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Invited Review

# Terrane history of the Iapetus Ocean as preserved in the northern Appalachians and western Caledonides

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ABSTRACT

The Iapetus Ocean was the first ancient ocean to be identified following the development of plate tectonics; its history has been fundamental in relating orogenesis and plate motion. The ocean probably formed following 3-way rifting between Laurentia, Baltica, and Amazonia – West Africa (a block that became incorporated in Gondwana). Closure of the ocean trapped numerous terranes during the development of the Appalachian–Caledonide Orogen. Subsequent deformation, including late Paleozoic strike slip, transpression, and transtension, and Mesozoic stretching during Pangea breakup, must be taken into account in models for orogen development.

Traditional analyses of Iapetan terranes have focussed on Cambrian sedimentary successions, and on isotopic criteria, to classify terranes into larger domains: Ganderia, Avalonia and Megumia. Detrital zircon data show that these domains did not cross the Iapetus as single entities, while paleomagnetic data reveal significant vertical-axis terrane rotations. We here review and interpret 17 paleomagnetic poles and >350 published detrital zircon data sets from the northern Appalachians and western Caledonides, using consistent and rigorous criteria for the selection and presentation of data. We place these data on an integrated stratigraphic chart to show timing relations and to seek constraints on the provenance and travel of terranes in the Iapetus Ocean. We distinguish groups of terranes that likely travelled together as terrane assemblages.

In the Taconian/Grampian Orogeny, Furongian to Katian continent–arc collision involved off-margin blocks along the hyperextended Laurentian margin. In New England, early Taconian collision by 475 Ma involved the Gondwana-derived Moretown assemblage. An assemblage of the Bronson and Popelogan arc terranes probably arrived at the main Laurentian margin 25-30 Myr later. Subduction polarity reversal then led to the progressive accretion of additional terrane assemblages (Salinian Orogeny). The Miramichi–Victoria assemblage arrived close to the Ordovician–Silurian boundary. The Miramichi terrane underwent partial subduction in the Québec re-entrant, whereas the Victoria terrane was juxtaposed with the Newfoundland promontory without major metamorphism. In mid-Silurian time, an assemblage including the Gander terrane of Newfoundland and related portions of Britain and Ireland was accreted to Laurentia, along with Baltica (Scandian Orogeny). The St. Croix – La Poile assemblage may have been accreted slightly later, but is distinguished by the development of a Silurian arc–backarc system (coastal igneous belt) above a northwest-dipping subduction zone. The Avalon–Brookville assemblage encountered this system in Přídolí to Middle Devonian time (Acadian Orogeny), leading to the collapse of the backarc basin and northwest-vergent thrust emplacement onto Laurentia during sinistral transpression in the Appalachian Orogen. Acadian deformation involved mainly sinistral strike slip in Britain and Ireland.

Several of the terranes that were accreted to the Laurentian margin carried internal records of earlier deformation that took place near Amazonia – West Africa in Early Ordovician time and earlier (Monian/Penobscottian

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Orogeny). The Iapetus Ocean thus contained a complex array of terranes, small ocean basins, arcs, and previously emplaced ophiolites analogous to modern southeast Asia. It closed to form a complex array of sutures in an orogen within which no single Iapetus suture can be clearly identified.

## 1. Introduction

The Appalachian–Caledonide Orogen, extending from southeastern USA to northern Norway, Greenland and Svalbard (Fig. 1a), originated during the progressive assembly of Pangea in Paleozoic time. The existence of an ancient ocean, preserved within the orogen, was first proposed by Wilson (1966) who asked the question “Did the Atlantic close and then re-open?” during the early development of the theory of plate tectonics. Wilson’s picture was simple, reinterpreting a “geosyncline” (e.g. Williams, 1964) actualistically as two continental margins and an intervening “Atlantic Ocean of early Paleozoic time”. Harland and Gayer (1972), working in the Caledonides of Svalbard and Scandinavia, proposed the name “Iapetus” for this Paleozoic predecessor of the Atlantic. The picture rapidly proved to be more complex; later syntheses of the orogen (e.g. Fig. 2) have proposed numerous subdivisions representing microcontinents, arcs, and other crustal fragments that existed within the broad oceanic area proposed by Wilson, and have identified a second ocean, the Rheic, between accreted fragments and Gondwana. In this paper we review these accreted terranes, with a focus on their provenance, stratigraphy, and the paleomagnetic record, to simplify and improve understanding of their evolution, both in geological time, and in the more than five decades of geological investigation that followed Wilson’s (1966) ground-breaking paper.

As knowledge of modern plate motions increased, many authors attempted to develop models for the complexities of the orogen, involving processes of plate movement and ocean closure comparable to those operating in the modern Earth (e.g. Dewey, 1969; Harland and Gayer, 1972; Dewey and Shackleton, 1984; Keppie, 1993; Pickering and Smith, 1995; Dalziel, 1997; van Staal et al., 1998; Valverde-Vaquero et al., 2006a; Waldron et al., 2014b; Dalziel and Dewey, 2019; van Staal et al., 2020). These models have typically synthesized one or more of the available datasets: biostratigraphy and faunal provinciality (the main arguments used by Wilson, 1966), geochronology, paleomagnetism, sedimentology, igneous petrology and geochemistry. Many of these models focus on particular segments of the Appalachian–Caledonide Orogen, constructing 2-dimensional cross-sections through time in well understood regions, and extrapolating into areas where data are less available. While this technique can be powerful, it tends to minimize the effects of 3-dimensional phenomena such as along-strike variation and orogen-parallel displacements, both of which are important in the history of orogens.

Many recent orogen-scale reviews have focussed on igneous rocks, where high-precision U-Pb dating of zircon has dramatically improved understanding of the sequence of events (e.g. Jenner et al., 1991; Dunning et al., 1991; Cawood et al., 2001; Thompson et al., 2010b; van Staal et al., 2020, 2021). However, most of the Paleozoic stratified units contain fossils of organisms (trilobites, graptolites, conodonts) that underwent rapid evolutionary change in the early Paleozoic. A legacy of biostratigraphic data exists, from work extending back to the 19th century, but at the time many of these data were collected, it was difficult to correlate biostratigraphic ages with isotopic ages from igneous rocks. Dramatic improvements in the calibration of the time scale (Cohen et al., 2013, 2020; Gradstein et al., 2012, 2020) now allow these biostratigraphic data to be aligned with isotopic ages, permitting more precise and comprehensive understanding of terrane stratigraphy and correlation. In addition, advances in U-Pb geochronology in the last 25 years have led to the acquisition of large amounts of detrital zircon data that provide evidence for the linkages between these terranes and larger source continents. However, these data are scattered in the literature and are presented in a variety of formats, making comparisons difficult.

In this paper we review the development of the northern Appalachian Orogen and the Caledonides of Britain and Ireland (Fig. 1) using these diverse data sets. To keep the task manageable, we consider neither the southern Appalachians nor the Caledonides of Scandinavia and Greenland. Most previous syntheses propose *terranes* within the Iapetus Ocean, smaller units of crust, presumably attached to plates that moved independently of the major bounding continents. Some models (e.g. Hibbard et al., 2006, 2007) group these terranes into larger entities such as *domains* and *realms*. We examine these various subdivisions by comparing their stratigraphies and detrital zircon provenance, using paleomagnetism and other characteristics to add constraints to their motion histories and interactions within the Iapetus Ocean where possible. We make recommendations for the nomenclature of tectonostratigraphic entities to avoid confusion and simplify terminology, especially for students new to the orogen. We consider the roles of major along-strike discontinuities and, critically, of orogen-parallel motion, in the development of the orogen. We then suggest options for kinematic models for orogen development, and examine the associated uncertainties, in order to suggest avenues for future research in understanding the evolution of the orogen as a whole.

## 2. Regional geology and tectonics

### 2.1. Iapetus and Rheic oceans

Following Wilson’s (1966) identification, mostly on biostratigraphic grounds, of an “Atlantic Ocean” of Paleozoic time, models for the orogen based on the newly developed concepts of plate tectonics were proposed by John Dewey and co-workers (Dewey, 1969; Bird and Dewey, 1970; Dewey and Bird, 1971). Many of these early papers focussed on transects in Britain, Ireland, and Newfoundland (Fig. 1), where Stevens (1970) identified the ophiolitic source of foreland-basin sediments deposited on the western margin of the ocean. The ocean from which these ophiolites were derived was named *Iapetus* by Harland and Gayer (1972).

A consensus has gradually emerged (e.g. Cawood et al., 2001) that the Iapetus originated by 3-way rifting among the cratons *Laurentia*, *Baltica*, and *Amazonia – West Africa* (AWA, a block that was incorporated in Gondwana during its formation early in the Cambrian, and then separated during later Atlantic opening), although some discussion has revolved around whether or not Gondwana had fully assembled prior to the departure of AWA forming a short-lived supercontinent *Pannotia* (e.g. Murphy et al., 2020). The continental margin of Iapetus on the Laurentian side was rapidly identified in the shelf and slope successions of eastern North America, NW Scotland, and Greenland (e.g. Williams and Stevens, 1974), and subsequent work has elaborated on the analogy between these successions and modern passive margins (e.g. Williams and Hiscott, 1987; James et al., 1989; Leslie et al., 2008).

Continental margins on the SE (present orientation) side of Iapetus present a more complex history. Smaller continental blocks typically described as “peri-Gondwanan” and assigned to the domains *Avalonia, Ganderia,* and *Megumia* were progressively accreted to Laurentia during the Paleozoic era, forming a progressively expanded continent which may be referred to as *composite Laurentia*. Baltica, already amalgamated with parts of Avalonia along the *Tornquist line* (Torsvik and Rehnström, 2003), collided with the Greenland margin of Laurentia during the Silurian. The resulting enlarged continental mass is referred to as *Laurussia*. Full amalgamation of the main mass of Gondwana, forming the supercontinent *Pangea*, followed in the Carboniferous to Permian interval. The ocean that existed between Avalonia–Baltica and

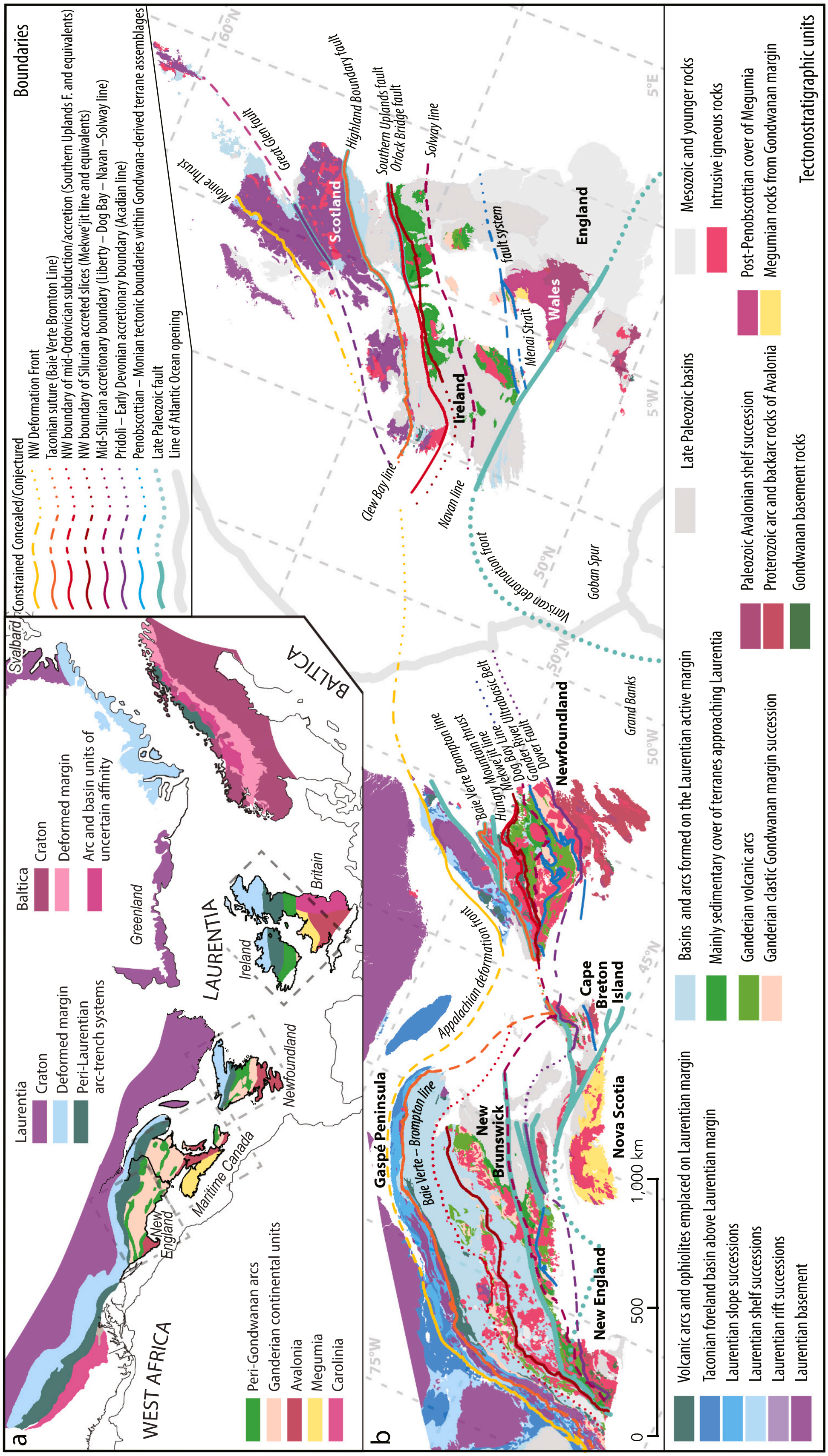

**Fig. 1.** (a) General map of the Appalachian–Caledonide Orogen restored in a Pangea reconstruction. Dashed lines outline Figs. 7 to 10. (b) Tectonic subdivisions and major boundaries in the northern Appalachian and western Caledonide orogens. F: Fault; I: Island; P: Peninsula; Z: Zone. (Barr and Raeside, 1989; Bluck et al., 1992; Hibbard et al., 2007; Fyffe et al., 2011; Ady and Whittaker, 2019; Waldron et al., 2019b). Colour palette based on Krzywinsky (2022).

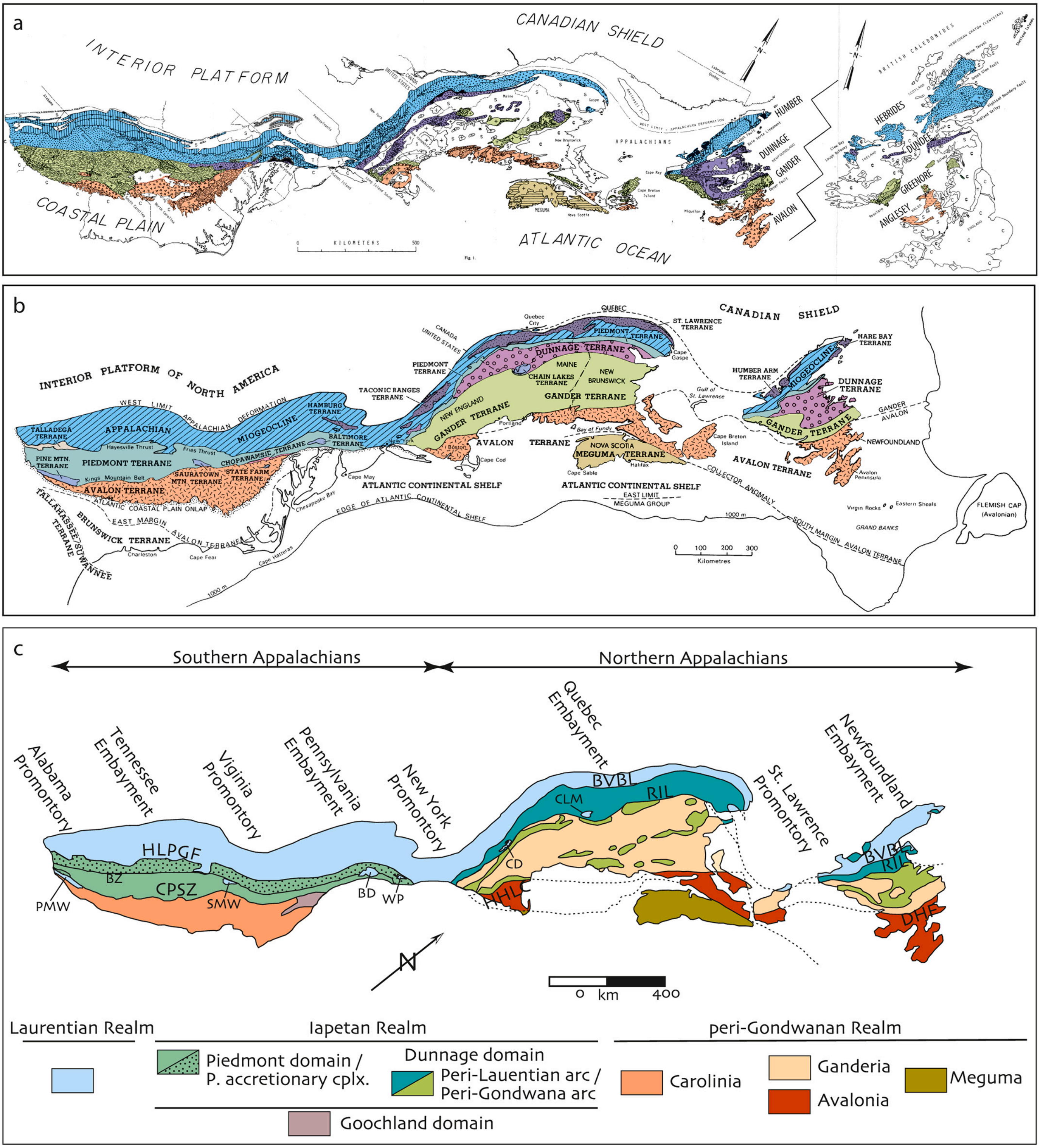

**Fig. 2.** Historical subdivisions of the Appalachian–Caledonide Orogen, at reduced size. See Supplementary Material for fine details. (a) Zonal subdivision of the northern Appalachians and western Caledonides after Williams (1978b, 1978a, 1979); colours added. (b) Terrane subdivision of the orogen proposed by Williams and Hatcher (1982, 1983); colours added. (c) Domain subdivision of the orogen by Hibbard et al. (2006, 2007). BD = Baltimore domes; BVBL = Baie Verte – Brompton line; BZ = Brevard zone; CD = Chester Dome; CLM = Chain Lakes massif; CPSZ = Central Piedmont shear zone. DHF = Dover – Hermitage Bay faults; HHLC = Honey Hill – Lake Char fault system; HLPGF = Hollins Line – Pleasant Grove fault system; PMW = Pine Mountain window; RIL = Red Indian line; SMW= Sauratown Mountains window; WP = Westchester prong.

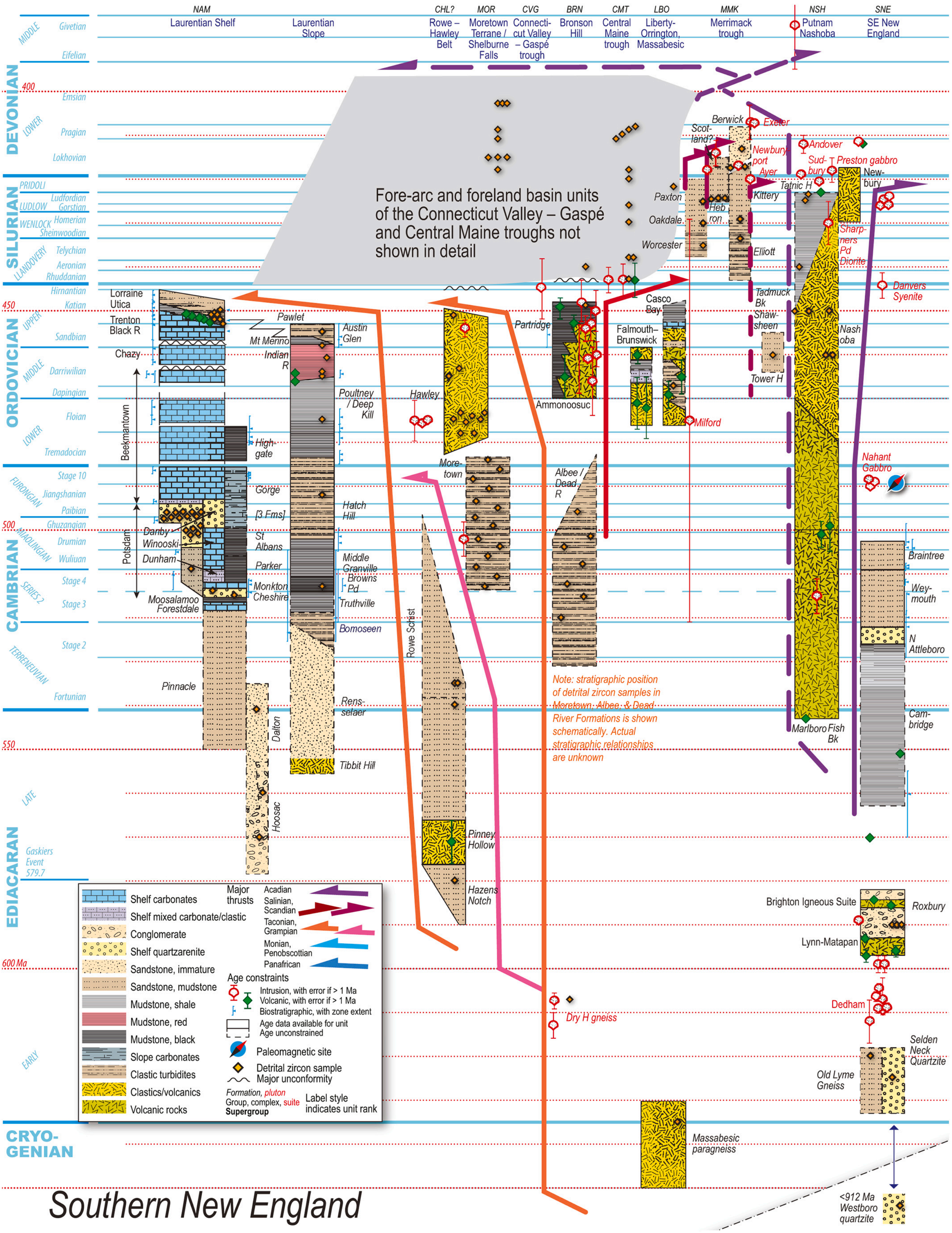

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**Fig. 3.** Representative stratigraphic columns for terranes in Southern New England showing stratigraphic position of available detrital zircon and paleomagnetic data points. Dashed borders indicate units with neither direct geochronologic nor biostratigraphic data. Formation names omitted where group names are available. Selected intrusion names designate granitoid rocks except where rock-type is named. Laurentian shelf and slope successions based mainly on Landing (Landing, 2007, 2012; Landing et al., 2009). Additional data sources, unit names, and sample identifiers are provided in the Supplementary Material. Abbreviations: B = Bay; Bk = Brook; Ck= Creek; Cv = Cove; H = Hill; Hd = Head; Hr = Harbour; Is = Island; La = Lake; L = Lower; Lt = Little; Mt = Mount, Mountain; Pd = Pond; Pt = Point; R = River; Rd = Road; St = Saint; U = Upper.

Gondwana has been named *Rheic* (Ziegler et al., 1977). Its closure occurred during the late Paleozoic Variscan (or Hercynian) Orogeny in central Europe. However, Avalonia does not extend into the southern Appalachian region, where the northern Iapetus and Rheic oceans connected into a larger oceanic area between composite Laurentia and Gondwana. This oceanic area, typically included in Iapetus (e.g. Robert et al., 2021), finally closed in the late Paleozoic Alleghanian Orogeny, approximately contemporary with Variscan convergence in Europe. Although the closure of the Rheic Ocean was directly connected with Alleghanian orogenesis in the southern Appalachians, and was linked with varied late Paleozoic tectonism in the northern Appalachians (e.g. Waldron et al., 2015), those late Paleozoic deformation episodes are mostly beyond the scope of this paper.

