of northern and western New Brunswick, Canada. New Brunswick Department of Energy and Resource Development, Geological Surveys Branch. Memoir 4, 319 p.

Wilson, R.A., Kamo, S., 2008. New U-Pb ages from the Chaleurs and Dalhousie groups: Implications for regional correlations and tectonic evolution of northern New Brunswick, *in* Martin, G.L., ed., Geological Investigations in New Brunswick for 2007. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division. Mineral Resource Report 2008–1, 55–77.

Wilson, R.A., Kamo, S.L., 2012. The Salinic Orogeny in northern New Brunswick: Geochronological constraints and implications for Silurian stratigraphic nomenclature. Can. J. Earth Sci. 49, 222–238.

Wilson, R.A., Burden, E.T., Bertrand, R., Asselin, E., McCracken, A.D., 2004. Stratigraphy and tectono-sedimentary evolution of the Late Ordovician to Middle Devonian Gaspé Belt in northern New Brunswick: Evidence from the Restigouche area. Can. J. Earth Sci. 41, 527–551.

Wilson, R.A., Kamo, S., Burden, E.T., 2005. Geology of the Val d'Amour Formation: Revisiting the type area of the Dalhousie Group, northern New Brunswick, *in* Martin, G.L., ed., Geological Investigations in New Brunswick for 2004. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division. Mineral Resource Report 2005–1, 167–212.

Wilson, R.A., van Staal, C.R., Kamo, S., 2008. Lower Silurian subduction-related volcanic rocks in the Chaleurs Group, northern New Brunswick. Canada. Can. J. Earth Sci. 45, 981–998.

Wilson, R.A., Van Staal, C.R., McClelland, W.C., 2015. Synaccretionary sedimentary and volcanic rocks in the Ordovician Tetagouche backarc basin, New Brunswick, Canada: Evidence for a transition from foredeep to forearc basin sedimentation. Am. J. Sci. 315, 958–1001.

Wilson, R.A., van Staal, C.R., Kamo, S.L., 2017. Rapid transition from the Salinic to Acadian orogenic cycles in the Northern Appalachian orogen: evidence from Northern New Brunswick, Canada. Am. J. Sci. 317, 448–481.

Wood, D.A., 1980. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. Earth Planet. Sci. Lett. 50, 11–30.

Woodcock, N.H., Soper, N.J., Strachan, R.A., 2007. A Rheic cause for the Acadian deformation in Europe. J. Geol. Soc. 164 (5), 1023–1036.

Woodcock, N.H., 2012a. Ordovician Volcanism and Sedimentation on Eastern Avalonia, *in* Woodcock, N.H., Strachan, R., eds., Geological history of Britain and Ireland: Second Edition. Wiley–Blackwell, Chapter 10.

Woodcock, N.H., 2012b. Late Ordovician to Silurian Evolution of Eastern Avalonia during Iapetus Closure, *in* Woodcock, N.H., Strachan, R., eds., Geological history of Britain and Ireland: Second Edition. Wiley–Blackwell, Chapter 11.

Woodcock, N.H., 2012c. The Acadian Orogeny and its Mid-Late Devonian Depositional Aftermath, *in* Woodcock, N.H., Strachan, R., eds., Geological history of Britain and Ireland: Second Edition. Wiley–Blackwell, Chapter 13.

Zagorevski, A., van Staal, C.R., McNicoll, V., Rogers, N., Valverde-Vaquero, P., Draut, A., Clift, P.D., Scholl, D.W., 2008. Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians, *in* Draut, A. et al., eds., Formation and applications of the sedimentary record in arc-collision zones. Geological Society of America - Special Paper, vol. 436, pp. 309–333, doi:10.1130/2008.2436(14).

Zagorevski, A., van Staal, C.R., Rogers, N., McNicoll, V., Dunning, G.R., Pollock, J.C., 2010. Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians, *in* Tollo, R.P., et al., eds., From Rodinia to Pangea: the lithotectonic record of the Appalachian region. Geological Society of America Memoir, vol. 206, pp. 367–396.

Zagorevski, A., van Staal, C.R., McNicoll, V.J., Hartree, L., Rogers, N., 2012. Tectonic evolution of the Dunnage mélange tract and its significance to the closure of Iapetus. Tectonophysics 568–569, 371–387.

Zhu, D.C., Wang, Q., Zhao, Z.D., Chung, S.L., Cawood, P.A., Niu, Y., Liu, S.A., Wu, F.Y., Mo, X.X., 2015. Magmatic record of India-Asia collision. Sci. Rep. 5 (1), 1–9.

Ziegler, A.M., Mckerrow, W.S., Burne, R.V., Baker, P.E., 1969. Correlation and environmental setting of the Skomer Volcanic Group, Pembrokeshire. Proc. Geol. Assoc. 80, 409–439.

Ziegler, A.M., Scotese, C.R., McKerrow, W.S., Johnson, M.E., Bambach, R.K., 1977. Paleozoic biogeography of continents bordering the Iapetus (pre–Caledonian) and Rheic (pre–Hercynian) oceans, *in* Paleontology and Plate Tectonics, Milwaukee Public Museum Special Publication in Biology and Geology, vol. 2, pp. 1–21.