### 2.2. Zonal subdivisions of the orogen

Initial attempts to rationalize the complex and variable geology of the northern Appalachians focussed on the identification of *zones* of similar stratigraphy, comparable to the *isopic* (“same facies”) zones identified in the European Alpine orogens (e.g. Aubouin, 1965). The culmination of those efforts is arguably represented by the syntheses of Williams (1964, 1978b, 1979) that identified roughly orogen-parallel zones named *Humber, Dunnage, Gander, Avalon, and Meguma* (Fig. 2a). A parallel paper (Williams, 1978a) identified corresponding zonal names in Britain and Ireland, though these names were not widely used. These syntheses were supported by paleontological studies, particularly of shallow-marine groups such as trilobites and brachiopods, that showed faunal provinciality in the Paleozoic Era, allowing Laurentian faunas in the Humber Zone to be clearly distinguished from Acado-Baltic or Gondwanan faunas in the Avalon zone. Neuman (1984) examined faunas in the Dunnage zone and defined an intermediate, Celtic faunal province, thought to represent islands in the Iapetus Ocean. The Gander zone remained difficult to characterize biostratigraphically, because high metamorphic grades limited fossil finds to small areas. The preponderance of evidence, however, showed that the Gander zone originated far from Laurentia in the vicinity of Gondwana (e.g. van Staal et al., 1996).

### 2.3. Terrane concept

Following the introduction of the terrane concept in the North American Cordillera by Coney (1978) and Coney et al. (1980), Williams and Hatcher (1982, 1983) re-identified most of the zones as “suspect” terranes, to indicate their lack of clear stratigraphic linkage to the Laurentian margin (Fig. 2 b). However, the Humber Zone of Williams (1979) was not designated as a terrane because of its clear linkage to Laurentia, and was instead referred to as the *miogeocline*, a term proposed by Dietz and Holden (1966) based on the earlier *miogeosyncline* of pre-plate tectonic thought (e.g. Kay, 1951).

In the following years, zonal and terrane nomenclatures were sometimes used interchangeably, and in an influential report subdividing central Newfoundland, Williams et al. (1988) expressed a preference for the older style, identifying new subdivisions as “subzones” within the Dunnage and Gander zones of Williams (1979). However, subsequent publications (e.g. Dallmeyer, 1989; Nance and Thompson, 1996), recognized terranes in increasing numbers, many of which were in effect subdivisions of those enumerated by Williams and Hatcher (1982, 1983). Most authors in these volumes recognized the validity of the original broad divisions, using the modified terms *Ganderia* and *Avalonia* for the larger entities that included the smaller terranes such as *Gander, Meelpaeg, Avalon, and Mira,* establishing a somewhat confusing hierarchy of terranes within terranes.

### 2.4. Subdivisions based on isotopic data

During 1980s and 1990s, isotopic methods increasingly supplemented the original stratigraphic definitions of the zones and terranes. The larger-scale divisions identified by Williams (1979) and Williams and Hatcher (1982, 1983) were found to have distinctive Sm-Nd isotopic characteristics. The Humber zone or Laurentian margin, founded on Archean to Proterozoic rocks of the Laurentian craton (presently exposed in the Canadian Shield and the Caledonian NW foreland of Scotland) was shown to display highly evolved isotopic signatures, consistent with its heritage of Archean continental crust within the earlier supercontinent Rodinia (Patchett and Ruiz, 1989; Daly and McLelland, 1991). In contrast, Avalonia was shown to be characterized by juvenile isotopic signatures (Barr and Hegner, 1992; Nance and Murphy, 1994; Kerr et al., 1995), suggesting that, unlike most components of Pangea, it was not part of the earlier supercontinent Rodinia. Igneous rocks in Ganderia were found to be significantly more evolved than those in Avalonia, though less so than those in Laurentia (Kerr et al., 1995; Samson et al., 2000). Pollock et al. (2012) noted that basement sources beneath Ganderia are significantly less evolved than the clastic Paleozoic cover rocks, suggesting that it was built on ~1 Ga crust on which sediment derived from an older craton was deposited.

Lead and oxygen isotopes have also been used to differentiate domains within the orogen. (Ayuso et al., 1996; Potter et al., 2008a, 2008b). The Pb-isotopic compositions of feldspars in granitoid rocks in both Ganderia and Avalonia in the northern Appalachian Orogen are more radiogenic than plutons derived from Grenvillian sources (e.g. Ayuso et al., 1996). However, variations in the data suggest mixing of non-radiogenic with radiogenic sources. Depletion in $^{18}$O relative to $^{16}$O is characteristic of a large majority of the Neoproterozoic felsic igneous rocks of Avalonia. In contrast, this depletion is observed in very few Paleozoic Avalonian felsic igneous rocks, and also in very few of the felsic igneous rocks from the inboard Ganderian terranes. Potter et al. (2008a, 2008b) related the low-$^{18}$O character of the Neoproterozoic igneous rocks in Avalonia to regional alteration by predominantly meteoric–hydrothermal fluids during late Neoproterozoic transtension. It was postulated that the regional $^{18}$O-depletion can be used to distinguish Avalonia from other terranes exotic to Laurentia. On this basis Schofield et al. (2016) suggested that East Avalonia in Britain has closer affinities to Ganderia than West Avalonia.

Isotopic work on broadly ophiolitic rocks included in the original Dunnage zone of Williams (1979) showed that these rocks were not, as originally conceived, vestiges of Iapetan ocean floor formed at a central mid-ocean ridge; instead, these rocks are now known to represent almost exclusively supra-subduction environments analogous to arcs and backarc basins of the modern west Pacific (Swinden et al., 1997). Many contain either isotopic traces or actual remnants of attenuated Precambrian continental or arc basements, allowing Hibbard et al. (2006, 2007) to subdivide the former Dunnage zone (or terrane) into two portions characterized by peri-Laurentian and peri-Gondwanan arcs, corresponding respectively to the *Notre Dame* and *Exploits* subzones previously defined by Williams et al. (1988), and separated by a line (Fig. 1) here termed the *Mekwe'jit line* (White and Waldron, 2022) for a lake in Newfoundland (Indigenous name

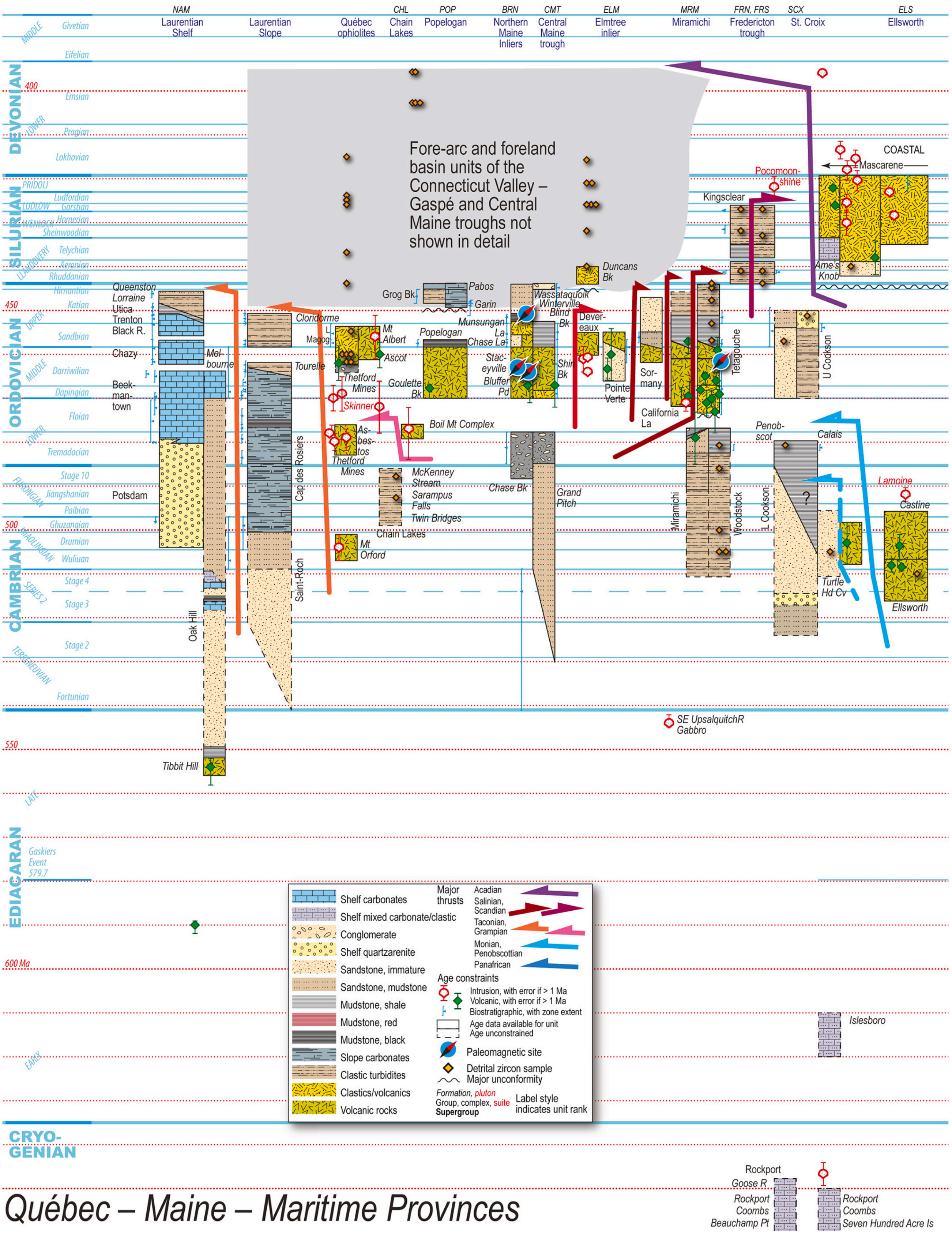


**Fig. 4.** Representative stratigraphic columns for terranes in Nova Scotia, New Brunswick, Maine, and adjacent Québec showing stratigraphic position of available detrital zircon and paleomagnetic data points. Abbreviations as Fig. 3. Data sources, additional unit names, and sample identifiers are provided in the Supplementary Material.

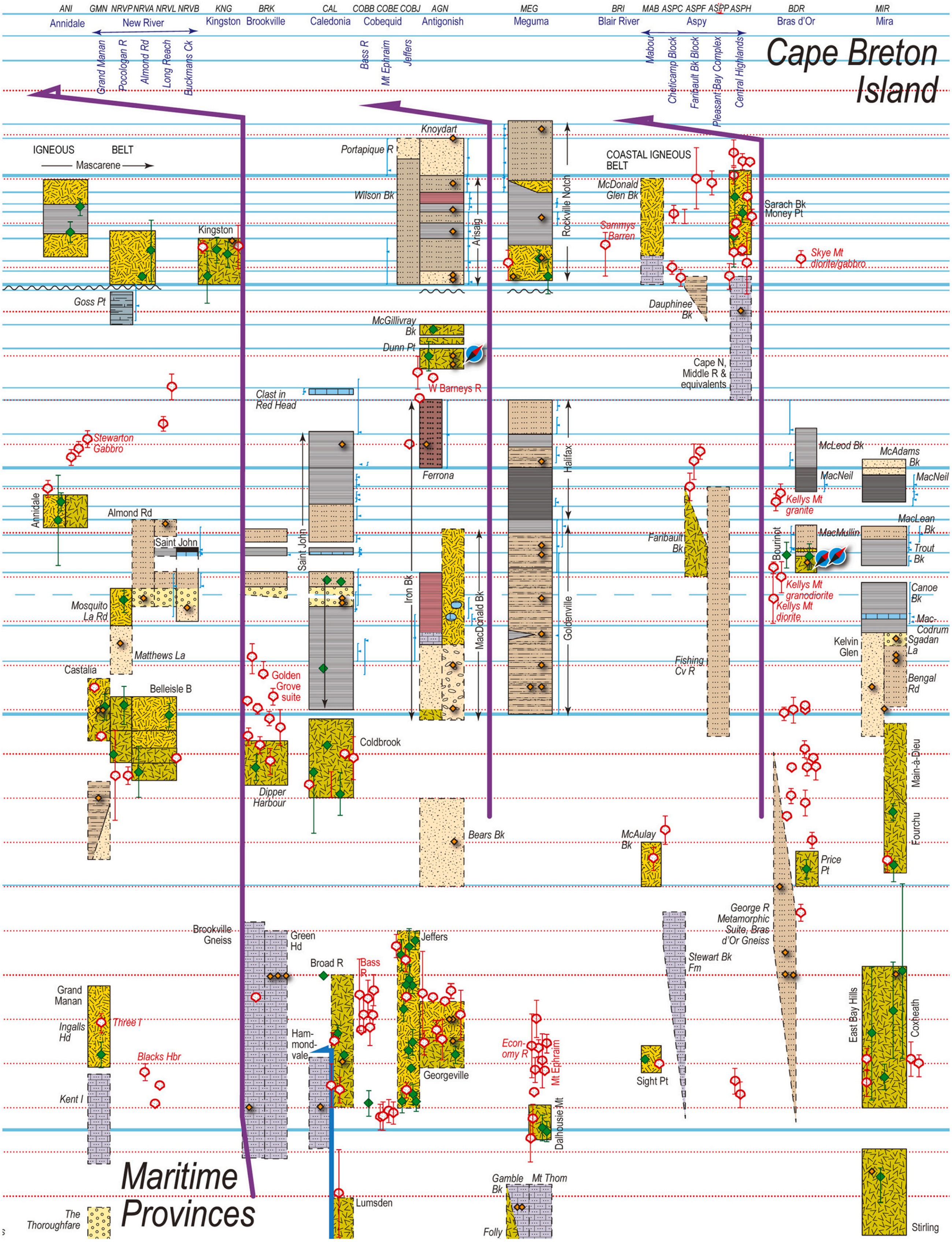


**Fig. 4.** (*continued*).

from Matthews and Robinson, 2018, previously Red Indian line or RIL), viewed as a fundamental suture separating terranes of Laurentian and Gondwanan origin.

### 2.5. Detrital zircon provenance studies

Large amounts of detrital zircon data produced since 2000 have revolutionized the treatment of sedimentary provenance. In the Appalachian–Caledonide Orogen, tectonic studies have taken advantage of fortuitously clear differences between sources in the major continents that surrounded the Iapetus Ocean. For example, detrital zircon populations from the Laurentian margin show a characteristic asymmetric peak at ~1.0 Ga associated with sources in the Grenville Orogen (Cawood et al., 2007; Cawood and Nemchin, 2001; Waldron et al., 2008; White et al., 2019; Kuiper and Hepburn, 2021). The Avalon terrane in Newfoundland is characterized by an abundance of Ediacaran arc volcanic rocks, hypothesized to form part of the *Pan-African* Orogen (O'Brien et al., 1983); these ages are clearly reflected in the detrital zircon characteristics of overlying sandstone units (Pollock et al., 2009). The Meguma terrane, long associated with West Africa (e.g. Schenk, 1971), shows a small but distinct component of zircon in the age range 1.95 – 2.2 Ga (Waldron et al., 2009). This age range is typical of the Eburnean Orogen (e.g. Lerouge et al., 2006; Schofield et al., 2006) of West Africa, although also found in parts of Baltica (Paszkowski et al., 2021) and South America (Santos et al., 2003) that lay adjacent to West Africa before breakup of the supercontinent Rodinia. Finally, sandstones from the Gander terrane and related units contain a broad distribution of Mesoproterozoic and Paleoproterozoic zircon consistent with an origin adjacent to Amazonia (van Staal, 1994; Fyffe et al., 2009; van Staal et al., 2012; Waldron et al., 2014a), although Bradley et al. (2015) showed that similar distributions are present in parts of West Africa that were adjacent to Amazonia prior to Atlantic opening. These observations have led to the characterizations of Ganderia, Avalonia, and Megumia as *peri-Gondwanan* (e.g. Hibbard et al., 2007). This term has been criticized because their positions were not "around Gondwana" (P. Karabinos, personal communication, 2020) throughout their history, and because included terranes may have originated nearer to Baltica (Landing et al., 2022). We retain it here for terranes that approached Laurentia from the general direction of Gondwana, while recognizing that this designation includes the possibility of an origin in or around adjacent parts of Baltica.

Some terranes show a change in detrital zircon provenance during their evolution. For non-Laurentian terranes, this change helps to time their departure from Gondwana (e.g. Pollock et al., 2009) or their arrival at Laurentia (Waldron et al., 2014a, 2019b). Using these data Waldron et al. (2019b) showed that first arrival of peri-Gondwanan terranes at the Laurentian margin was strongly diachronous. Hence the Laurentian-Gondwanan boundary is a composite boundary of many different ages drawn through an anastomosing network of faults developed at different times during subduction–accretion at the Laurentian margin, and only locally coincides with the Mekwe'jit line.

### 2.6. Hierarchy of tectonostratigraphic subdivisions

In their substantial reviews of Appalachian tectonostratigraphy, Hibbard et al. (2006, 2007) attempted to resolve confusion resulting from "terranes within terranes" by erecting a hierarchy of tectonostratigraphic subdivisions (Fig. 2 c) in both the northern and southern Appalachians. At the highest level, they recognized three *realms*, termed Laurentian, Iapetan and Gondwanan, which were further subdivided into *domains* corresponding roughly to the original zonal divisions (*Avalon, Gander* etc.) of Williams (1979; Williams et al., 1988), now referred to with their modified names (*Avalonia, Ganderia* etc.) popularized during the 1990s (e.g. Dallmeyer, 1989; Nance and Thompson, 1996). Waldron et al. (2011) added a domain *Megumia* to comprise the Meguma terrane and the Welsh basin, between which they identified close stratigraphic parallels during the Cambrian, when both were interpreted to lie on the Gondwanan margin. Within these domains, the numerous terranes identified during the 1980s and 1990s exist at a third, lowest level of the tectonostratigraphic hierarchy.

These publications have been effective at focussing discussion of terrane affinities in subsequent publications, although the term *domain* has not been as widely used; the larger entities Avalonia, Ganderia, and more recently Megumia, are still referred to as *terranes* in the literature since 2007. Terrane and domain names have been used interchangeably, as in the case of "Southeastern New England Avalonia" (e.g. Barr et al., 2011) or "Southeast New England Avalon terrane" (e.g. Kuiper et al., 2022). We now recommend that these usages be avoided, and that terrane-level subdivisions be referred to by local names (using expressions such as "Southeastern New England terrane", "Gander terrane"). The names Avalonia, Ganderia, and Megumia are best used for the interpreted broader paleogeographic domains on the Gondwanan margin from which the terranes were derived (Fig. 1).

### 2.7. Orogenic episodes

The nomenclature of orogenic episodes in the northern Appalachians also has a confusing history. Prior to ~1990, Ordovician (*Taconian* or Taconic), Devonian (*Acadian*) and Pennsylvanian-Permian (*Alleghanian*) episodes were recognized. In the Caledonides an Ordovician event, similar to the Taconian, was termed *Grampian*, while mild Middle Devonian deformation was termed *Acadian*. In Scandinavia, collision between Baltica and composite Laurentia occurred in the Silurian *Scandian* event. These episodes were mostly identified with continental collisions, and were regarded as separated by hiatuses during which mainly extension and basin subsidence occurred.

However, actualistic interpretations of orogenesis (e.g. van Staal et al., 1998) predict that over the length of an orogen, convergence and collision are likely to be diachronous; at any given time, deformation is likely to be taking place at some location in a developing orogen. Division of the tectonic history into discrete orogenic episodes tends to break down, therefore, when episodes are correlated outside their areas of definition. Taconian deformation, initially defined as Late Ordovician in the Taconic mountains of New York, was recognized to include progressively earlier episodes extending back into the Cambrian (Waldron and van Staal, 2001; van Staal et al., 2007). The term Acadian evolved through time to include Silurian and Mississippian events in different parts of the orogen. Increasing recognition of Silurian deformation, metamorphism, and syntectonic plutonism in Newfoundland led to the recognition of the Salinic, or *Salinian*, Orogeny (Dunning et al., 1990a; Cawood et al., 1994) initially defined in the late Ludlow to Gedinnian (Boucot, 1962) but extended to include most of the Silurian (e.g. van Staal et al., 2008). In an attempt to rationalize terminology, Robinson et al. (1998) restricted the Acadian Orogeny to ca. 420–385 Ma, encompassing approximately the latest Silurian to the Middle Devonian. Later deformation, from 366 to 350 Ma, was distinguished as Neo-Acadian, but Robinson later proposed the name *Quaboagian* for this episode (Robinson, 2003).

Because of the difficulty of correlating temporal episodes laterally within a diachronously evolving orogen, orogenic pulses have in some cases been re-defined based on an inferred tectonic process. Thus van Staal (2005) equated the Acadian Orogeny with the accretion of west Avalonia to North America, and attributed the Neo-Acadian to the accretion of the Meguma terrane. However, deformation in the Meguma terrane that is commonly assumed to have been associated with its accretion was dated by Hicks et al. (1999) at 395-388 Ma, well within the time interval recognized as Acadian in New England (Robinson et al., 1998; Bradley et al., 2000), so this sense of "Neo-Acadian" differs from the original definition by Robinson et al., which referred to deformation from 366–350 Ma. The relationship of the deformation, metamorphism, and plutonism in the Meguma terrane to the classical Acadian Orogeny in New England remains enigmatic (van Staal, 2005; van Staal et al., 2009; White and Barr, 2012)

In the following account, we attempt to use these terms in a manner that preserves their original definitions, using tectonic interpretations only where we see a consensus in the published literature. We prefer endings *-ian* rather than *-ic* for consistency with *Acadian*, and to avoid confusion with specific locations and rock units such as the Taconic allochthon in the Taconic Mountains of southern New England.

In our approach, *Taconian* encompasses Furongian to Katian, primarily west-vergent deformation that affected the margin of Laurentia. *Salinian* refers to Katian to Ludfordian east-vergent deformation associated with subduction beneath the composite Laurentian margin. In the northern Caledonides, deformation during this interval culminated in the Wenlock with continent–continent collision, a much shorter-lived but more intense deformation event termed the *Scandian* Orogeny. The Scandian collision produced a bivergent orogen and resulted in west-vergent thrusts in the Greenland Caledonides and in NW Scotland. In the British sector it accounts for an influx of Laurentia-derived zircon into peri-Gondwanan northern England. *Acadian* refers to deformation and metamorphism during the Přídolí to Middle Devonian interval that most obviously affects large parts of New England, but which is also recorded in some areas to the NE. The major Acadian thrusts and folds are NW-vergent but the polarity of subduction that led to Acadian deformation is in doubt, as will be discussed further below.

Deformation that led to major dextral strike-slip motion and transtension in the Maritime provinces of Canada during the Devonian and Mississippian probably occurred at a releasing bend on a roughly orogen-parallel strike-slip system (Hibbard and Waldron, 2009), and may have been related to dextral transpression in southern New England (Massey et al., 2017) that gave rise to major crustal thickening, termed Neo-Acadian by Robinson et al. (1998) or Quaboagian by Robinson (2003). Because of confusion with the earlier deformation and metamorphism in the Meguma terrane, we simply refer to this deformation in Atlantic Canada as *Devono-Carboniferous*. *Alleghanian* (Permian) deformation, associated with the final assembly of the supercontinent Pangea, is prominent in the southern Appalachians but is significant mainly in the southernmost part of the area considered in this review, mainly in Connecticut and Massachusetts (e.g. Wintsch et al., 2014), although Permian granites extend into western Maine (Hibbard et al., 2006).

Other orogenic episodes are recognized within the orogen and did not affect the Laurentian margin along its NW boundary. A regional unconformity in Early Ordovician peri-Gondwanan rocks of northern Maine records a *Penobscottian* Orogeny (Neuman, 1967; Neuman and Max, 1989). Although this took place concurrently with the Taconian Orogeny on the Laurentian margin, its position amongst peri-Gondwanan terranes has led most recent authors to interpret it as a separate event involving subduction on the opposite side of the Iapetus Ocean (e.g. van Staal et al., 2012). However, Waldron et al. (2014a) suggested that the two convergent systems were linked via a single, highly sinuous plate boundary analogous to that bounding the modern Caribbean Plate.

A localized zone of high strain and contrasting metamorphism occurs in Anglesey, North Wales, leading to the definition of the *Monian* Orogeny, originally interpreted to have occurred in the Neoproterozoic. However, identifications of trace fossils, together with increasingly abundant detrital zircon data, have shown that some of the rocks involved are Cambrian (McIlroy and Horak, 2006). The deformation is now known to be early Paleozoic (Schofield et al., 2020). An upper limit to the deformation is provided by a Floian overstep sequence, suggesting that most of the Monian deformation occurred at around 480 Ma, simultaneously with Penobscottian deformation in the northern Appalachians.

Still earlier episodes of deformation affected several peri-Gondwanan terranes during the Ediacaran, producing multiple unconformities, typically in association with voluminous arc-related intrusive and extrusive rocks. Local blueschists and other high-pressure low-temperature metamorphic rocks (White et al., 2001; Schofield et al., 2020) suggest that both lower-plate and upper-plate settings were preserved. Some authors have related these convergent events to an *Avalonian* Orogeny related to *Pan-African* orogenic events more widely recorded in Gondwana (e.g. Hughes, 1970; O'Brien et al., 1983). Therefore the "Avalonian Orogeny" was not confined to the domain "Avalonia", and this terminology causes ambiguity when rocks are described as "Avalonian". We suggest that the term "Avalonian" be restricted to the paleogeographic domain, and simply use the term *Ediacaran* to describe these convergent orogenic events in peri-Gondwanan terranes.

Some older orogenic events show up as major peaks in distributions of detrital zircon that we review. We use the term *Grenvillian* to refer to events between 1.2 and 0.9 Ga that affected Laurentia, and the term *Eburnean* to describe events between 2.2 and 1.95 Ga in West Africa.

## 3. Methods

In the account that follows, we examine three principal lines of evidence for terrane affinities: stratigraphic, isotopic, and paleomagnetic.

### 3.1. *Stratigraphy*

Originally, zones and terranes in the Appalachians and Caledonides were defined stratigraphically, and many syntheses have portrayed numerous stratigraphic columns to display similarities and dissimilarities between terranes in different parts of the orogen (e.g. Kennedy, 1979; Keppie, 1993; Berry and Osberg, 1989; Landing, 1996; van Staal et al., 2020, 2021). The applicability of such diagrams in earlier studies was limited by lack of correspondence between isotopic and biostratigraphic timescales, which has improved greatly since 2000. In this paper we have constructed a new summary of representative stratigraphic columns (Figs. 3–6) for the principal terranes, replotting, where necessary, original biostratigraphic data so that they are correctly placed on a consistent numerical timescale, in order to relate them to isotopic ages from igneous and metamorphic units. In orogenic settings, facies belts migrate over time, resulting in diachronous lithological units. This effect is particularly apparent in the migration of foredeep shale and sandstone across the Laurentian margin (Bradley, 1989; Bradley et al., 2000; White and Waldron, 2022). In areas where few fossils are available, authors have tended to extrapolate ages determined from single fossil finds over large areas based only on lithology; a prime example is the Partridge Formation of the Bronson Hill terrane in New England (Fig. 7), which is clearly diachronous (see section 5.2.2.1). We are careful to use biostratigraphic data only in the immediate areas where samples were collected. We have added symbols showing major convergent tectonic deformation episodes that may have juxtaposed terranes. To keep the review manageable, we focus on the central portion of the orogen, from southern Connecticut to eastern Britain (Figs. 7–10).

In compiling stratigraphic information, we have made use of the biostratigraphic schemes and geochronologic ties laid out by Gradstein et al. (2012; summarized by Cohen et al., 2013, 2021) hereinafter referred to as GTS2012. Boundaries in the recently published GTS2020 match those in GTS2012 within 2.2 Myr, the largest discrepancy being the lower boundary of the Darriwilian Stage (Middle Ordovician) which is shown at 467.3 Ma in GTS2012 but 469.42 Ma in GTS2020.

While there is considerable confidence in the correspondences between biostratigraphic zones and geochronologic ages for the Ordovician and Silurian periods, there is less so for the Cambrian. In addition, Cambrian biota were highly provincial, and GTS2012 does not illustrate the zonal schemes most applicable to many terranes in the Appalachian–Caledonide system. We therefore use Geyer (2020) and GTS2020 as supplements to GTS2012 in matching Cambrian biostratigraphy to a numerical time scale. Geyer noted a number of new geochronologic tie points that were not available to GTS2012. These points reveal that the numerical estimate of the boundary between Cambrian Series 2 and 3 (Miaolingian) may be considerably younger than estimated in GTS2012 (~505 rather than 509 Ma). We anticipate

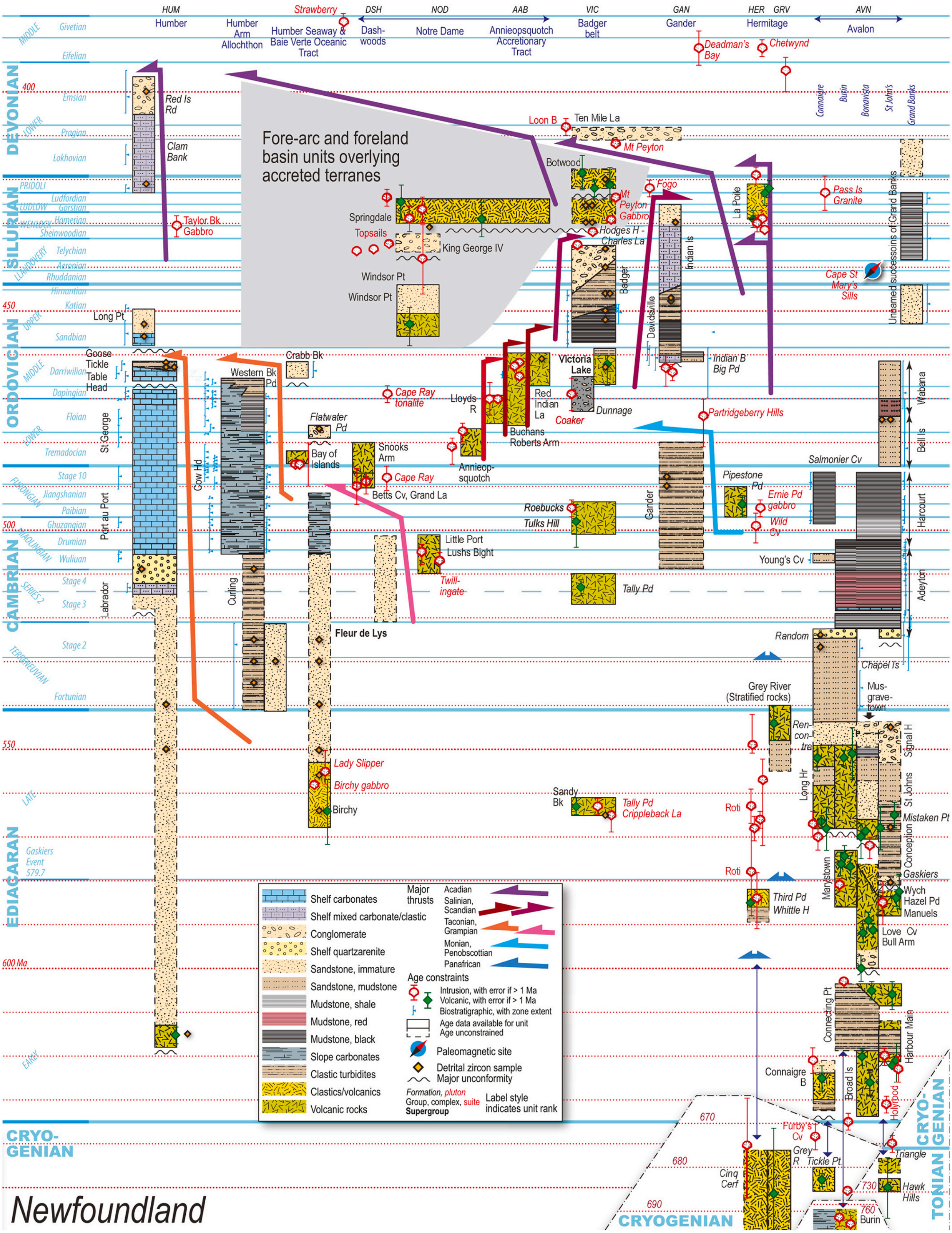


**Fig. 5.** Representative stratigraphic columns for terranes in Newfoundland showing stratigraphic position of available detrital zircon and paleomagnetic data points. Abbreviations as Fig. 3. Data sources, additional unit names, and sample identifiers are provided in the Supplementary Material.

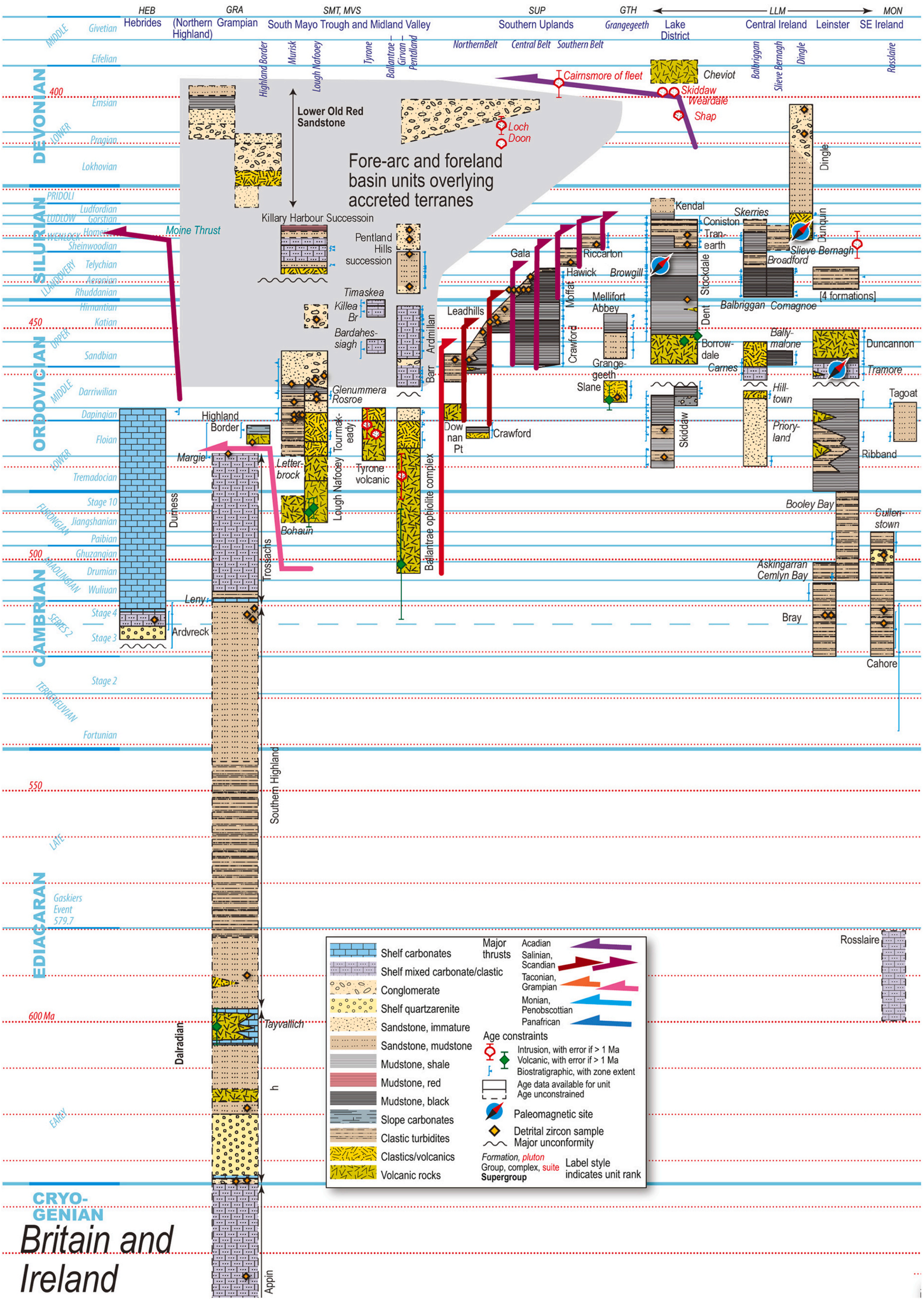


**Fig. 6.** Representative stratigraphic columns for terranes in Britain and Ireland showing stratigraphic position of available detrital zircon and paleomagnetic data points. Abbreviations as Fig. 3. Data sources, additional unit names, and sample identifiers are provided in the Supplementary Material.

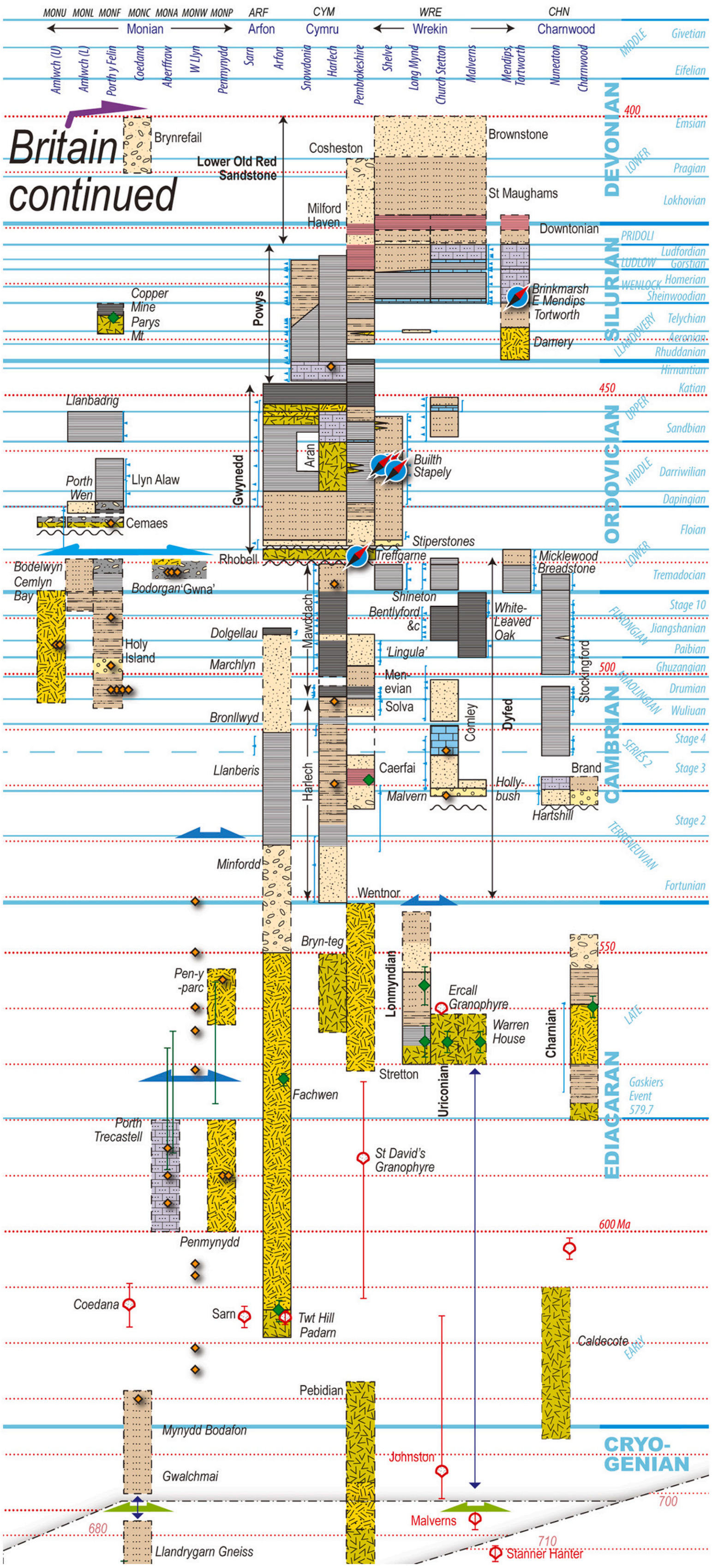


Fig. 6. (continued).

that biostratigraphically constrained sedimentary units shown in Figs. 3–6 may eventually need adjustment, extending the time allotted to Series 2 units, and shrinking the Miaolingian, relative to the numerical time scale.

### 3.2. Isotopic data

In the years since the first terrane-level subdivisions of the Appalachians and Caledonides were published (e.g. Williams and Hatcher, 1982, 1983; Bluck et al., 1992), isotopic data have become increasingly precise and more important in the terrane analysis of the orogen. We

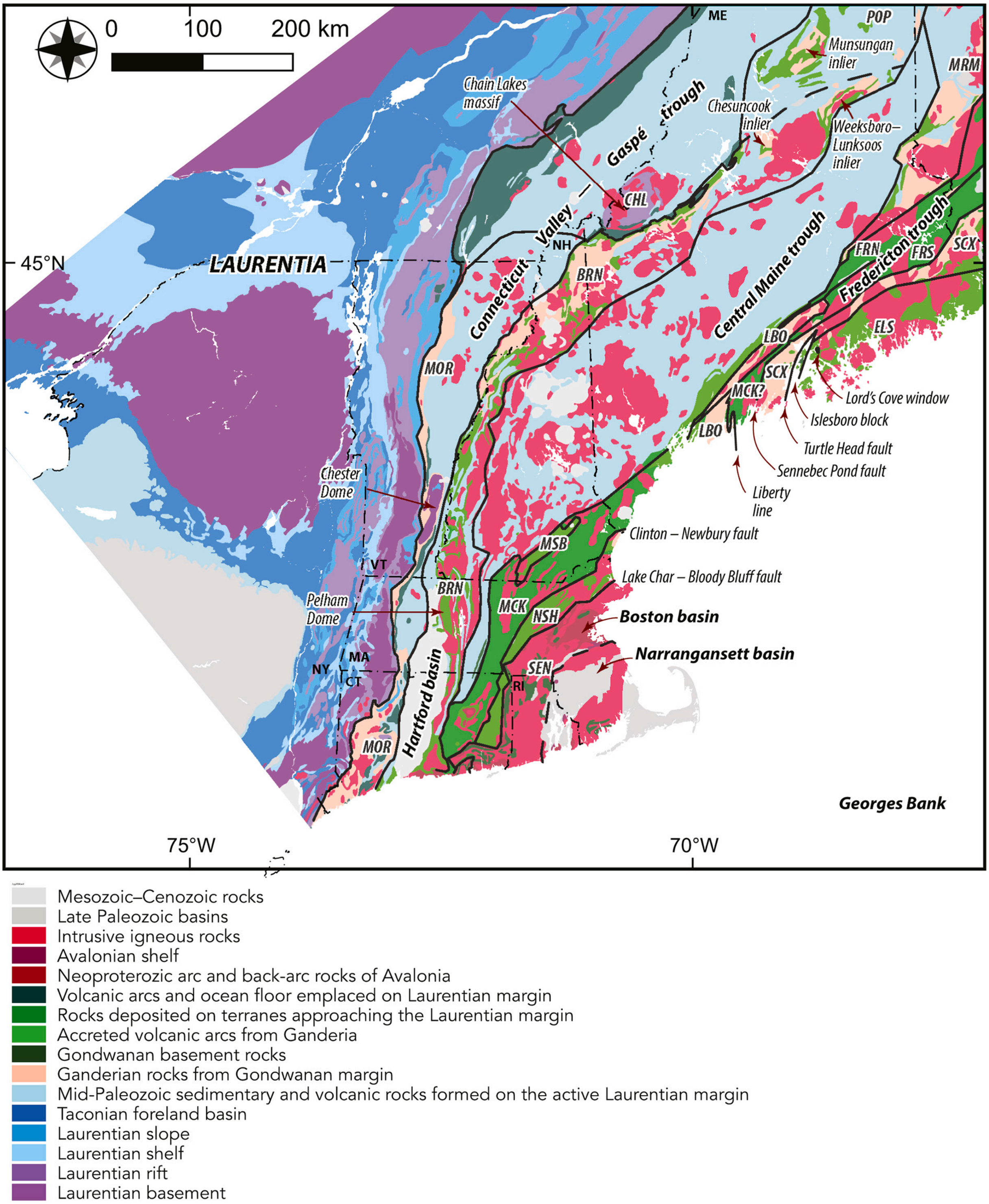


**Fig. 7.** Appalachians of New England and adjacent parts of Canada. (a) Tectonostratigraphic subdivisions, boundaries and terranes. Terrane abbreviations are defined in Table 3. (b) Available detrital zircon data as pie charts with areas proportional to number of analyses. Available paleomagnetic orientations show direction of interpreted south pole. Data sources are listed in the Supplementary Material. Geological map base after Hibbard et al. (2006). State abbreviations: CT = Connecticut; MA = Massachusetts; ME = Maine; NH = New Hampshire; NY = New York; RI = Rhode Island; VT = Vermont.

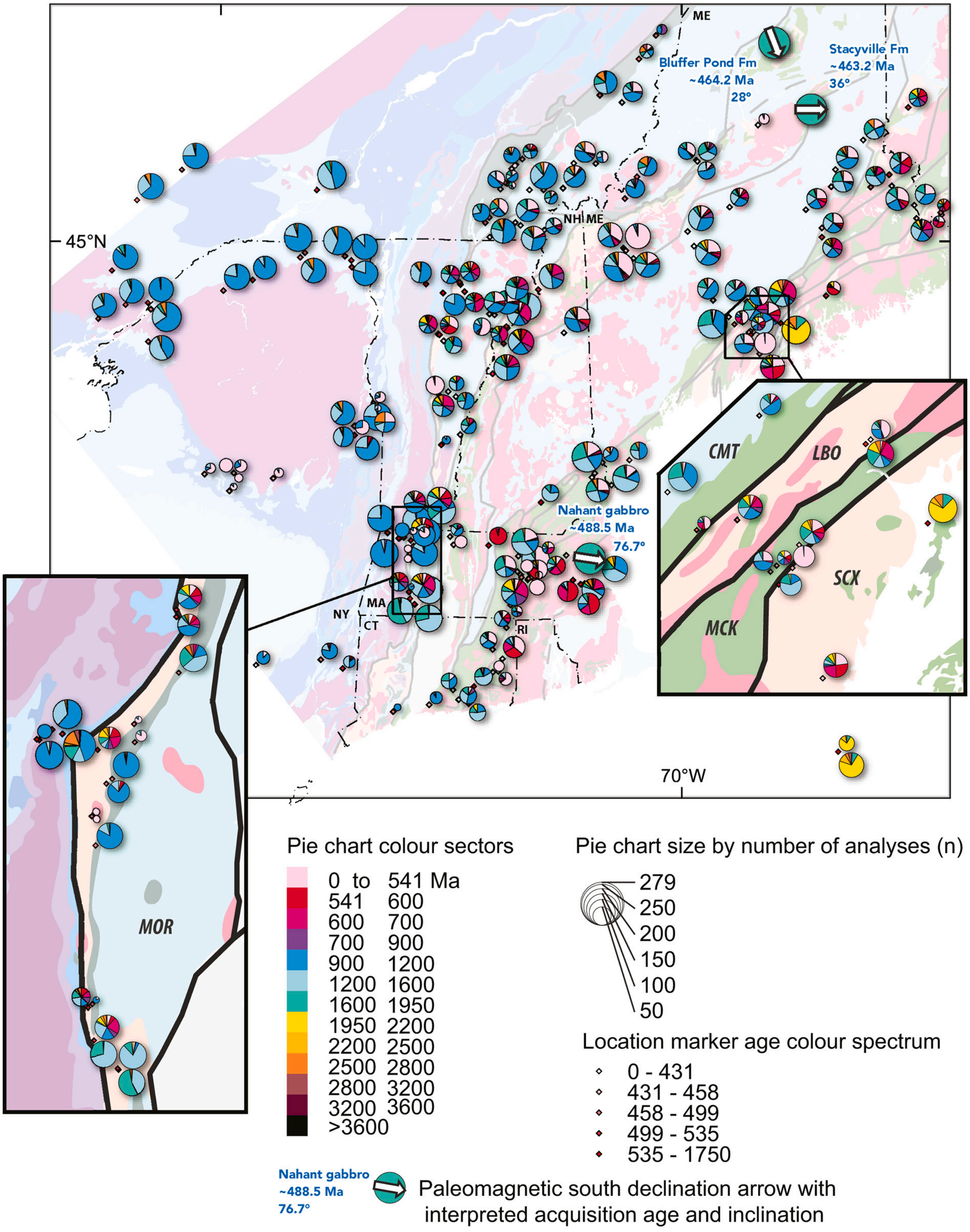


**Fig. 7.** (*continued*).

focus on the large amounts of detrital zircon provenance data that have become available for the northern Appalachians and western Caledonides in the last 20 years. Data prior to 2016 were reviewed by Waldron et al. (2019b); however, that paper focussed on the Ordovician to Silurian accretionary history of terranes against the Laurentian margin, neglecting samples with early Cambrian (Series 1-2), Precambrian, or unknown depositional ages. We have not tabulated or re-evaluated other forms of isotopic data (e.g. $\varepsilon_{Nd}$, $\varepsilon_{Hf}$, Pb isotopes) but have reported the conclusions of the more recent results in these areas.

New detrital zircon data appear frequently. For this paper we have tabulated data from locations the northern Appalachians and Caledonides of Britain and Ireland with publication dates up to mid-2021.

These data are provided in the Supplementary Material. Newer data that became available during the writing and review process will be referred to in passing. It is our hope to build an ongoing publicly accessible database in order to supplement the data provided here with new results as they become available.

Detrital zircon data are collected with varied instruments and published using different protocols for the selection of analytical results. Where possible we have returned to the original data tables attached to published papers, but we have not attempted to correct for the different data integration protocols, standards, or assumptions used by the original authors. However, we impose a common threshold for concordance (±10%) in place of the varied criteria in the literature. Because of the different decay constants of $^{235}$U and $^{238}$U, $^{206}$Pb/$^{238}$U ages show higher precision for younger grains whereas $^{207}$Pb/$^{206}$Pb ages are more precise

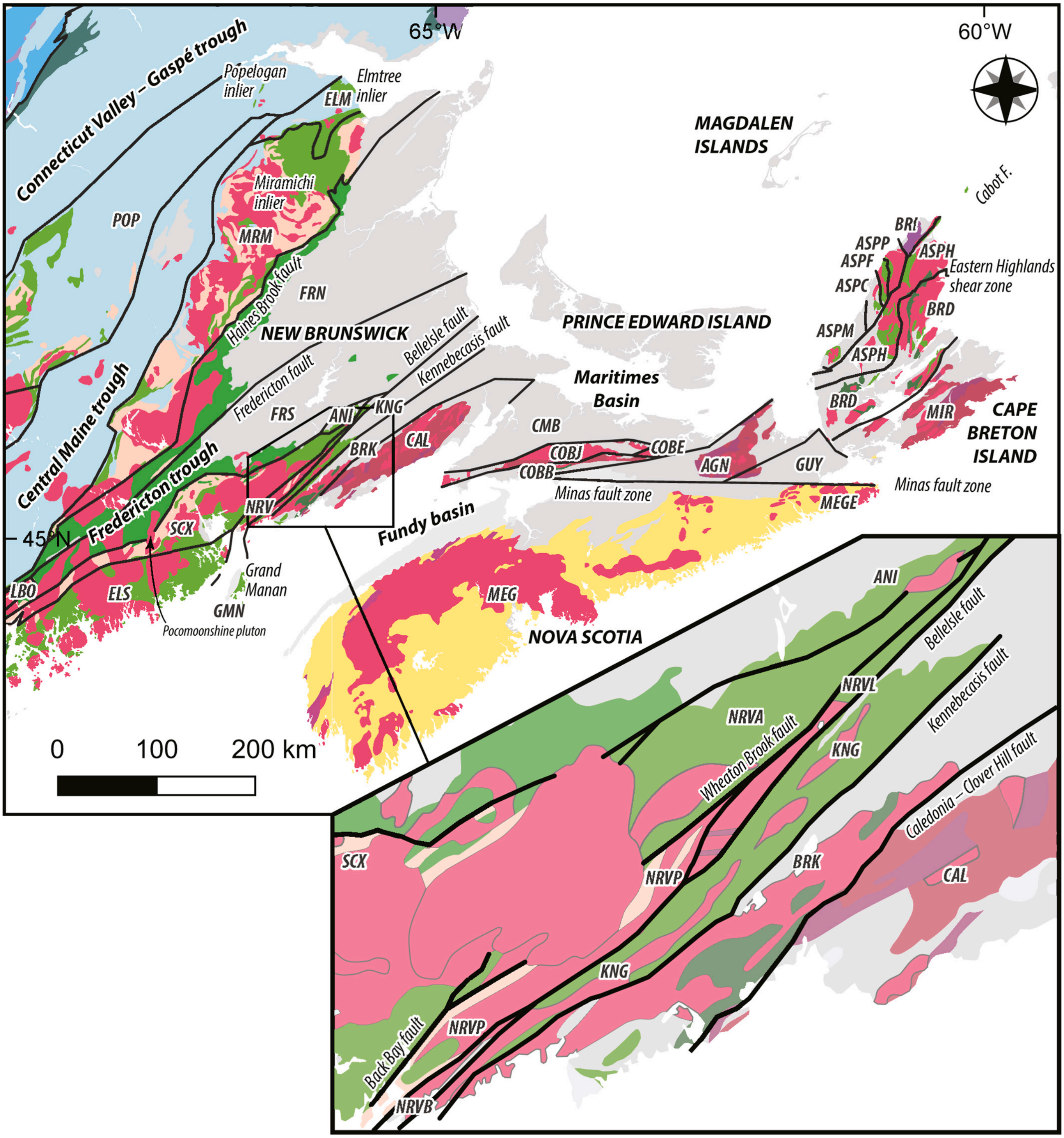


**Fig. 8.** Appalachians of Maritime Canada and adjacent Quebec. (a) Tectonostratigraphic subdivisions, boundaries and terranes. Terrane abbreviations are defined in Table 3. (b) Available detrital zircon data as pie charts with areas proportional to number of analyses. Legend as Fig. 7. Available paleomagnetic orientations show direction of interpreted south pole. Data sources are listed in the Supplementary Material. Geological map base after Hibbard et al. (2006).

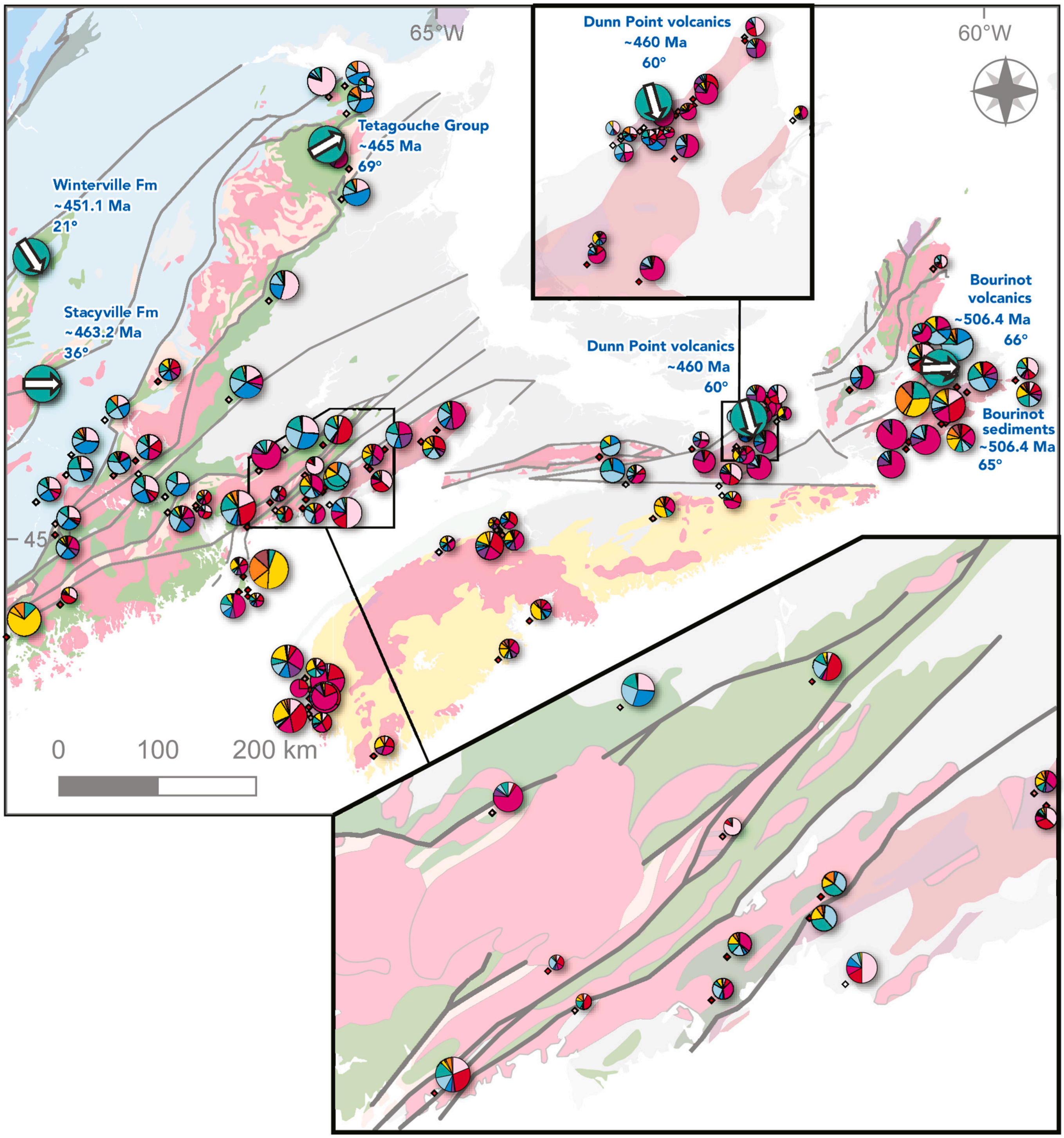


**Fig. 8.** (*continued*).

for older grains. Because of this difference, authors have inconsistently imposed arbitrary changeover ages between the two isotopic systems when plotting, potentially creating a break in the distribution when data are slightly discordant. To avoid this artifact, we have selected $^{207}Pb/^{206}Pb$ vs. $^{206}Pb/^{238}U$ ages based on whichever exhibits the higher analytical precision (lower uncertainty) in the original authors' data tables. In plotting the results, we show kernel density estimates (KDE) with bandwidth of 20 Ma based on the typical standard error of the least precise analyses, using the software IsoplotR (Vermeesch, 2018).

In addition to these standard methods, we have devised plots that bring out the distinctive characteristics of zircon derived from potential source areas on the continental blocks surrounding the Iapetus Ocean. To do this we first sorted the detrital zircon data into age bins reflecting potential source areas in surrounding cratons (Table 1).

Once binned, it is possible with geographic information systems to automate the display of detrital zircon populations as pie charts at their geographic locations (Figs. 7–10) supplementing traditional presentations in a way that illustrates their spatial relationships.

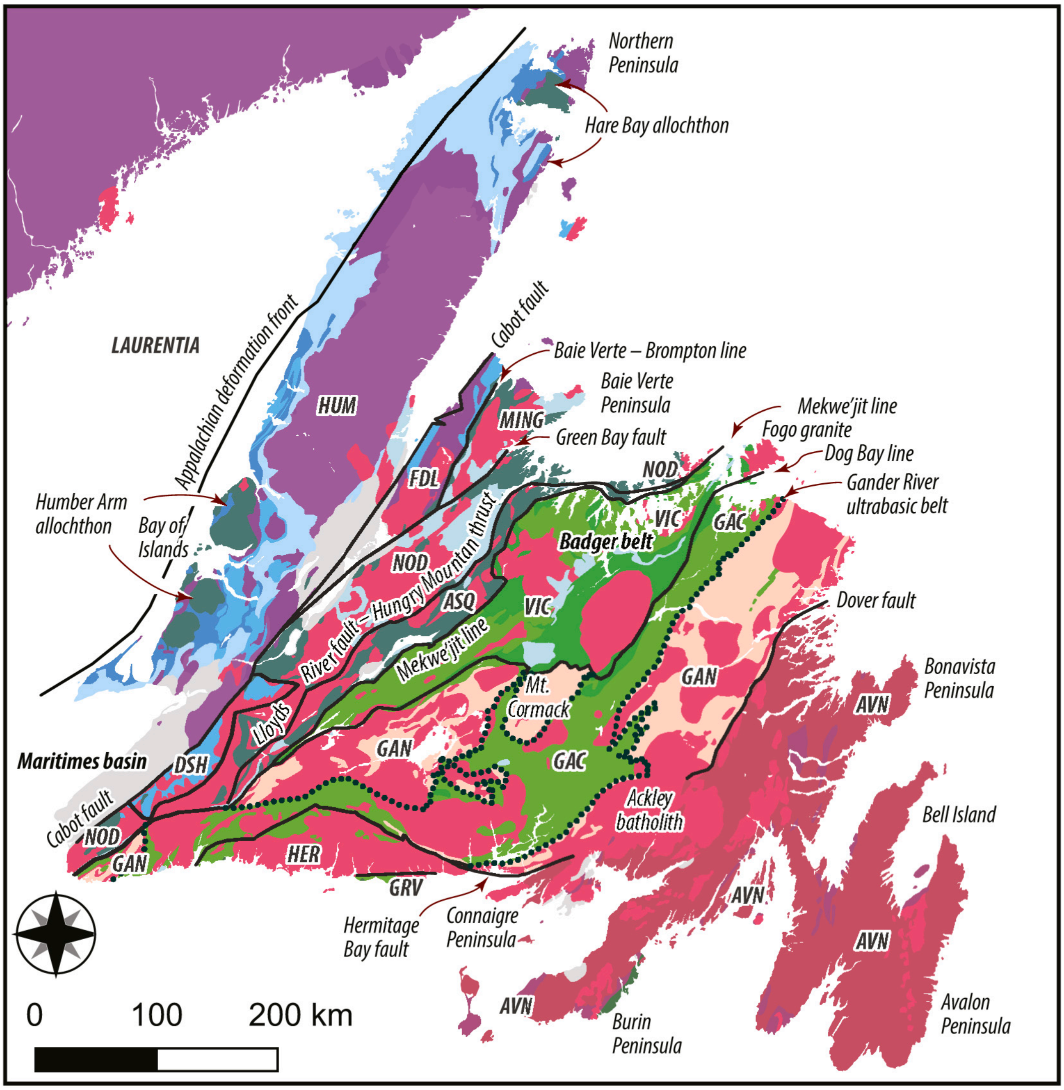


**Fig. 9.** Appalachians of Newfoundland. (a) Tectonostratigraphic subdivisions, boundaries and terranes. Terrane abbreviations are defined in Table 3. (b) Available detrital zircon data as pie charts with areas proportional to number of analyses. Legend as Fig. 7. Available paleomagnetic orientations show direction of interpreted south pole. Data sources are listed in the Supplementary Material. Geological map base after Hibbard et al. (2006)

Populations sourced from Laurentia (e.g. Cawood et al., 2007; Kuiper and Hepburn, 2021) typically have abundant zircon derived from the Grenville Orogen (bin E) whereas those sourced from West Africa (e.g. Bradley et al., 2015) typically show abundant zircon in the Ediacaran and mid-Paleoproterozoic (bins B, C, & H). Amazonian sources, prominent in the domain Ganderia (van Staal et al., 1996, 2012, 2021) are thought to be characterized by older Mesoproterozoic (bins F & G) zircon derived from sources from the orogens in the pre-Rodinian Nuna supercontinent. Compilation maps (Figs. 7–10) all show a clear across-strike transition from predominantly Laurentian sources in the NW to predominantly Gondwanan sources in the SE.

In addition, GIS (geographic information system) software allows the detrital zircon data sets to be imported into the plate-reconstruction software Gplates (Müller et al., 2018), where, once assigned to a plate ID, they can be moved around the globe with geographic features in paleotectonic reconstructions. Once exported, the detrital zircon data may be displayed in reconstructed positions to test hypotheses for the proximity of terranes to potential sources at different times.

Extracting these data and compiling them into a common format is a somewhat repetitive task. We have therefore made the compiled data tables available in the supplementary data, so that other types of analysis may be accomplished by future researchers. We encourage others to cite the original sources of these data, in addition to our compilation, in making use of them.

### 3.3. Paleomagnetism

Paleomagnetic data have been important in attempts to unravel the history of the Iapetus Ocean since it was first proposed (Deutsch, 1969; Briden et al., 1973; Van der Voo, 1993). Because individual paleomagnetic results provide no information on paleolongitude (Van der Voo, 1993; Steinberger and Torsvik, 2008; Wu et al., 2017), interpretations have mainly focussed on paleomagnetic inclinations as measures of paleolatitude. Based on compilations of paleomagnetic results, many authors (e.g. Channell et al., 1993; Potts et al., 1993; Mac Niocaill, 2000; van Staal et al., 2012) have interpreted the change in paleolatitudes of terranes as a record of their dominant northward component of drift with respect to Baltica and the Laurentian margin, which was oriented

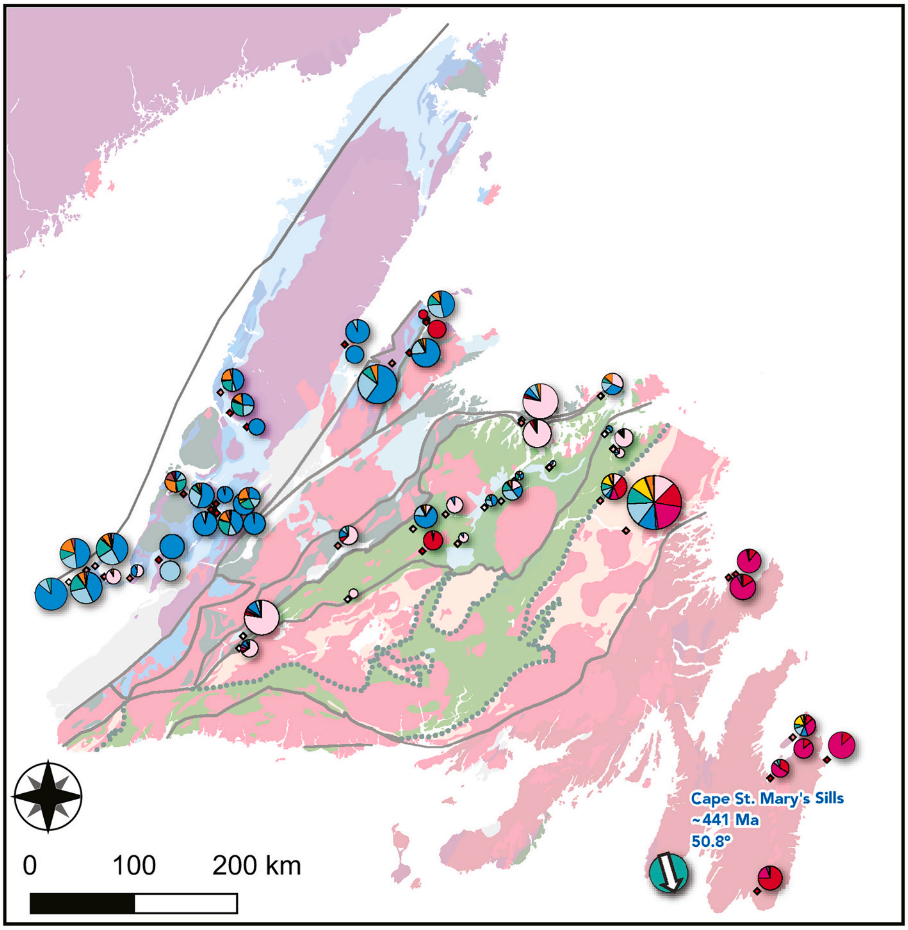


**Fig. 9.** (*continued*).

roughly east–west near the equator for much of the early Paleozoic Era (Cocks and Torsvik, 2011; Domeier, 2016; Wu et al., 2022). However, paleomagnetic data also include declinations, which record net vertical-axis rotations since the acquisition of stable magnetic remanence. Many data from Appalachian–Caledonide terranes show evidence of such rotations; many publications have presented these declinations as paleosouth-seeking arrows (e.g. Figs. 7–10), but have attributed relative rotations between results to local fault activity, without regard for the presence of suitable faults. We believe that these data contain potentially useful information about the extent and timing of larger-scale terrane rotations, and we attempt to interpret them here.

As more units were sampled for paleomagnetic work from the 1970s onwards, there have been marked improvements in paleomagnetic techniques in the laboratory and in the understanding of the behaviour of remanence-carrying minerals, including the recognition of widespread chemical remagnetization of Paleozoic rocks (e.g. Butler, 1992; Van der Voo, 1993; Elmore et al., 2012) and of compaction-induced inclination shallowing of the primary remanence in fine-grained clastic sedimentary rocks (Anson and Kodama, 1987; Hodych and Bijaksana, 1993; Tan and Kodama, 2003). We have compiled paleomagnetic results from constituent Iapetan terranes of the northern Appalachians and Caledonides, taking this opportunity to re-evaluate the evidence for the age of the remanence in light of revised biostratigraphic control. A compilation of published paleomagnetic results is given in Table 2; individual entries are discussed below in reference to their respective host terranes. Paleomagnetic results are herein assigned a reliability index (R $\leq 7$) based on the scheme of Meert et al. (2020), which, in recognition of advances in paleomagnetic techniques and analysis over 30 years, was modified from the widely used quality index introduced by Van der Voo (1990) and Van der Voo (1993). In particular, reliability criterion #5 (structural control) for each published result is evaluated with respect to the host terrane: can the result be considered to adequately represent the terrane as a coherent unit? This question has relevance for the consideration of paleomagnetic declination data, and will be discussed case-by-case below.

For the positions of the major continents we have used the apparent polar wander paths and rotations of Wu et al. (2021), with longitudes (unconstrained by paleomagnetic data) modified to accommodate migration of the many terranes within the Iapetus Ocean. However, during the Ordovician, a time of poor control on the position of Laurentia, we have moved Laurentia 10° towards the equator in a manner that follows the paleomagnetic arguments and model of Swanson-Hysell and Macdonald (2017), to accommodate the paleomagnetically determined latitudes of Appalachian terranes.

### 3.4. Post-Devonian deformation

Many plate-tectonic reconstructions of the northern Appalachian–Caledonide system work backwards from "Pangea" reconstructions showing the inferred positions of the major modern continental elements prior to Atlantic opening. However, differences among published reconstructions, although of minor significance at global scale, are critical for pre-Pangea Appalachian–Caledonide relationships. Many of these reconstructions make the tacit assumption that late Paleozoic and early Mesozoic deformation was negligible, but abundant seismic and gravity data make clear that the Mesozoic continental margins were substantially stretched before Atlantic opening (e.g. Welford et al., 2012; Ady and Whittaker, 2019); such stretching should be restored before attempting to explain the kinematics of the Appalachian–Caledonide Orogen. Prior to Mesozoic stretching, the late Paleozoic history of the orogen also included major strike slip, combined with episodes of extension and shortening (e.g. Murphy et al., 2011; Waldron et al., 2015), that are in general much less well constrained than those involved in pre-Atlantic stretching. To account for these motions, we use the Mesozoic reconstruction of Ady and Whittaker (2019), because it restores stretching of the Mesozoic continental margins, and the maps of Waldron et al. (2015), modified to present motion of a spherical surface using GPlates (Müller et al., 2018), so as to build a possible mid-Devonian reconstruction (Fig. 11) for use as an end-point. We stress that this reconstruction is just one of a range of possibilities consistent with present data on the late Paleozoic and Mesozoic history of the region. However, any tectonic reconstruction that ignores these post-Acadian relative motions is necessarily incorrect.

### 3.5. The terrane parade

The principal characteristics used to define, classify, and track terranes in previous work on the orogen have been: (i) the stratigraphic character of cover successions, mainly Cambrian, together with the nature of associated igneous and metamorphic rocks (e.g. Williams, 1979; Kennan and Kennedy, 1983; Landing, 1996); (ii) the progress of units across the Iapetus Ocean, using mainly paleomagnetic and faunal evidence from Ordovician and Silurian strata (e.g. Neuman, 1984; Mac Niocaill et al., 1997; van Staal et al., 2012; Waldron et al., 2019b) and (iii) the isotopic character of basement rocks, mainly Precambrian, and igneous intrusions sourced from them (e.g. Barr and Hegner, 1992; Nance and Murphy, 1994; Kerr et al., 1995). These three overlapping characteristics produce a mosaic of terranes distinguished by different

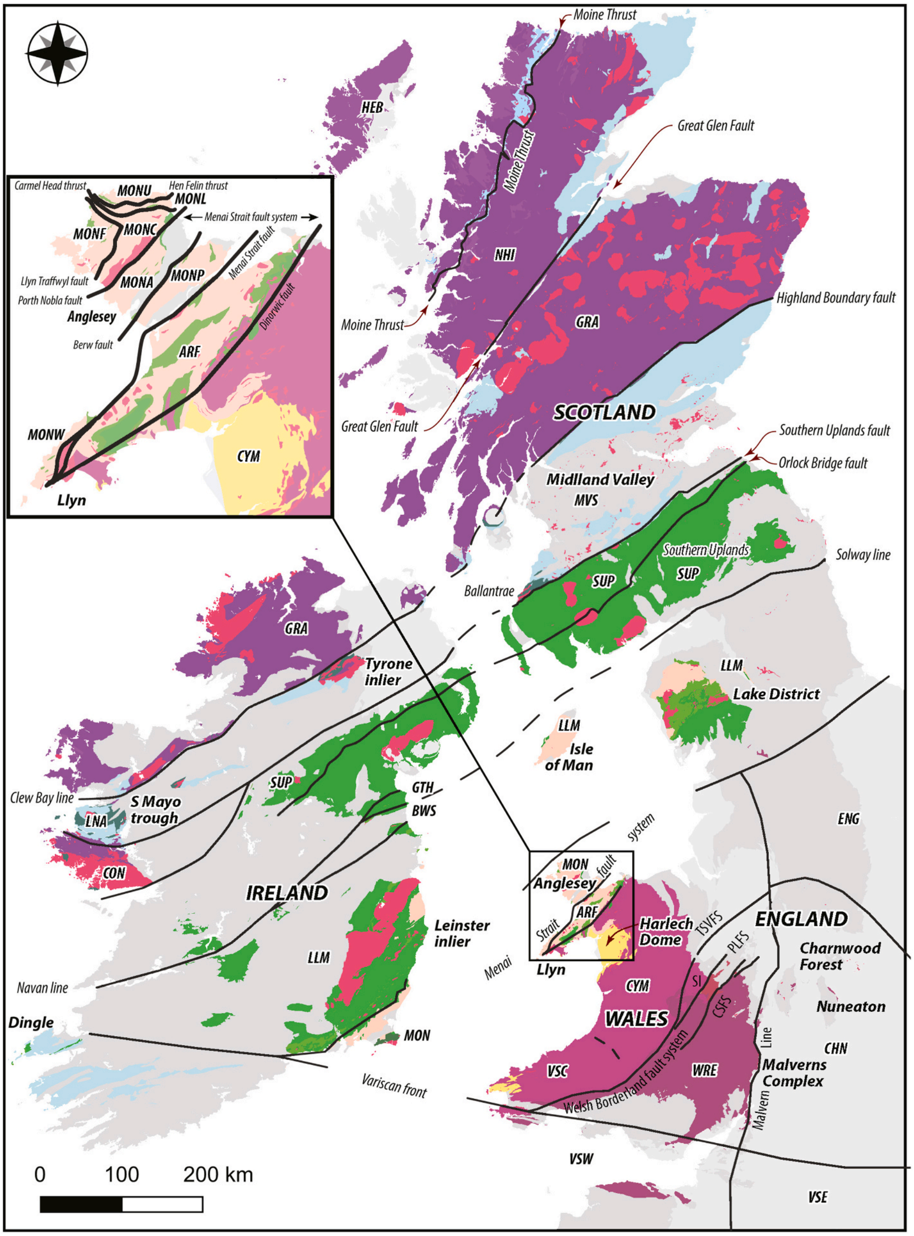


**Fig. 10.** Caledonides of Ireland and Britain. (a) Tectonostratigraphic subdivisions, boundaries and terranes. Terrane abbreviations are defined in Table 3. (b) Available detrital zircon data as pie charts with areas proportional to number of analyses. Legend as Fig. 7. Available paleomagnetic orientations show direction of interpreted south pole. Data sources are listed in the Supplementary Material. Geological base compiled from Geological Survey of Ireland (McConnell and Gatley, 2006) and British Geological Survey (2007). CSFS = Church Stretton fault system. PLFS = Pontesford–Linley fault system. SI = Shelve inlier.

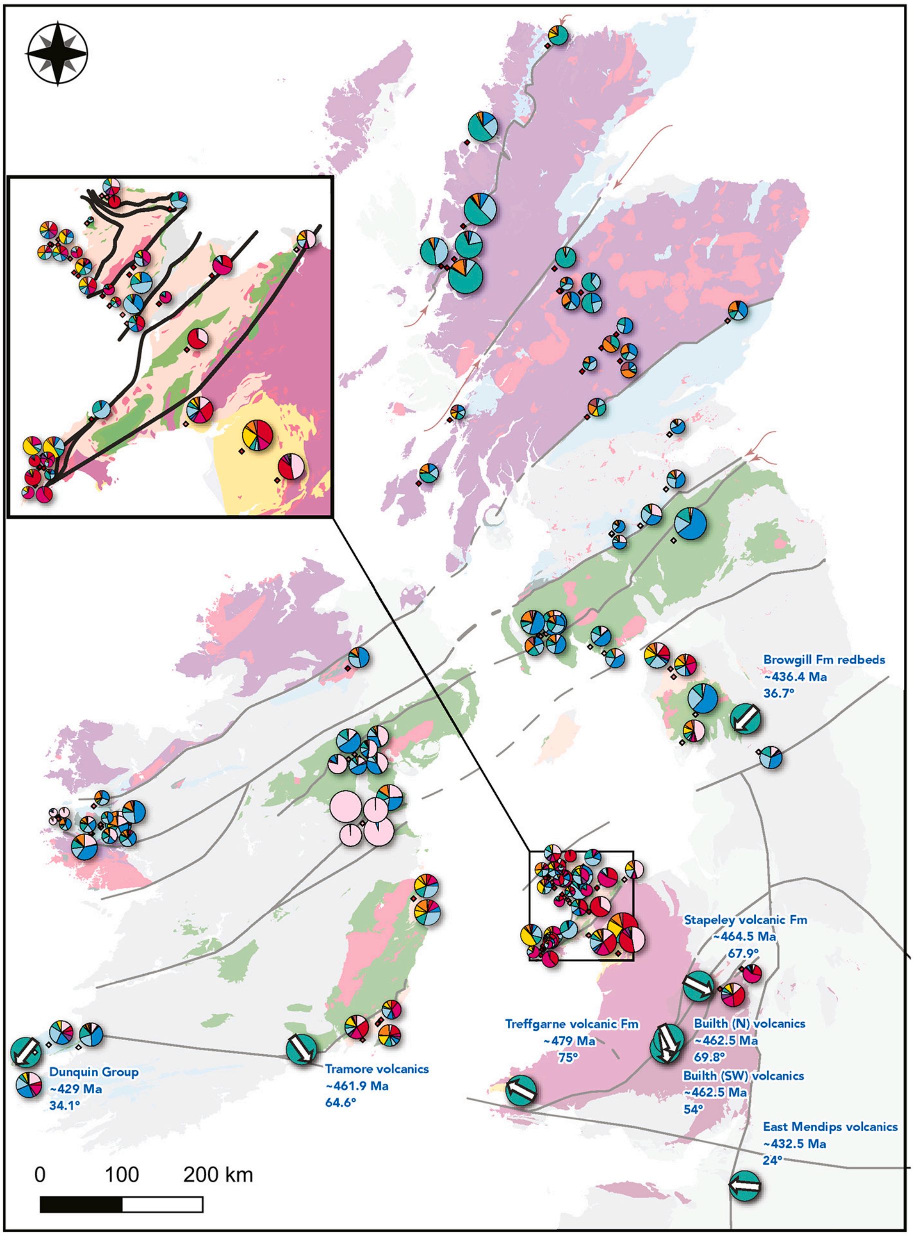


**Fig. 10.** (*continued*).

combinations of criteria, and combined in different ways at different times in geologic history, as illustrated schematically in Fig. 12 a-c. In addition, terranes that are initially considered "suspect" may later be found to have stratigraphic relations, but such relations may be controversial (e.g. Landing et al., 2022). In this review we recognize as terranes all those areas that, for some part of their geologic history, show features that cannot be correlated into adjacent areas. We have thus intentionally erred on the side of identifying most of those entities that have, at one time or another, been considered "suspect terranes", so as to consider a variety of paleogeographic options. It is important to note that although we identify many terranes using these criteria, the number of separate plates that existed at any one time was much smaller, because terranes were combined in groups, here termed *terrane assemblages*. We therefore do not imply that every terrane represents a separate microcontinent.

In reviewing previously described terranes we have noted that some contain multiple tectonic units, only a few kilometres wide, with contrasting or progressively varying stratigraphy. Examples include the Aspy and New River "terranes" of Atlantic Canada, the Southern Uplands "terrane" of Scotland, and the Monian "terrane" or "superterrane" of N. Wales. We describe these regions as *belts*. In order to avoid further proliferating the already large number of terrane names, we name the constituent parts of these belts variously as "block", "complex" or "slice" depending on usage in previous work, even though, in some cases, these small structurally-bounded units would qualify as terranes by some definitions (Coney et al., 1980).

In drawing paleogeographic maps it has been easy for most previous authors to assume that domains defined on the basis of isotopic character or continental-margin stratigraphy were the same entities that travelled across the Iapetus Ocean. We regard this assumption as fundamentally incorrect (Fig. 12). We therefore avoid using the *domain* names (Ganderia, Avalonia, Megumia etc.) interchangeably with *terrane* names for entities within the Iapetus Ocean. Instead, in the following account, after first reviewing peri-Laurentian terranes, we identify Gondwana-derived (or Baltica-derived) *terrane assemblages* (Fig. 12 b) that arrived together at the Laurentian margin, and that may have

**Table 1**
Age bins used in detrital zircon presentation. Colour selections based on 24-colour palette of Krzywinsky (2022).

| Bin | From | To (Ma) | Potential sources | Colour (RGB hexadecimal) |
|---|---|---|---|---|
| A | 0 | 541 | Arcs within the Iapetus Ocean | #ffcfe2 |
| B | 541 | 600 | Younger Ediacaran (Avalonian / Panafrican) sources in Gondwana; rift-phase rocks from Iapetan margins. | #f60239 |
| C | 600 | 700 | Older Ediacaran (Avalonian / Panafrican) sources in Gondwana; rift-phase rocks from Iapetan margins. | #ef0096 |
| D | 700 | 900 | Oceanic arc basement of Avalonia; otherwise scarce in the Appalachian orogen. | #9400e6 |
| E | 900 | 1200 | Grenville orogen of eastern Laurentia; Sunsas Orogen in Amazonia | #009ffa |
| F | 1200 | 1600 | Mesoproterozoic orogens, precursors to the Grenville orogen on the eastern margin of Laurentia and in Amazonia | #7cfffa |
| G | 1600 | 1950 | Trans-Hudson and related Paleoproterozoic orogens of Laurentia | #00dcb5 |
| H | 1950 | 2200 | Eburnean orogen of West Africa. Paleoproterozoic orogens of Ukraine and Amazonia. Rare in Laurentian margin samples | #ffdc3d |
| I | 2200 | 2500 | Scarce in the Appalachian orogen | #ffb935 |
| J | 2500 | 2800 | Neo-Archean rocks of the Laurentian craton; also Amazonia, West Africa, Baltica | #ff8735 |
| K | 2800 | 3200 | Meso-Archean rocks of the Laurentian craton; also Amazonia, West Africa, Baltica | #a34f5d |
| L | 3200 | 3600 | Paleo-Archean to Hadean rocks of the Laurentian craton | #68023f |
| M | 3600 | 4567 | Eo-Archean and Hadean rocks; largely absent | #000000 |

included material from more than one domain or basement province. Some of the assemblages so identified contain terranes from all three interpreted peri-Gondwanan domains. We then work backwards, using stratigraphic, paleomagnetic, and provenance data to consider their earlier paleogeography and possible origins on the Gondwanan or Baltican margin (Fig. 12 a).

In reviewing the history of the many terranes involved in the Appalachian–Caledonide system, we use the results of Waldron et al. (2019b), who compiled stratigraphic arguments and detrital zircon provenance data to bracket the time of arrival of terranes at the Laurentian margin. Thus, a series of terranes, designated *peri-Laurentian*, display detrital zircon signatures that are characteristically Laurentian (e.g. with a large proportion of zircon in the "Grenvillian" 1.0 – 1.2 Ga range) throughout their known history. Many of these terranes show evidence of deformation in an Ordovician *Taconian* series of deformational events widely interpreted as the result of a somewhat diachronous collision of an island arc with the Laurentian margin at a SE-dipping subduction zone, which was followed by a subduction polarity reversal (or "flip") to NW-dipping subduction (Stanley and Ratcliffe, 1985; van Staal et al., 1998; Waldron and van Staal, 2001; White et al., 2020).

Other terranes show different times of arrival at the Laurentian margin, typically marked by unconformities that separate underlying strata that display Gondwanan characteristics (e.g. large Ediacaran and Eburnean zircon populations) from unconformably overlying forearc basin strata with Laurentian or mixed provenance. Many of these were accreted as a result of NW-dipping *Salinian* subduction at the margin of composite Laurentia (e.g. van Staal et al., 2008). However, the latest units were accreted during *Acadian* deformation in the latest Silurian to Middle Devonian. This deformation resulted in emplacement of substantial NW-vergent thrusts and recumbent folds in southwestern parts of the orogen, producing a foreland basin (Bradley et al., 2000), but appears to have been associated with relatively mild sinistral transpression in Britain and Ireland (Woodcock et al., 2006, 2007, 2019).

The northern, carbonate-dominated margin of the Australian continent provides a powerful modern analog for Taconian events along the Laurentian margin (e.g. van Staal et al., 1998; White et al., 2020; White and Waldron, 2022). Subduction polarity reversal is progressing westwards along this margin at the present day, converting the Australian margin from passive to active (Fig. 13). In the east, in Papua New Guinea, a large ophiolite slab has already been emplaced onto the Australian margin, and Pacific Ocean floor is being subducted beneath the Australian plate, whereas in the west, arc-continent collision is yet to take place. Fig. 13 (c) shows a possible future evolution of this margin, rotated and reflected into an orientation analogous to Ordovician Laurentia. A parade of small continental and arc fragments is likely to be accreted to the Australian margin, some of which already carry internal collisional and strike-slip tectonic zones analogous to Penobscottian and Monian structures that developed in peri-Gondwanan terranes prior to their accretion.

## 4. Peri-Laurentian domain

Several terranes that appear as inliers or fault-bounded blocks near the northwest margin of the orogen have been interpreted as off-margin blocks or ribbons of Laurentian crust, formed during Iapetan rifting as

**Table 2**
Paleomagnetic results selected for this study. RESULT#: paleomagnetic database result number. PlateID: GPlates number. Plate: GPlates code. Dom: Domain. SLAT, SLONG: station location. Q: quality index.

| UNIT | Terrane | ID | Plate | Dom. | Region | SLAT | SLONG | PLAT | PLONG | A95 | Age basis | Age Max | Age | Age Min | R | *AUTHORS* | *Yr* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dunquin Group | Leinster Lakesman | 39281 | LLM | G | Variscan SW Ireland | 52.13 | -10.46 | -11.6 | 312.4 | 6.8 | Biostratigraphy | 430.5 | 429.0 | 427.4 | 4 | *MacNiocaill* | *###* |
| East Mendips volcanics | Wrekin | 31595 | WRE | A | Variscan SW England | 51.21 | -2.49 | 12.9 | 271.6 | 6.9 | Biostratigraphy | *432.4* | 432.5 | *432.6* | 5 | *Torsvik et al.* | *1993* |
| Browgill Fm redbeds | Leinster Lakesman | 39281 | LLM | G | Lake District | 54.35 | -2.48 | -6.5 | 317.1 | 11.1 | Biostratigraphy | *436.6* | 436.4 | *436.2* | 5 | *Channell et al.* | *1993* |
| Cape St. Mary's Sills | Avalon | 10800 | AVN | A | Avalon Peninsula | 46.85 | -54.00 | -10.3 | 320.0 | 10.0 | U-Pb zircon | 443.0 | 441.0 | 439.0 | 7 | *Hodych and Buchan* | *1998* |
| Winterville Fm | Bronson-Popelogan | 18457 | POP | G | Pennington Inlier | 46.80 | -68.70 | -25.2 | 327.6 | 7.1 | Biostratigraphy | 458.4 | 451.1 | 443.8 | 4 | *Potts et al.* | *1995* |
| Dunn Point volcanics | Antigonish | 10860 | AGN | A | Nova Scotia | 45.78 | -62.15 | -2.2 | 309.9 | 5.4 | U-Pb zircon | 463.4 | 460.0 | 456.6 | 6 | *Johnson and Van der Voo* | *1990* |
| Tramore volcanics | Leinster Lakesman | 39281 | LLM | G | Leinster | 52.15 | -7.40 | 13.3 | 17.0 | 12.2 | Biostratigraphy | 465.3 | 461.9 | 458.4 | 7 | *Deutsch* | *1980* |
| Builth (SW) volcanics | Wrekin | 31595 | WRE | A | Welsh Borders | 52.16 | -3.37 | -2.9 | 4.0 | 8.6 | Biostratigraphy | *463.5* | 462.5 | *461.4* | 5 | *Trench et al.* | *1991* |
| Builth (N) volcanics | Wrekin | 31595 | WRE | A | Welsh Borders | 52.22 | -3.33 | 18.1 | 12.7 | 15.9 | Biostratigraphy | *463.5* | 462.5 | *461.4* | 4 | *McCabe et al.* | *1992* |
| Stacyville Fm | Bronson-Popelogan | 18457 | POP | G | Lunksoos Inlier | 46.00 | -68.60 | 14.2 | 7.2 | 10.5 | Biostratigraphy | 468.0 | 463.2 | 458.4 | 3 | *Wellensiek et al.* | *1990* |
| Bluffer Pond Fm | Bronson-Popelogan | 18463 | BRN | G | Munsungun Inlier | 46.50 | -69.00 | -25.8 | 313.6 | 9.6 | Biostratigraphy | 470.0 | 464.2 | 458.4 | 4 | *Potts et al.* | *1993* |
| Stapeley volcanic Fm | Wrekin | 31595 | WRE | A | Welsh Borders | 52.58 | -3.00 | 26.6 | 36.1 | 7.5 | Biostratigraphy | 465.3 | 464.5 | 463.6 | 6 | *McCabe and Channell* | *1990* |
| Tetagouche Group | Miramichi | 18459 | MRM | G |  | 47.50 | -66.00 | 52.2 | 353.4 | 20.4 | U-Pb zircon in correlative rocks | 473.0 | 465.0 | 457.0 | 4 | *Liss et al.* | *1993* |
| Treffgarne volcanic Fm | Cymru | 31572 | CYM | M | Variscan SW Wales | 51.87 | -4.97 | 56.1 | 306.6 | 9.6 | Biostratigraphy | *495.0* | 479.0 | *475.9* | 5 | *Trench et al.* | *1992* |
| Nahant gabbro | SENE | 10862 | SEN | A |  | 42.50 | -71.00 | 34.3 | 319.8 | 6.9 | U-Pb zircon | 489.3 | 488.5 | 487.7 | 6 | *Thompson et al.* | *2010* |
| Bourinot volcanics | Bras d'Or | 18465 | BDR | G | Bourinot belt | 46.10 | -60.40 | 21.0 | 340.6 | 11.9 | Biostratigraphy | *507.5* | 506.4 | *505.3* | 7 | *Johnson and Van der Voo* | *1985* |
| Bourinot sediments | Bras d'Or | 18465 | BDR | G | Bourinot belt | 46.10 | -60.40 | 33.5 | 354.3 | 12.3 | Biostratigraphy | *507.5* | 506.4 | *505.3* | 6 | *Johnson and Van der Voo* | *1985* |

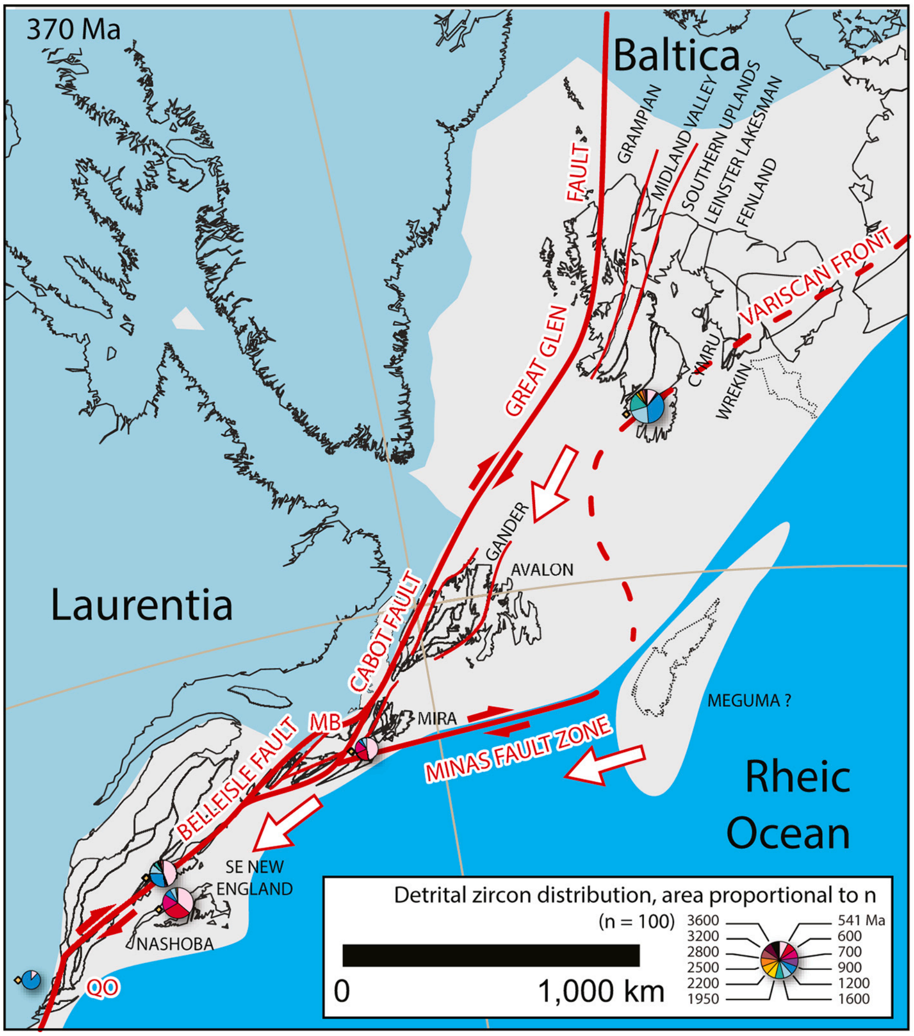


**Fig. 11.** Possible distribution of tectonostratigraphic units prior to late Paleozoic strike slip, produced by implementing a simplified Pangea reconstruction (Ady and Whittaker, 2019), and the schematic late Paleozoic kinematic model of Waldron et al. (2015) on a spherical Earth at 370 Ma using the software GPlates (Müller et al., 2018). Dextral transpression in southern New England based on Massey et al. (2017) and references therein. Detrital zircon data sets shown for depositional ages between 380 and 360 Ma. CF = Cabot Fault. GGF = Great Glen Fault. MB = Future Maritimes Basin. QO = Future Quaboagian Orogen

part of an attenuated Laurentian margin (Cawood et al., 2001; Chew and van Staal, 2014). In some cases (Dashwoods, Chain Lakes, Grampian) a record of early deformation or metamorphism (Waldron and van Staal, 2001; Gerbi et al., 2006b) implies a position well offshore of the Laurentian margin during early stages of the Taconian/Grampian Orogeny. In other cases (Blair River, Chester Dome), inliers of Laurentia have typically been assumed to have subsurface connection with the Laurentian margin, but this cannot be proven (e.g. Miller and Barr, 2004).

All these terranes are too metamorphosed to display a biostratigraphic or primary paleomagnetic record of paleogeographic significance. In most cases the Laurentian character of these units is identifiable from distinctive Mesoproterozoic (“Grenville”) ages of basement rocks, and/or detrital zircon in overlying Cambrian rift and passive-margin successions. Determining their position relative to the Laurentian margin is more difficult, and typically depends on arguments based on their tectonic history, relative to the timing of foreland basin development on the Laurentian margin (White et al., 2019), which are the subject of a companion paper (White and Waldron, 2022). We here show updated summed detrital zircon plots for the Appalachian and Caledonide sectors of the margin.

Detrital zircon distributions from the Laurentian margin, reviewed by Kuiper and Hepburn (2021) and White and Waldron (2022), typically show strong representation of zircon from the Grenville Orogen in the eastern Canadian Shield, typified by major peaks between 0.95 and 1.2 Ga, representing the main phases of the Grenvillian orogenesis. They are typically accompanied by lesser amounts of older Mesoproterozoic zircon extending back to ~1.95 Ga, and smaller amounts of Archean zircon. However, marked differences in detail occur both along and across the margin (White and Waldron, 2022). Samples from New England are dominated by late Mesoproterozoic zircon whereas those from Newfoundland show larger amounts of older zircon (Fig. 14). In many samples from the British Isles the older Mesoproterozoic and Paleoproterozoic components are dominant. This south-to-north trend of increasing older components is mirrored by a comparable, although less pronounced, trend from proximal to distal components of the margin: off-margin units such as the Fleur de Lys Supergroup in Newfoundland (Fig. 5) and the Dalradian Supergroup in the Grampian terrane of Scotland (Fig. 6) show larger amounts of older zircon than corresponding units from the autochthonous Laurentian margin.

Southeast of these units, and in some cases overlying them, are rock successions that show Laurentian isotopic characteristics but display a Late Ordovician to Silurian history of subduction. In some cases, these terranes incorporate older, ophiolitic arc rocks that were emplaced onto the Laurentian margin in Furongian to Ordovician Grampian or Taconian arc-continent collisions. These terranes include the Notre Dame subzone (Williams et al., 1988) in Newfoundland (Fig. 9), the South Mayo Trough in Ireland, and the Midland Valley terrane and Southern Uplands belt in Britain and Ireland (Fig. 10), which record various stages of sedimentation and deformation during Taconian/Grampian arc-continent collision, subduction polarity reversal, and subsequent NW-dipping subduction beneath the composite Laurentian margin (e.g. Leggett et al., 1979; Zagorevski et al., 2009).

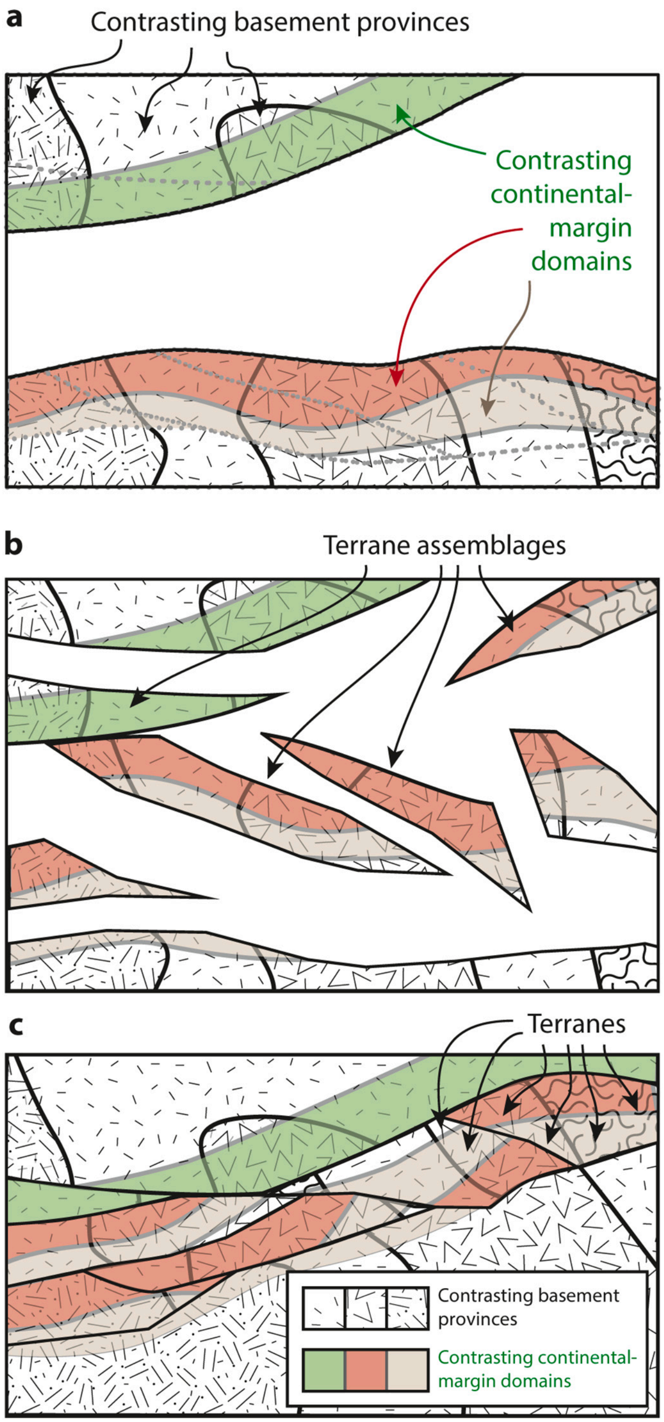


**Fig. 12.** Cartoon showing multiple criteria that have been used in terrane definition. (a) Ideal configuration of two former continental margins and an intervening ocean with *provinces* defined by contrasting basement isotopic character and *domains* defined by contrasting cover stratigraphy. (b) *Terrane assemblages* in transit within former ocean may include multiple provinces and domains. (c) Resulting orogen comprising multiple *terranes* distinguished by differences in basement isotopic character (stipple), cover succession (colour), and/or time of accretion (bold outlines).

### 4.1. *Fragments of the extended Laurentian margin*

#### 4.1.1. *Rowe–Hawley belt and Chester dome*

Although the *Chester dome* of Vermont (Fig. 7) has typically been interpreted as a modified tectonic window into the Laurentian margin (e.g. Stanley and Ratcliffe, 1985), Karabinos et al. (1998) suggested that it may represent a portion of the Laurentian margin separated during rifting and brought back into contact with the margin during Taconian arc-continent collision. Tectonically overlying the Chester Dome are allochthonous rocks assigned to the Rowe Schist (Fig. 3) by Macdonald et al. (2014) and Karabinos et al. (2017), interpreted as derived from the extended passive margin of Laurentia. Subsequent discovery (Macdonald et al., 2014) of an allochthonous peri-Gondwanan unit, the Moretown terrane (Fig. 7) has strengthened the argument of Karabinos et al. (1998), because the thrust contact between the Moretown terrane and Laurentian rocks of the dome is intersected by ~475 Ma intrusive rocks of the Shelburne Falls arc. This arc contains Laurentia-derived zircon (Macdonald et al., 2014; Karabinos et al., 2017), and developed before the Late Ordovician development of a flexural foreland basin (Fig. 3) on the Laurentian margin (White and Waldron, 2022). This relation indicates that the collision between the Moretown terrane and underlying Laurentia-derived crust occurred at some large distance from the margin, relative to the flexural wavelength of the Laurentian lithosphere.

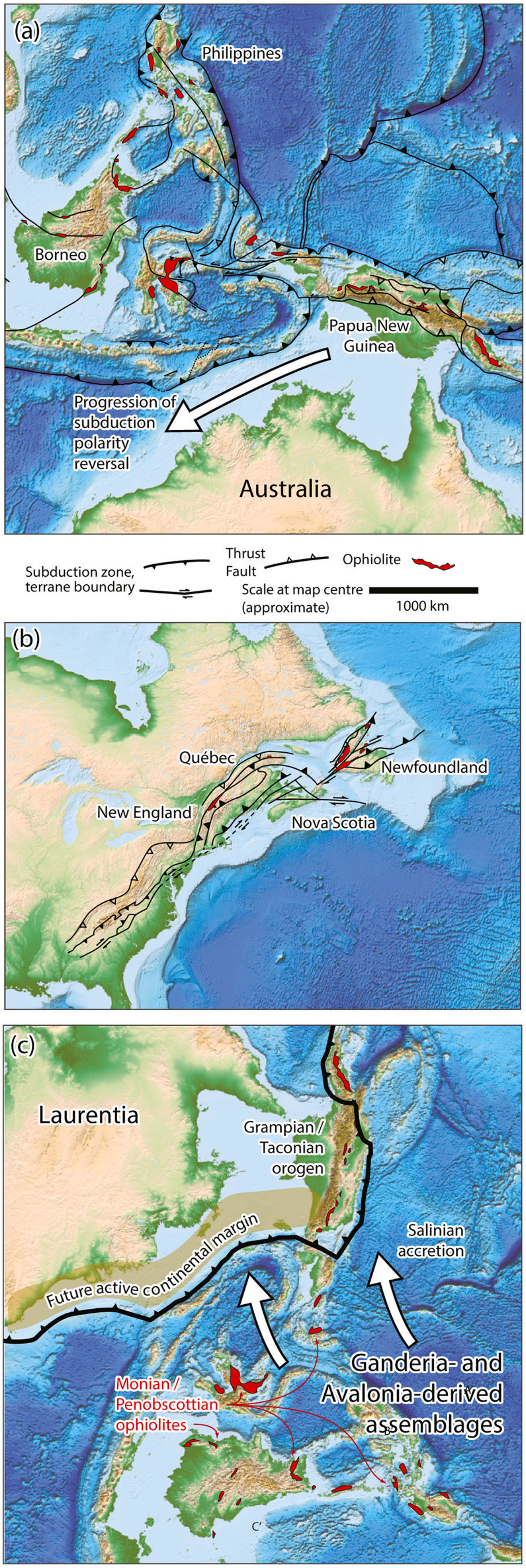
Rocks of the tectonically overlying *Rowe belt* show a typical “Laurentian” detrital zircon pattern (Fig. 14 b), with a large, asymmetric peak at ~1 Ga and an extended Mesoproterozoic to late Paleoproterozoic tail. The spectrum is similar to that for the Laurentian margin (Fig. 14 a) but shows a relatively larger proportion of zircon in the Paleoproterozoic at ~ 1.7 Ga, and in the Neoarchean at 2.6-2.8 Ga.

#### 4.1.2. *Chain Lakes massif*

The *Chain Lakes massif* that straddles the border between Québec and Maine (Fig. 7, CHL), occupies an analogous position. Although Kusky et al. (1997) interpreted the massif as part of the leading edge of Ganderia, samples analysed by Gerbi et al. (2006b) display a detrital zircon signature similar to that of the Rowe belt (Fig. 14 b, d), suggesting that the metasedimentary part of the massif is of Laurentian affinity. However, its relation to the Québec ophiolites has been controversial. Tremblay and Pinet (2016) suggested a “maximum allochthony” model, in which ophiolites, ranging in spreading age from 504 to 477 Ma, were formed outboard of the Chain Lakes massif and emplaced as a single nappe in Taconian deformation, whereas Gerbi et al. (2006a) recognized a contact along which the arc-related Skinner pluton intruded the Chain Lakes massif, suggesting an upper-plate position of the massif by ~472 Ma. On this basis, van Staal and Barr (2012) preferred a “multiple oceanic tracts” (Tremblay and Pinet, 2016) model in which the source for the younger ophiolites was between the Chain Lakes massif and the main Laurentian margin. Regardless of the source of the ophiolites, an off-margin location is also supported by widespread partial melting of the metasedimentary rocks at ~479 Ma (Gerbi et al., 2006b). At this time, sedimentary successions on the outer margin of the Laurentian platform show pelagic facies with no indication of foreland basin development, suggesting that the Chain Lakes block was deformed well before the main Laurentian margin (White et al., 2020; White and Waldron, 2022) (Fig. 4).

#### 4.1.3. *Blair River Complex*

The northernmost portion of Cape Breton Island (Fig. 8, BRI) consists of felsic and mafic gneiss, anorthosite, granite, gabbro and syenite of the *Blair River Complex* or “inlier”, identified as representing broadly “Grenvillian” crust of the Laurentian margin (Barr et al., 1987), yielding crystallization ages from >1217 to 970 Ma and metamorphic ages in the range 1050 to 990 Ma (Miller et al., 1996). Mafic dykes with compositions similar to those elsewhere on the Laurentian margin record the opening of the Iapetus at ca. 580 Ma (Miller and Barr, 2004). Marble in fault-bounded slivers may represent fragments of the Paleozoic Laurentian margin but original sedimentary relationships are not preserved (Miller and Barr, 2000). A Silurian thermal overprint is recorded by magmatism at ~435 Ma and ~425 Ma and by cooling ages ~423 Ma (Miller et al., 1996; Shellnutt et al., 2020). The Blair River Complex is



*(caption on next column)*

**Fig. 13.** Maps showing analogy with SE Asia (topography & bathymetry after Amante and Eakins, 2009). (a) Tectonic map of SE Asia and the northern margin of the Australian plate showing effects of arc-continent collision and subduction polarity reversal, and the distribution of ophiolites (Hall, 2002, 2012; Zahirovic et al., 2014; White et al., 2020; White and Waldron, 2022). (b) Map of Appalachian orogen at similar scale. (c) Future Australian margin, shown schematically after completion of subduction polarity reversal. Map is reflected, rotated and relabelled to emphasize analogy with Ordovician Laurentia.

isolated from other Laurentian rocks by the Gulf of St. Lawrence. It may represent an autochthonous promontory of the Laurentian margin (e.g. Stockmal et al., 1990) but an allochthonous origin as an off-margin block cannot be excluded.

### 4.1.4. *Dashwoods terrane and the Fleur de Lys Supergroup*

A comparable, although slightly earlier, accretion history was inferred for the *Dashwoods terrane* in SW Newfoundland (Fig. 9, DSH) by Waldron and van Staal (2001), who highlighted the timing of deformation within the terrane, post-dated by an intrusion at 488 Ma. This timing is significantly earlier than the first effects of Taconian deformation in the Laurentian margin at ~470 Ma, suggesting that, like the Chain Lakes massif, the Dashwoods terrane represents an offshore Laurentian microcontinent that underwent arc-continent collision, and was first incorporated into an arc edifice, substantially offshore of the Laurentian margin. This interpretation has recently been questioned by Karabinos et al. (2017) and Macdonald et al. (2017), who correlated the Gondwanan Moretown terrane from New England to Newfoundland. In the absence of distinctive Gondwanan input in any of the Laurentian margin basins in western Newfoundland prior to the Devonian (White et al., 2019), we consider it more likely that the timing of arrival of Gondwanan fragments was diachronous along the Laurentian margin (Waldron et al., 2014a, 2019b).

Comparable rocks of the Fleur de Lys Supergroup occur on the Baie Verte Peninsula (Fig. 9) in Newfoundland, showing a similar pattern of detrital zircon ages to the Chain Lakes block and the Rowe belt (Fig. 14). Once again, there is a slightly larger proportion of Mesoproterozoic and Archean zircon than in contemporary rocks deposited on the corresponding part of the Laurentian margin. Like the Dashwoods terrane, the Fleur de Lys Supergroup was deformed and overthrust by ophiolites somewhat earlier than the main Laurentian margin, as demonstrated by a Floian unconformable cover (Flatwater Pond Group) (Fig. 5) constrained between 476 and 479 Ma (Skulski et al., 2010), at a time when Tremadocian–Floian pelagic shale of the Cow Head Group was being deposited on the distal part of the main Laurentian margin.

### 4.1.5. *Grampian terrane*

The *Grampian terrane* of Ireland and Scotland (Fig. 10, GRA) displays substantial Neoproterozoic to Cambrian basin-fill, the Dalradian Supergroup (Fig. 6). Leslie et al. (2008) and Stephenson et al. (2013) provided summaries of the stratigraphy and paleogeography. Group-level subdivisions of the Dalradian succession, some formations, and major structural elements can be confidently correlated into the main area of Dalradian rocks in Ireland (Chew, 2009), which is included in the Grampian terrane (Fig. 10).

The basin appears to have been built on Paleoproterozoic basement exposed in the 1779 ± 3 Ma Rhinns Complex and the 1753 ± 3 Ma and younger Annagh Gneiss Complex (Daly, 2009 and references therein). The initiation of sedimentation in the Grampian basin is poorly dated, but was estimated at 730 Ma by Leslie et al. (2008) who inferred that an initial rift between Baltica and Laurentia began at this time, simultaneously with the early breakup of Rodinia along the western margin of Laurentia (e.g. Ross, 1991). An episode of mafic volcanism (Tayvallich Volcanics) at 595 Ma and an associated felsic intrusion (Ben Vurich pluton) at 590 Ma are comparable in their timing to rift magmatism throughout the Appalachians (McCausland et al., 2007, 2011), related to

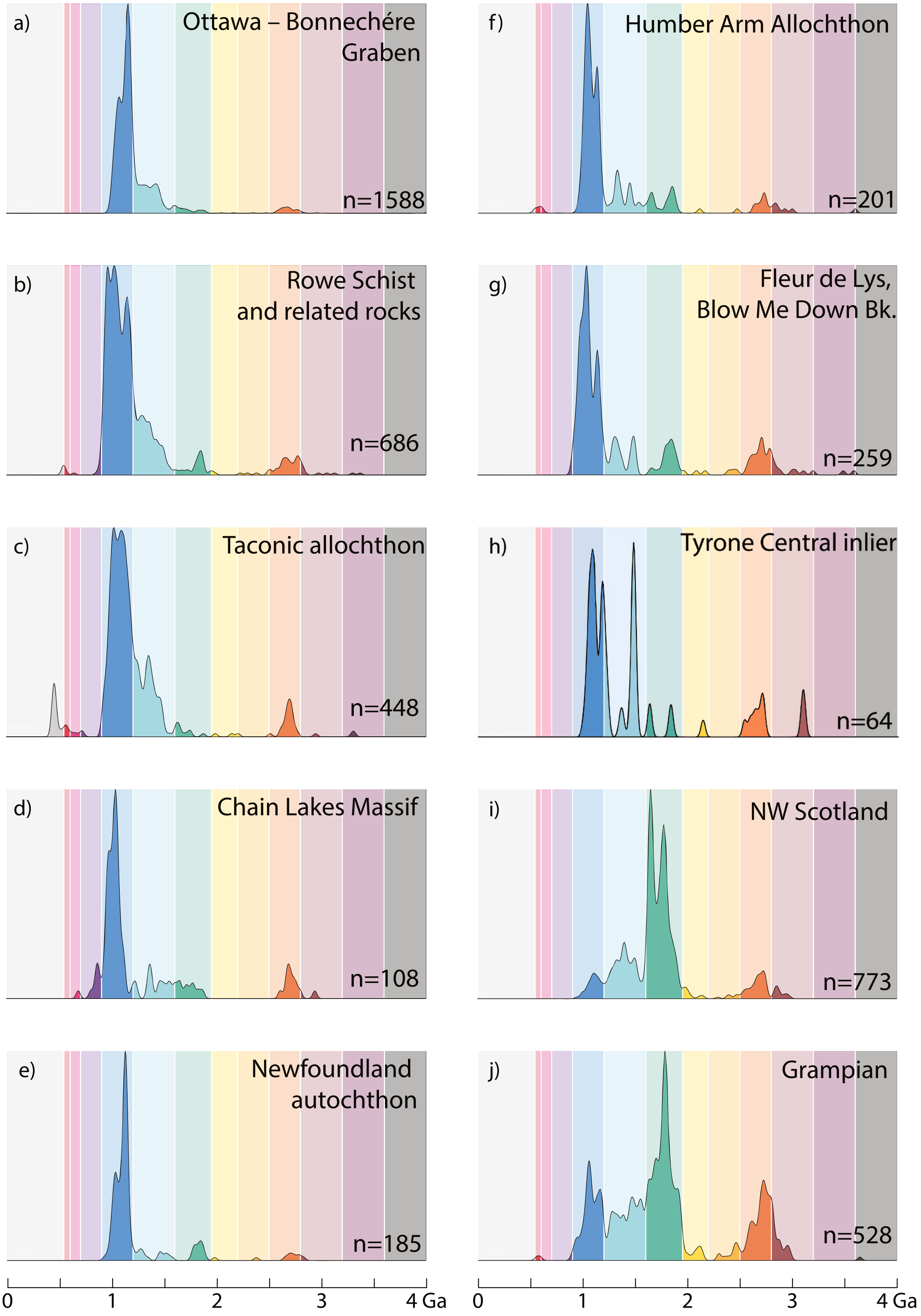


**Fig. 14.** Combined detrital zircon data sets from the Laurentian margin (Cawood and Nemchin, 2001; McLennan et al., 2001; Cawood et al., 2003, 2004, 2007, 2012; Gerbi et al., 2006a; Chew et al., 2008; Allen, 2009; Macdonald et al., 2014, 2017; Willner et al., 2014; McConnell et al., 2016; Karabinos et al., 2017; Krabbendam et al., 2017; Lowe et al., 2018). (a) Laurentian shelf in the Ottawa-Bonnechère graben. (b) Rowe Schist and related rocks of the New England platform-margin belt (c) Taconic allochthon of New York, Vermont. (d) Chain Lakes massif. (e) Laurentian rift and shelf in Newfoundland. (f) Humber Arm Allochthon in Newfoundland (lower slices). (g) Fleur de Lys Supergroup and upper slice of Humber Arm Allochthon in Newfoundland. (h) Tyrone central inlier, Ireland. (i) Laurentian shelf and Proterozoic rift (?) successions of NW Scotland. (j) Grampian terrane of Scotland.

the 3-way breakup of Laurentia, Baltica, and Amazonia – West Africa (AWA) (Cawood et al., 2001). With the exception of this dated marker, timing of events in the Dalradian succession is dependent on disputed correlation of glacial units with known Neoproterozoic episodes; in Fig. 6 we follow the interpretation of Leslie et al. (2008). Detailed study of both structure and stratigraphy in the Dalradian Supergroup has led to the recognition of a series of fault-bounded sub-basins lying to the northwest of a microcontinental block that may extend under the adjacent Midland Valley terrane, the outermost part of an extended continental margin that was ~1000 km wide (Leslie et al., 2008). At the top of the Dalradian succession, the condensed Trossachs group (Tanner and Sutherland, 2007) contains, at its base, trilobites correlative with the middle *Bonnia-Olenellus* zone of Laurentia, corresponding to an age of ca. 514–512 Ma, and at the top, conodonts of latest Tremadocian to Floian age (Ethington, 2008) or 480–470 Ma.

Ordovician deformation and metamorphism in this domain are designated *Grampian* and are closely comparable in time to Taconian deformation in the Appalachians. As in the Appalachians they are attributed to arc-continent collision between 490 and 470 Ma (Chew et al., 2010) that was followed by peak metamorphism and subduction polarity reversal around 470 Ma. Early structures were probably NW-vergent and related to an overthrust ophiolite, now largely removed by erosion (e.g. Dewey and Shackleton, 1984; Chew et al., 2010). They are overprinted by a major SE-vergent nappe-forming episode possibly related to subduction polarity reversal (Krabbendam et al., 1997; Tanner, 2014). A later episode, designated *Grampian II,* affected the Northern Highlands around 450 Ma (Bird et al., 2013). The corresponding carbonate shelf on the Laurentian margin in NW Scotland (Durness succession; Fig. 6) extends into the *Histodiella altifrons* conodont zone (Raine and Smith, 2012) at ~468 Ma, slightly younger than the youngest pre-Taconian shelf rocks in Newfoundland, and significantly younger than the start of ophiolite emplacement. This age difference suggests that, as in the Appalachians, it is likely that distal parts of the hyperextended Laurentian margin, possibly including off-margin microcontinental blocks, were deformed substantially before the Laurentian shelf was affected by the Taconian–Grampian Orogeny. However, it is also clear that strike-slip motion has played a role in the juxtaposition of terranes in the Scottish Highlands, because a substantial block of uplifted Tonian (early Neoproterozoic) metasedimentary rocks in the Northern Highlands (Fig. 10), the Moine Supergroup, was highly deformed and thrust westward in Scandian deformation that did not affect the Grampian terrane to the SE, except in the Shetland Islands far to the NE. This contrast was explained by Dewey and Strachan (2003) as the result of a large-scale sinistral offset between the two blocks, such that the Northern Highlands lay between Greenland and Baltica in the Silurian – both blocks were affected by Scandian deformation, whereas the Grampian terrane lay ~1000 km to the SW. This inference of post-Scandian sinistral offset has important implications for Acadian deformation in the Appalachians (discussed in section 6.2.1).

Despite this inference of major strike-slip motion, detrital zircon distributions in NW Scotland and the Grampian terrane of Scotland (Fig. 14) are broadly similar, and differ from those in the Appalachians in displaying much smaller proportions of late Mesoproterozoic ("Grenville") zircon, and much larger amounts of late Paleoproterozoic (1.6-1.9 Ga) zircon. However, more recent results from the Silurian cover of the Grampian and Connemara terranes in Ireland (Riggs et al., 2022) display much larger proportions of zircon in this age bracket. These differences are consistent with the reduced contribution of the Grenville Orogen to the northwest foreland of the Caledonides; the Appalachian-Caledonide front intersects the Grenville front somewhere under the modern continental shelves of Newfoundland and Ireland. Thus, despite evidence for Silurian–Devonian sinistral strike slip and Devonian–Carboniferous dextral strike slip in both parts of the orogen, these movements apparently did not result in a large (>1000 km) net translation of the Grampian terrane along the margin.

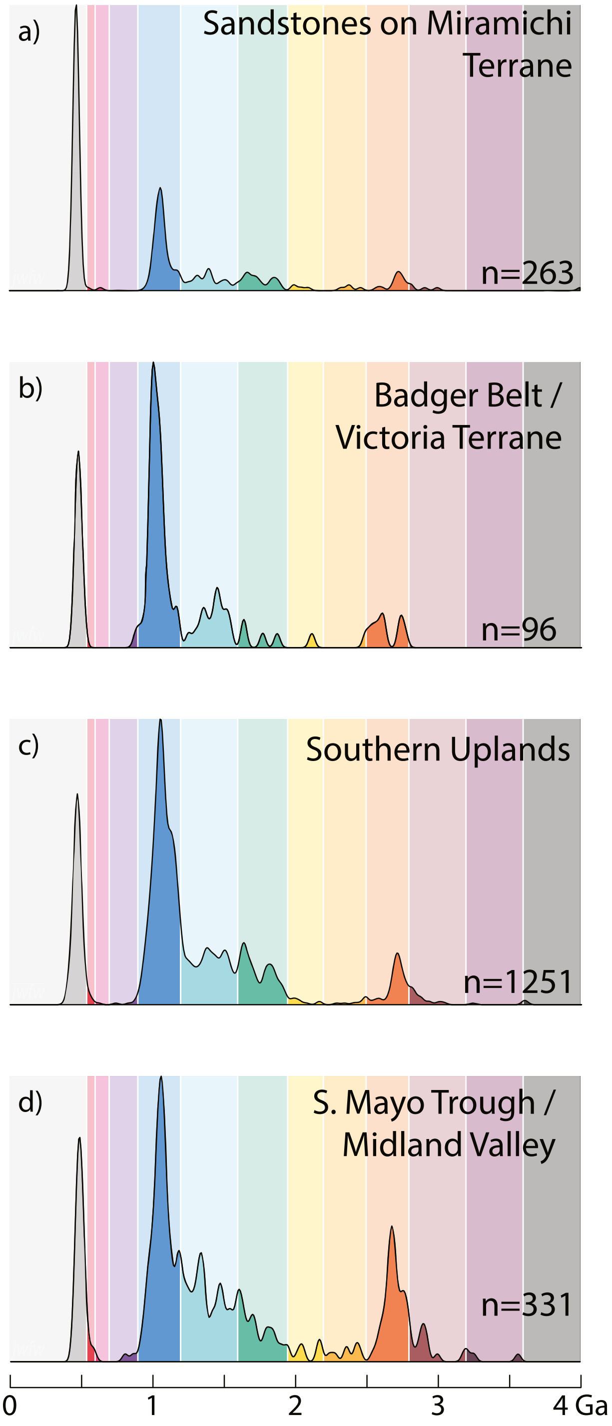


**Fig. 15.** Combined detrital zircon data sets from inferred trench/foredeep deposits formed during subduction beneath the Laurentian margin (Waldron et al., 2008, 2012, 2014a; Clift et al., 2009; McConnell et al., 2009, 2016; Phillips et al., 2009; Yin et al., 2012; Wilson et al., 2015; van Staal et al., 2016; Karabinos et al., 2017). (a) Later Ordovician sandstone deposited on the Miramichi terrane as it approached Laurentia. (b) Late Ordovician and Siluran sandstone deposited on the Victoria terrane as it approached Laurentia. (c) Late Ordovician and Silurian trench-fill in the Southern Uplands terrane. (d) Ordovician syn- and post-accretion deposits on the Loch Nafooey arc, S. Mayo trough and adjoining areas, NW Ireland. (e) Late Ordovician Partridge Formation deposited on the Bronson Hill terrane

#### 4.1.6. *Tyrone central inlier*

A small area of inferred Dalradian rocks in the Midland Valley terrane in Ireland (Fig. 10 Section 4.2.1), the *Tyrone central inlier* (Fig. 10), is surrounded by an ophiolitic and younger rocks; the inlier was interpreted by Chew et al. (2008) and Cooper et al. (2011) to represent an offshore microcontinent detached from the Laurentian margin. A single detrital zircon data set reported by Chew et al. shows a typical Laurentian distribution of zircon, though with an unusually large peak at 1.5 Ga (Fig. 14 h). The distribution more nearly resembles distributions from allochthonous rocks in Newfoundland (Fig. 14 f, g) than the Dalradian rocks in Scotland (Fig. 14 i, j), which show smaller "Grenville" peaks and more abundant zircon in the younger Paleoproterozoic Era (1.6–1.95 Ga).

#### 4.1.7. *Connemara*

A block of dominantly metamorphic rocks assigned to the Dalradian Supergroup occurs in an anomalous position (compared with other Laurentian margin units) to the south of Iapetan arc rocks of the South

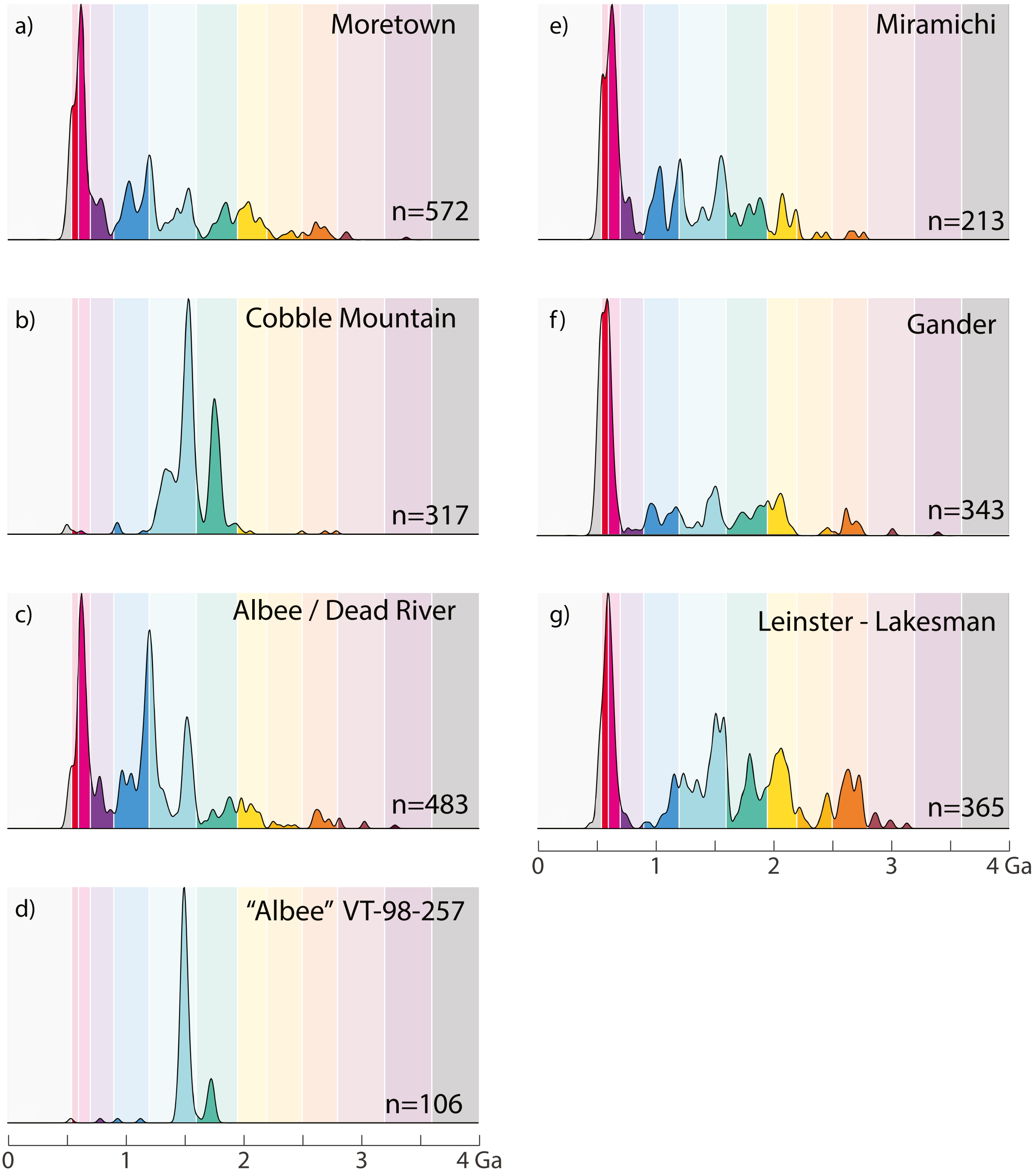


**Fig. 16.** Detrital zircon data from the first Ganderian cover succession (Fyffe et al., 2009; Macdonald et al., 2014; Waldron et al., 2014a; Willner et al., 2014; Wilson et al., 2015; van Staal et al., 2016, 2021; Karabinos et al., 2017; Henderson et al., 2018; Ludman et al., 2018). (a) Combined detrital zircon data showing typical Moretown terrane provenance). (b) Combined data from samples showing provenance typical of Cobble Mountain Formation. (c) Combined detrital zircon data from the Albee and Dead River Formation, Bronson Hill terrane. (d) Sample of Albee Formation comparable to Cobble Mountain terrane. (e) Combined data from Cambrian sandstone formations in the Miramichi – Liberty – Orrington belt. (f) Combined data from the Gander Group of Newfoundland. (g) Combined data from the Leinster–Lakesman terrane of Britain and Ireland.

Mayo trough (Fig. 10). Despite this anomalous position, the stratigraphy and Grampian tectonic history of the *Connemara block* is closely comparable to that of the main body of Dalradian rocks (Chew, 2009). This similarity has led to the suggestion (e.g. Dewey and Shackleton, 1984; Hutton and Dewey, 1986) that the Connemara Dalradian was brought into its present position by sinistral strike slip which duplicated a portion of the Laurentian margin, possibly coincident with the mid-Paleozoic strike-slip motion inferred to have juxtaposed the Scottish Grampian and Northern Highland terranes. However, more recent models have suggested that the Connemara block represents a most distal portion of the hyperextended Laurentian margin (Dewey and Ryan, 2016). Riggs et al. (2022) report detrital zircon populations containing a large "Grenville" peak from the cover of the Connemara block.

### 4.2. Iapetan oceanic and subduction-related rocks along the Laurentian margin

#### 4.2.1. South Mayo and Midland Valley terrane

South of the Grampian terrane, and separated from it by the Highland Boundary Fault (Fig. 1 b, Fig. 10) in Scotland, lies a belt in which Cambrian and Ordovician rocks of oceanic and arc aspect appear in a series of inliers below younger, Silurian to Carboniferous cover (Fig. 10, LNA, MVS). These regions are interpreted to represent oceanic arcs that were emplaced onto the Laurentian margin during Grampian arc–continent collision at a SE-dipping subduction zone, and then preserved as forearc basins above NW-dipping subduction. The largest of the inliers occurs in the *Clew Bay – S Mayo trough* area of western Ireland (Fig. 10), where ophiolitic rocks of late Cambrian to Early Ordovician age are overlain by a succession of arc-related volcanic and sedimentary rocks that have an excellent biostratigraphic record and a large detrital zircon database. The stratigraphy of the S Mayo trough spans the interval (~470 Ma) of peak Grampian metamorphism in the Grampian terrane to the N, so the S Mayo area was located in the upper plate of the Grampian arc-continent collision. Higher stratigraphic units record initial exposure and erosion of the Grampian terrane in their detrital provenance, showing distinctively Laurentian distributions with a large asymmetric "Grenville" peak in the Mesoproterozoic, a scarcity of early Paleoproterozoic grains, and a small Archean population (Clift et al., 2009; McConnell et al., 2009; Yin et al., 2012). These data are consistent with a model in which, following Taconian–Grampian arc-continent collision, a portion of the accreted arc / backarc terrane was trapped between the continental margin and a new trench formed by subduction polarity reversal (Dewey and Ryan, 2016).

Farther NE, the Tyrone central inlier (Fig. 10) is surrounded by an overthrust ophiolite with suprasubduction affinities, overlain by an arc succession interpreted by Chew et al. (2008) and Cooper et al. (2011) to represent an arc emplaced onto an offshore Laurentian microcontinent early in the Grampian orogeny.

In Scotland, analogous relationships are preserved along the Highland Boundary Fault (Fig. 10) in a series of highly deformed slices (Tanner and Sutherland, 2007) that appear to have been thrust over highest units of the Dalradian succession (Cawood et al., 2012) in the earliest stages of the Grampian event. However, the most studied ophiolitic rocks in Scotland occur at Ballantrae (Fig. 10), along the SE boundary of the *Midland Valley terrane*, where Cambrian to Early Ordovician ophiolitic rocks were highly dismembered prior to deposition of a Middle to Late Ordovician succession of fossiliferous shale, limestone, and conglomerate (Stone, 2014 and references therein).

#### 4.2.2. Notre Dame terrane

The Dashwoods block (Fig. 9, DSH), described in section 4.1.4, was overthrust onto ophiolitic and arc rocks of the *Notre Dame terrane* (or subzone; Williams et al., 1988) to the north between ~463 and 440 Ma (Brem et al., 2007). However, basement of the Dashwoods block has been interpreted to extend northward under the overthrust ophiolitic rocks (Lush's Bight oceanic tract; van Staal and Barr, 2012), based on zircon inheritance in plutons and volcanic rocks that were emplaced later in the Paleozoic Era. It is therefore likely that an initial early Taconian event emplaced the Notre Dame terrane above the Dashwoods block, and that a later, steeper thrust reversed this relationship along their current boundary.

#### 4.2.3. Annieopsquotch Accretionary belt

To the east of the Dashwoods block, a series of east-vergent, west-dipping thrust slices of ophiolitic rocks (ASQ, Fig. 9) make up the Annieopsquotch Accretionary tract of Lissenberg et al. (2005; Zagorevski et al., 2008, 2009), here termed *Annieopsquotch accretionary belt* because the term "tract" is used in a different sense in the Southern Uplands belt (section 4.2.4). The slices in the belt contain generally west-younging internal stratigraphy but overall, the slices young to the east from ~485 Ma to ~460 Ma. Exceptions are explained as the result of transcurrent movements along an irregular subduction boundary (van Staal et al., 2007). The Annieopsquotch Accretionary belt is presumed to record the subduction of Iapetan ocean floor, including arc fragments, following arc-continent collision and subduction polarity reversal or "flip" at the Laurentian margin.

#### 4.2.4. Southern Uplands belt

The *Southern Uplands belt* of Scotland and Ireland (Fig. 10, SUP) is dominated by turbidites of Late Ordovician to Wenlock age, which are disposed in a series of tectonic slices (or "tracts"), which become younger to the south (Fig. 6), but which show internal stratigraphy that dominantly youngs northward. Most tracts show a basal section of graptolitic pelagic shale (locally chert), overlain by immature sandstone turbidites; the incoming of turbidites is systematically younger from northwestern to southeastern tracts. These regularities led McKerrow et al. (1977); (Leggett et al., 1979) to suggest an origin in an accretionary wedge associated with subduction beneath the Laurentian margin. This reasonable suggestion was hotly contested in the late 20th century (e.g. Armstrong et al., 1996) but in the light of structural, metamorphic (Stone and Merriman, 2004), and provenance studies (Mange et al., 2005; Waldron et al., 2008) has come to be widely accepted since 2000.

#### 4.2.5. Detrital zircon record of peri-Laurentian accretion

Fig. 15 shows grouped detrital zircon data for turbidites deposited in the inferred trench along the composite Laurentian margin from Late Ordovician until Wenlock. Three plots show, respectively, distributions for the cover of the Miramichi terrane deposited as it was accreted to composite Laurentia, equivalent rocks of the Badger belt of Newfoundland, and a large data set for the Southern Uplands terrane in Ireland and Britain. The three distributions are markedly similar: all show a quantity of Paleozoic zircon presumably associated with arcs along the composite Laurentian margin, a large late Mesoproterozoic "Grenville" peak, and a smaller amount of older Mesoproterozoic and late Paleoproterozoic zircon. Early Paleoproterozoic zircon (2.0–2.5 Ga) is conspicuously scarce, whereas a small amount of Archean zircon is present in all the distributions. In contrast with the extended Ediacaran to Cambrian Laurentian margin, which shows considerable longitudinal variation in its detrital zircon, these Ordovician to Silurian foredeep deposits are remarkably homogeneous. As a result, the proportion of "Grenville" (0.9–1.2 Ga) zircon in the Southern Uplands is much greater, relative to older Mesoproterozoic components, than in the Grampian terrane, which lies adjacent to the north. A more detailed examination of the individual samples (Waldron et al., 2014a) showed that the accreted slices in the Southern Uplands become less "Grampian" and more "Appalachian" in character from NW to SE, with increasing "Grenville" content in the later-accreted slices. These changes suggests that material was increasingly transported northeastward along the margin with time during the Late Ordovician and early Silurian; however, this transport might have resulted from strike-slip motion of tectonic slices (e.g. Soper and Hutton, 1988) or from axial sedimentary transport (e.g. Stone et al., 2010).

## 5. Terranes associated with Gondwana or Baltica

### 5.1. Ganderia

The name Ganderia (van Staal et al., 1998) derives from the Gander Zone of Williams (Williams, 1979) and ultimately from the Gander Group of Newfoundland, a thick unit of continentally derived clastic metasedimentary rocks, probably mainly Cambrian in depositional age. Though often described as a "terrane", Ganderia is more properly understood as a domain (Hibbard et al., 2007) consisting of multiple individual terranes, of which the Gander terrane in Newfoundland is one. Authors have differed in their interpretations of the number of separate pieces of Ganderia that travelled across the Iapetus Ocean, from an original concept of a single terrane, that became divided prior to accretion to Laurentia, to two pieces separated by a Tetagouche-Exploits backarc basin (van Staal et al., 2012), to as many as four or five separate fragments (Waldron et al., 2019b).

Ganderia is the subject of a recent overview paper (van Staal et al., 2021) which synthesized previous work, described the main component terranes, and identified the Gander Group as a typical representative of Ganderia's first cover succession (GCS1). Comparable successions are found in many Ganderian terranes; they are typified by successions of grey-green quartzose metawacke, in many places exhibiting a "pinstriped" appearance due to a combination of original sedimentary lamination and multiple metamorphic fabrics. Their detrital zircon distributions are notably uniform from the Moretown terrane in southern New England to Anglesey in North Wales (Fig. 16), exhibiting large concentrations of Ediacaran zircon at ~550 and/or ~620 Ma, and broad distribution of Mesoproterozoic and Paleoproterozoic zircon including significant amounts in the "Eburnean" interval 1.95–2.2 Ga that is rare in Laurentia.

In contrast, in a number of Ganderian terranes, approximately the same time interval is represented by Cambrian arc to backarc igneous rocks termed the Penobscot arc (van Staal et al., 2021 and references therein). Deposition of GCS1 in the metaclastic-dominated terranes was followed by an orogenic episode or episodes, known as Penobscottian in the Appalachians and Monian in the Caledonides, which resulted in emplacement of Penobscot arc ophiolitic and rift-related rocks above GCS1 in, respectively, Newfoundland and Maine (Colman-Sadd et al., 1992; Pollock et al., 2022).

After Penobscottian deformation, a second cover succession (GCS2 of van Staal et al., 2021) is represented in some terranes by varied clastic sedimentary and volcanic rocks deposited during the Middle to Late Ordovician. Where volcanic-dominated, these successions are attributed to a second arc succession, the Popelogan–Victoria arc, behind which opened a backarc basin (Tetagouche–Exploits backarc) interpreted to have divided Ganderia, after the Penobscottian event, into at least two pieces, which were separately accreted to composite Laurentia at the beginning and end of the Silurian. The latter fragment, or fragments, carry Silurian volcanic and sedimentary successions that record a third interval of arc–backarc development, extending from coastal Maine to southern Newfoundland, here termed the *coastal igneous belt* (CIB). Silurian volcanic rocks are found in an analogous position in Anglesey, and in parts of SW Ireland, Wales and England.

The development of ideas on Ganderian terranes, and an emphasis on two-dimensional cross-sections, has led to a somewhat confusing terminology in which "leading" and "trailing" fragments of Ganderia are named in relation to their inferred motion towards Laurentia, and in which a "Gander margin" is actually a microcontinental fragment with two margins (e.g. van Staal et al., 2021). Studies in North Wales (e.g. Pothier et al., 2015a; Schofield et al., 2020) and in southern New Brunswick (e.g. Waldron et al., 2015) have emphasized that original terrane relations have been dismembered by strike-slip components of motion, making it difficult to apply terminology based solely on convergence and divergence. In the following sections we focus on the individual terranes attributed to Ganderia, using terrane names based on present-day geography, with emphasis on their sedimentary and paleomagnetic records. In the later discussion, we suggest revised grouping schemes that reflect, on the one hand, an inferred distribution on the margin of Gondwana in the Ediacaran to Cambrian, and on the other, an inferred history of transit across Iapetus and accretion to Laurentia from Ordovician to Devonian.

### 5.2. Ganderian terranes accreted in the Ordovician

#### 5.2.1. Moretown terrane

The *Moretown terrane* (Fig. 7, MOR) of New England was identified as a Gondwana-derived terrane by Macdonald et al. (2014) on the basis of detrital zircon signatures. The Moretown Formation, of probable Cambrian age, consists of "pinstriped" granofels and quartz-rich foliated metamorphic rocks with amphibolite, that were intruded by 502 ± 4 Ma (Miaolingian) tonalite (Macdonald et al., 2014). Its detrital zircon record (Fig. 16 a) is distinctively and clearly Gondwanan (Macdonald et al., 2014), containing prominent concentrations of Neoproterozoic zircon, typically at ~620 and/or ~550 Ma. Some samples contain early Cambrian (~530 Ma) zircon. Mesoproterozoic and Paleoproterozoic grains are abundant, and are typically present in subequal amounts, ranging back to ~2.2 Ga. Along the western margin, where the terrane is in contact with the Laurentian Rowe Schist (Fig. 3), ultramafic lenses suggest the presence of a suture (Karabinos et al., 2017), marking the boundary between Laurentia and peri-Gondwanan fragments. Moreover, the Moretown Formation is structurally overlain on its eastern margin by the Hawley Formation and equivalent units (Karabinos et al., 2017), consisting of pelitic and mafic schist and gneiss with characteristics of island-arc tholeiite, mid-ocean-ridge / backarc-basin and boninite (Kim and Jacobi, 1996) constrained to be 475.5 ± 0.2 Ma or older (Macdonald et al., 2014). The Hawley Formation shows clear input of Laurentian zircon (Macdonald et al., 2014), demonstrating that the Moretown terrane had arrived on at least a distal fragment of the Laurentian margin by 475 Ma (Floian).

To the northeast, the distinctive Gondwanan detrital zircon populations described by Macdonald et al. (2014) continue to a point close to the Vermont–Québec border; no equivalent Gondwanan detrital zircon populations have been described along strike to the north (Waldron et al., 2019b), although Karabinos et al. (2017) correlated the Moretown Formation with the Albee Formation of the Bronson Hill Arc (see section 5.2.2.1) to the east (Fig. 3, Fig. 7).

Southward, the Moretown terrane was traced by Karabinos et al. (2017) into Connecticut, where it is represented by the Cobble Mountain Formation. Three of four samples analysed by Karabinos et al. (2017) show detrital zircon populations (Fig. 16 b) dominated by twin peaks at ~1.55 and 1.7 Ga, almost entirely lacking Neoproterozoic zircon, distinctively different from the Moretown Formation, suggesting the presence of a separate Mesoproterozoic block that was not involved in Ediacaran events during the amalgamation of Gondwana. However, a fourth sample shows a population typical of the Moretown Formation farther north, suggesting that an undescribed terrane boundary is present within the mapped Cobble Mountain Formation. Intrusions of the Shelburne Falls Arc extend into the Late Ordovician in this area.

The Moretown terrane is heavily overprinted by deformation and metamorphism; no paleomagnetic results are available. Detrital zircon populations from overlying successions (compiled by Waldron et al., 2019b) are dominated by Mesoproterozoic ("Grenvillian") grains with input from Gondwanan terranes suggested by small Neoproterozoic and older Paleoproterozoic peaks. The entire edifice was folded in Acadian and Devono-Carboniferous, Quaboagian deformation (Robinson et al., 1998); an Alleghanian overprint increases in intensity southward (e.g. Wintsch et al., 2014).

### 5.2.2. Bronson Hill – Popelogan terrane

The *Bronson Hill arc* (Fig. 7, BRN) lies east of the Shelburne Falls arc in New England, across a Mesozoic half-graben (Hartford basin) associated with Atlantic Ocean opening. In the south, the inliers take the form of gneiss domes, strongly interfolded with Silurian–Devonian cover and overprinted by Acadian and Alleghenian metamorphism. An Ordovician volcanic succession (Ammonoosuc volcanics; Fig. 3) is commonly interpreted (e.g. Hibbard et al., 2007) to represent a peri-Gondwanan arc. Metaclastic rocks of the Albee and Dead River formations, previously interpreted as Ordovician, are clearly correlative with Ganderian GCS1 (van Staal et al., 2021), based on their detrital zircon provenance (Karabinos et al., 2017). To the north, the metamorphic grade declines but the belt becomes less continuous; a series of inliers can be traced at least as far as the Popelogan inlier in northern New Brunswick (Fig. 8). These inliers contain a record of pre-Ammonoosuc deformation attributed to the Penobscot (or Penobscottian) Orogeny (Neuman, 1967). Van Staal et al. (1996, 2016; van Staal and Barr, 2012) have correlated this unit with the Victoria Arc in Newfoundland; however, Waldron et al. (2019b) subsequently suggested that the timing of accretion of the Victoria Arc more nearly matches that of the Miramichi terrane to the SE (see section 5.3).

*5.2.2.1. Bronson Hill arc and underlying rocks.* The oldest rocks in the southern Bronson Hill arc (Fig. 7) are gneiss units exposed in the core of the Pelham Dome of Massachusetts dated from 613 ± 3 Ma (Tucker and Robinson, 1990) to 576 ± 2 Ma (Karabinos et al., 2017). Overlying these rocks is a thick gneiss succession including arc metavolcanic rocks yielding Late Ordovician ages from 454 +3/-2 to 443 +3/-2 Ma (Tucker and Robinson, 1990). Karabinos et al. (2017) compiled intrusive ages from the arc that range from ~475 Ma (Floian) to 442 (Llandovery), with a peak at ~450 Ma. The relationship between the basement rocks and the overlying gneisses is poorly understood, as the basement rocks appear to have escaped the Ordovician igneous activity and Devonian metamorphism that affected the cover succession, suggesting that basement may have been underthrust into its present position from the south or east during later deformation (Robinson et al., 1998)

The Neoproterozoic basement succession disappears north and south but the overlying Ordovician intrusive and volcanic rocks (Ammonoosuc volcanics; Fig. 3) can be traced northwards into NW Maine (Fig. 7), where they are underlain not by gneisses but by a metaclastic succession assigned to the Albee Formation and its correlatives. The Albee Formation resembles the Moretown Formation, both in its lithology and detrital zircon characteristics. Like the Moretown Formation, most samples display peaks in the KDE plots at ~620 Ma, with minor amounts of younger zircon at 550-530 Ma (Fig. 16 c). There is a broad distribution of Meso- and Paleoproterozoic zircon, but the majority of samples display a conspicuous peak at 1200 Ma, in contrast to the Moretown Formation. A single sample from the Karabinos et al. (2017) data set (Fig. 16 d) resembles the Cobble Mountain Formation of the Moretown terrane.

These overall similarities led Karabinos et al. (2017) to suggest that the Bronson Hill belt was part of the Moretown terrane. However, the overlying arc successions appear different; whereas the Hawley Formation, deposited on the Moretown terrane, includes clastic Laurentia-derived material prior to 475 Ma, the Bronson Hill / Ammonoosuc volcanic succession continues without evidence of such input into the Late Ordovician where Tucker and Robinson (1990) dated the upper part of the volcanic succession in Massachusetts at 453 ± 2 Ma. Hildebrand and Whalen (2021) interpreted plutons of similar, Late Ordovician age in the Bronson Hill arc as products of slab-break-off. The Ammonoosuc Volcanics are overlain, and apparently interfinger with, black shale and lesser (meta-) volcanic rocks of the Partridge Formation (Fig. 3). In Massachusetts (Fig. 7, close to the dated Ammonoosuc volcanics) these rocks are dated at 449 +3/-2 Ma (Katian). However, farther north, in northern New Hampshire, shale mapped as Partridge Formation overlying Ammonoosuc volcanics contains graptolites assigned to the Sandbian (458.4 – 453 Ma) *Climacograptus bicornis* or *Nemagraptus gracilis* biozones (Cooper et al., 2012). Even given potential errors in the timescale, these dates show that the Partridge Formation is strongly diachronous. The issue is significant, because the earliest Laurentia-derived zircon population in the Bronson Hill arc is interpreted in the Partridge Formation (Fig. 15 e) by Karabinos et al. (2017); (their Fig. 2) at 457 Ma. However, the unit sampled by Karabinos et al. lies far from the Sandbian graptolite locality but close to the unit dated by Tucker and Robinson (1990) at 449 +3/-2 Ma. This timing would place the accretion of the Bronson Hill terrane ~25 Myr later than that of the Moretown terrane, consistent with the timing of slab break-off inferred by Hildebrand and Whalen (2021), and also with relationships around the Popelogan inlier in New Brunswick, Canada (see section 5.2.2.3).

Succeeding detrital zircon populations from forearc basin deposits of the overlying Quimby succession (Moench and Aleinikoff, 2003) show large components of late Mesoproterozoic zircon derived from the Grenville Orogen and/or major input from the Laurentian active volcanic margin ~420 Ma, in many areas swamping input from the accreted Gondwanan terranes (Bradley and O'Sullivan, 2016; Waldron et al., 2019b).

*5.2.2.2. Northern Maine inliers.* Traced to the NE, the Bronson Hill arc is represented by a series of anticlinal inliers surrounded by younger rocks of the Connecticut Valley – Gaspé (CVG) and the Central Maine (CMT) troughs (Fig. 7). Their stratigraphy was summarized by Berry and Osberg (1989), based on compilations of earlier work (Neuman, 1967, 1984; Hall, 1970). Van Staal et al., 2016, 2021 compared the Popelogan inlier with the inliers of northern Maine and showed that all have comparable stratigraphies.

In the *Chesuncook inlier* (Fig. 7), Schoonmaker and Kidd (2006) reported a lower succession including Cambrian Dead River Formation (GCS1) analogous to that in the main outcrop of the arc to the SW, but passing laterally into quartzite and conglomerate (Sawmill Formation), and overlain by varied metaclastic rocks (Southeast Cove Formation). All were intruded by 473 Ma gabbro, and overlain by a volcanic unit (Dry Way Volcanics) that may be its extrusive equivalent. These igneous rocks were interpreted by Schoonmaker and Kidd (2006) to record subduction of a ridge.

In the *Weeksboro–Lunksoos inlier* (Fig. 7), Neuman (1967, 1987) identified early Cambrian clastic sedimentary rocks, assigned to the Grand Pitch Formation (Fig. 4), marked by the presence of the distinctive Cambrian trace fossil *Oldhamia*, that were deformed prior to deposition of an unconformable cover of tuffaceous sedimentary and volcanic rocks (Shin Brook Formation) with Middle Ordovician fossils, subsequently confirmed by an isotopic date of 467 ± 5 Ma. The event represented by the unconformity was named the Penobscot disturbance by Neuman, and subsequently identified widely in the terranes assigned to Ganderia. The Shin Brook volcanic succession is overlain by a succession of cherts and sparsely graptolitic shales that extend into the Late Ordovician (Neuman, 1967).

The *Munsungun inlier* (Fig. 7), to the NW, displays comparable geology, including an early succession, described as metaclastic by Hall (1970) but as a mélange by Berry and Osberg (1989), who also reported unpublished Tremadocian fossils from the unit. Wang (2019) confirmed the fragmental nature of the unit, interpreting it as an 'olistostromal mélange' but noting an extremely strong metamorphic fabric. It is overlain by a laterally variable succession of Middle Ordovician sedimentary and volcanic rocks, including a unit dated at 467 ± 4 Ma, identical to that in the Shin Brook succession. An overlying unit of Late Ordovician graptolitic shale occurs in a comparable position to, but slightly older than, that in the Weeksboro-Lunksoos inliner.

No detrital zircon data are available from pre-accretion deposits in these northern Maine inliers, but numerous data sets from the

Connecticut Valley – Gaspé trough to the north, and the Central Maine trough to the south, show predominant Laurentia-derived populations (with large peaks at ~0.95 – 1.2 Ga) (De Souza et al., 2014; Perrot et al., 2017, 2018).

Several paleomagnetic studies have focussed on the northern Maine inliers. Results have been reported for steeply dipping pillow basalt flows and associated gabbroic rocks of the Bluffer Pond Formation (Potts et al., 1993) and pillow basalt flows of the Winterville Formation (Potts et al., 1995) in the Munsungun and related Pennington inliers (Fig. 7), respectively (Table 2). Both studies resolved a characteristic remanent magnetization (ChRM) direction that predated folding and was interpreted to be of primary Ordovician age, with biostratigraphic constraints putting Bluffer Pond eruption at 464 Ma, shortly before interpreted accretion to Laurentia (Waldron et al., 2019b), and Winterville eruption at 451 Ma, approximately synchronous with stratigraphically estimated accretion. The resultant paleopoles are similar to Middle to Late Ordovician paleopoles for Laurentia (Torsvik et al., 2012; Jin et al., 2013; Domeier, 2016; Wu et al., 2022), implying that this portion of Ganderia was already close to the Laurentian margin by Middle Ordovician time, with little or no net rotation. One caveat is that the paleopoles also resemble the Early Carboniferous (340–320 Ma) portion of the apparent polar wander path (APWP) of Laurentia (Torsvik et al., 2012). However, if the pre-folding ChRM directions were an Early Carboniferous overprint, then the subsequent major deformation in the Munsungun inlier would be Alleghenian, for which there is no other evidence. Also, some sites in the Bluffer Pond Formation retain a post-folding overprint direction that is likely a Late Carboniferous remagnetization (Potts et al., 1993), indicating that folding occurred prior to Late Carboniferous. We therefore consider the two pre-folding results to be primary Ordovician magnetizations representing Ganderia, but note that their reliability index (R) value is lowered by their similarity to the Early Carboniferous APWP of Laurentia.

Paleomagnetic results are also reported from the Stacyville Formation pillow basalt flows of the Lunksoos inlier (Wellensiek et al., 1990), with a biostratigraphically constrained age of ~463 Ma. Two ChRM components were identified, the dominant magnetization in the collection having a post-folding direction corresponding to a Late Carboniferous overprint at 310–300 Ma. A limited number of samples from a few sites appear to retain an older high-temperature ChRM direction. Additional samples have mixed overprint and high-temperature ChRM components, for which great-circle analysis was used to isolate the ancient magnetization direction from the overprint direction. The tilt-corrected ancient ChRM direction cannot be younger than Ordovician, based on directions expected from the Laurentia APWP. No fold test was possible, however, so the authors concluded that the high-temperature ChRM could either be primary or a Late Ordovician overprint, oriented somewhat counter-clockwise (CCW) with respect to the expected Ordovician directions in Laurentia (Wellensiek et al., 1990), suggesting that this portion of the Bronson Hill arc underwent CCW rotation during or after its accretion.

*5.2.2.3. Popelogan inlier.* Farther NE, in New Brunswick, the Popelogan inlier (Fig. 4, POP) occupies an area of less than 20 km$^2$. Volcanic rocks of the Goulette Brook Formation, like those of the Chesuncook dome, record unusual arc environments probably correlated with subduction of a ridge (Wilson, 2003). They are overlain by a unit of shale and chert, the Popelogan Formation. These units are separated from the overlying Grog Brook and Matapedia groups of the Laurentian forearc basin by an angular unconformity (Fig. 4), interpreted (van Staal et al., 2016; Waldron et al., 2019b) as recording the accretion of the Popelogan arc to the Laurentian margin. Accretion is thereby bracketed between the *Nemagraptus gracilis* zone graptolites in the Popelogan Formation (~457–458 Ma) and fossils from the overlying Grog Brook Group, which potentially span the *Dicellograptus complanatus* and *D. anceps* zones (~445–448 Ma). There are no detrital zircon records from the Popelogan inlier itself, but detrital zircon data from the immediately overlying unconformable cover (Wilson et al., 2015) clearly show that the terrane had docked to Laurentia and was exposed at the surface by the earliest Silurian.

### *5.3. Terranes accreted near the Ordovician–Silurian boundary*

The Miramichi and Elmtree inliers occupy a large area of northern New Brunswick (Fig. 8), where they have been intensively documented in the work of van Staal and others (van Staal, 1987, 1994; van Staal et al., 1990, 1996, 2003, 2008; van Staal and de Roo, 1996; Wilson et al., 2015). The inliers consist of a broadly north-dipping stack of thrust slices that have undergone polyphase deformation and metamorphism locally to blueschist facies. Upper slices are ophiolitic. The lower slices include thick quartzose turbidites typical of GCS1, overlain by mid-Ordovician arc volcanic rocks and Late Ordovician turbidites that record the approach of the terrane to composite Laurentia. Fig. 4 shows the stratigraphy of selected slices; more complete details are shown by Wilson et al. (2015).

To the SW, equivalent rocks have been identified in the Liberty–Orrington belt of Maine, which mainly exposes mid-Ordovician arc metavolcanic rocks (West et al., 2003), located between the Central Maine trough and the Merrimack–Bucksport–Fredericton trough. The Massabesic gneiss (MSB) of southern New England is a possible correlative farther south (Fig. 7).

In Newfoundland (Fig. 9), peri-Gondwanan rocks accreted to Laurentia in the Late Ordovician are found in the western part of the Exploits subzone of Williams et al. (1988), known as the Badger belt. However, the Exploits subzone, as defined, also includes successions to the east of the Dog Bay line (Davidsville belt) which overlie the Gander terrane and show clear stratigraphic contrasts with the rocks to the west, which have no currently assigned terrane name. The rocks west of the Dog Bay line are here referred to as the *Victoria terrane* (Fig. 9, VIC).

#### *5.3.1. Elmtree inlier*

South and east of the Popelogan inlier, a stack of thrust slices is exposed in the *Elmtree inlier* (Fig. 8, ELM). The highest slice consists of Ordovician, ophiolitic rocks of the Fournier Supergroup, assigned to the Devereaux complex. These units lack pre-Ordovician basement and are presumed to have been largely oceanic, attributed to the ensimatic parts of the Tetagouche–Exploits backarc basin by Wilson et al. (2015); the lowest slice can be correlated into the Miramichi inlier to the south. The Elmtree inlier is unconformably overlain by Rhuddanian basal units of the Matapedia forearc basin (Duncans Brook Formation; Fig. 4) containing distinctively Laurentian detrital zircon, showing that accretion to the Laurentian margin and exhumation had occurred by about the Ordovician–Silurian boundary. Underlying slices of the Pointe Verte and Sormany Groups (Fig. 4) contain a mixture of clastic and mafic volcanic rocks, from which several detrital zircon data sets are available, with depositional ages here inferred at ~457 to ~448 Ma. Most of these samples contain few Precambrian zircon grains and cannot unequivocally be assigned to Laurentian or Gondwanan sources. However, the youngest and largest (n=76) sample (Val Michaud Formation) is clearly Laurentian, and was probably deposited while the succession was entering the trench at the Laurentian margin (included in Fig. 15 a).

#### *5.3.2. Miramichi inlier*

Northernmost parts of the *Miramichi inlier* (Fig. 8, MRM) are correlated with the lower slices of the Elmtree inlier to the north, and assigned to the Sormany Group which locally overlies older mafic basement represented by the 543 Ma Southeast Upsalquitch River Gabbro. To the southeast, and lower in the structural stack, an Ordovician volcanic succession is represented by the arc-related Tetagouche Group, which overlies a substantial mainly clastic older succession assigned to the Miramichi Group (Fig. 4), part of GCS1 regarded as typical of the “Gander margin”, and assigned to the trailing margin of Ganderia, SE of the Tetagouche-Exploits backarc basin (e.g. van Staal, 2007; van Staal and Barr, 2012); these rocks can be broadly correlated stratigraphically with the Gander Group of Newfoundland. The Miramichi Group is largely unfossiliferous but its age is bracketed between 479 Ma rhyolite near the top of the succession (McNicoll et al., 2002) and early Cambrian (~535 Ma) youngest detrital zircons in a lower unit (Fyffe et al., 2009). The contact between the Tetagouche and Miramichi groups is at least locally unconformable, and was interpreted by van Staal, 1994 to record the Penobscottian orogenic event.

Detrital zircon populations in the Miramichi Group (Fig. 16) are distinctively Gondwanan, showing large concentrations of Neoproterozoic zircon grains at ~620 and/or 550 Ma. Most samples contain more Mesoproterozoic than Paleoproterozoic zircon; a peak at ~1.1 Ga is present in most samples, but the largest Mesoproterozoic peaks are typically at ~1.25 and ~1.55 Ga. Most samples contain a small amount of Paleoproterozoic zircon in the distinctive "Eburnean" interval 1.95-2.2 Ga.

Parts of the thrust stack in the Miramichi inlier have been subject to high-pressure, low-temperature metamorphism which reached pressures of 0.72 GPa at 375°C in the north during underplating of parts of the California Lake slice at 442 Ma (van Staal et al., 2008). Rapid exhumation followed, to preserve the localized blueschist assemblages and allow sedimentation of the unconformable early Silurian cover succession.

Despite the high degree of deformation and metamorphism, particularly in the California Lake slice, higher units in the inlier are preserved at low grade. Paleomagnetic results from the Tetagouche Group have been reported (Liss, 1993). Volcanic flows of ca. 465 Ma age (472–457 Ma U-Pb ages; van Staal et al., 1990), and a site in the underlying Fournier Group ophiolite complex, carry ChRM mean directions that cluster well after bedding correction, giving a steep, dual-polarity magnetization direction (Table 2). The resulting paleopole does not resemble any from Laurentia, and the steep tilt-corrected direction yields a paleolatitude of 53°S (Liss, 1993). Notably, the Tetagouche tilt-corrected declination is generally similar to that of the high temperature ChRM found in the ca. 463 Ma Stacyville Formation, suggesting that both ChRMs may have a similar, primary origin. Nonetheless, taken at face value, the results position the Tetagouche Group at least 1500 km south of the Laurentian margin at 465 Ma, and suggest substantial CCW rotation of the block as it approached Laurentia between 460 and 440 Ma. These results also indicate a position for the Miramichi terrane far from the Ordovician location of the Bronson Hill – Popelogan terrane, a result used as evidence for the existence of a substantial Tetagouche–Exploits backarc basin by van Staal et al., 2012. The structural correction for the Tetagouche result, however, is for regional-scale Silurian or later folding only; D1 structures inferred to be of Late Ordovician – early Silurian age (van Staal et al., 1990) are not accounted for, leaving open the possibility that the observed pre-folding dual-polarity ChRM may not be primary and could be an overprint magnetization as young as early Silurian (Liss, 1993) with uncertain reference to paleohorizontal and paleoazimuth.

### 5.3.3. Liberty–Orrington belt

Traced southwest in New England, the Miramichi inlier corresponds in position to high-grade metamorphic rocks in the *Liberty–Orrington belt* (Fig. 7, LBO) (Berry and Osberg, 1989; Tucker et al., 2001; West et al., 2003). The stratigraphic order of units is somewhat controversial, as most contacts are faulted, but the oldest rocks appear to be volcanic rocks of the Early to Middle Ordovician Cushing Formation (Fig. 3). Overlying units of the Casco Bay Group, and the laterally equivalent Passagassawakeag Gneiss, include multiple volcanic and clastic units that appear approximately equivalent to the Tetagouche Group of the Miramichi inlier. However, a thick quartzose metasedimentary unit, the Cape Elizabeth Formation, is also present in the belt. Structural cross-sections (Tucker et al., 2001; Hussey and Berry, 2002; Hussey and Marvinney, 2002; West et al., 2021) show the Cape Elizabeth Formation in an allochthonous thrust sheet thrust over rocks of the Bucksport Formation of the Fredericton – Bucksport – Merrimack belt.

Ordovician rocks of the Liberty–Orrington belt are overlain by Silurian to Devonian strata of the Central Maine trough (Fig. 7) that extend northward to the Lunksoos–Weeksboro and Munsungun inliers, described above. However, farther NE in Maine, there is a gap between the Liberty–Orrington belt and the Miramichi inlier, where Silurian forearc basin rocks of the Central Maine trough are juxtaposed with Silurian turbidites of the Merrimack–Bucksport–Fredericton (MBF) or "Merribuckfred" (Hussey et al., 2010) belt. The two belts display similar facies and ages, and the boundary between them is difficult to define (Ludman et al., 2018). Most of the sedimentary strata in the Central Maine trough and the northern part of the Fredericton belt are dominated by Laurentian zircon, although some samples show mixed Laurentian and Gondwanan provenance (Dokken et al., 2018; Ludman et al., 2018)

The southernmost inlier of pre-Silurian rock in the belt that separates the Merrimack and Central Maine troughs is the *Massabesic Gneiss complex* of New Hampshire (MSB; Fig. 7). Although the rocks have undergone Acadian and Alleghanian metamorphism, a protolith age of orthogneiss at ~625 Ma has been reported, together with geochemical characteristics, including positive $\varepsilon_{Nd}$ values in paragneisses, that are compatible with other Ganderian terranes (Dorais et al., 2001, 2012a and references therein). A single sample of paragneiss yielded a distinctive detrital zircon population dominated by ~1.25 and ~1.55 Ga zircon, lacking the other components (Neoproterozoic and "Eburnean" populations) typical of Ganderia (Fig. 17a). Like the Cape Elizabeth Formation, its zircon distribution shows similarities with rocks in the St. Croix terrane, and also with samples from the Monian terranes of Britain, and with basement units of the Southeastern New England terrane generally attributed to Avalonia.

### 5.3.4. Badger belt and Victoria terrane

To the northeast, rocks in the Badger belt of Newfoundland (Fig. 9), here termed the Victoria terrane for the Victoria Lake Supergroup (e.g. Zagorevski et al., 2007), began their accretion to Laurentia at about the same time as the Miramichi terrane. However, they differ from the Miramichi terrane rocks in several important respects.

Much of the terrane consists of a series of originally west-dipping structural slices (Fig. 5), in which the oldest rocks are Ediacaran (~563 Ma) intrusive rocks and volcanic successions (Rogers et al., 2006). Negative $\varepsilon_{Nd}$ values indicate derivation from older Ganderian crustal rocks, but the Victoria terrane lacks Cambrian clastic rocks attributable to GCS1, in contrast to the Gander terrane to the SE, and the Miramichi and Bronson Hill terranes along strike to the SW in New Brunswick and New England. Two younger arc successions occur within the multiple thrust sheets shown by Zagorevski et al. (2010). Cambrian arc rocks (515–485 Ma: the Penobscot arc of Zagorevski et al., 2010) record large amounts of extension in a suprasubduction environment, including the development of an ophiolite (South Lake Igneous complex), whereas the younger Victoria arc (473–450 Ma) includes a mix of sedimentary and diverse volcanic rocks, correlative with "Ganderia's second cover succession" (GCS2) of van Staal et al. (2021). The two arc successions are separated by an inferred unconformity representing the Penobscottian Orogeny (van Staal et al., 2021).

In the northwesternmost thrust sheet of the Badger belt (Toogood thrust sheet), Ordovician volcanic rocks are unconformably overlain by Silurian conglomerate (Reusch, 1987). In remaining thrust sheets to the SE, these arc rocks are conformably overlain by late Ordovician to Silurian black shale and sandstone turbidites of the Badger Group, showing a first influx of Laurentian detrital zircon in the *Dicranograptus clingani* zone (Sandbian), ~453–451 Ma. In contrast to the Miramichi terrane, this succession is not immediately truncated by thrust faults, nor metamorphosed under high pressure/temperature (P/T) conditions, but continues into the Telychian (~435 Ma). It is cut by numerous thrusts, some of which were active during sedimentation (Reusch, 1987; van Staal et al., 2014; O'Brien, 2003) indicating a continued tectonically active depositional environment. The Badger group was eventually intruded by plutonic rocks ~435 Ma and unconformably overlain by the Charles Lake volcanic suite (~429 Ma) and the Botwood Group (~429 to 423 Ma). Subsequent NW-vergent Acadian thrusting has reworked the late Salinian SE-vergent thrusts that stacked sheets within the Victoria terrane.

Pre-accretion successions in the Victoria terrane largely lack sandstone units suitable for detrital zircon provenance studies. The available data from Late Ordovician and younger rocks are dominated by Laurentian "Grenville" sources and are inferred to record stages in the accretion of the terrane to Laurentia (Waldron et al., 2012) (Fig. 15).

### 5.4. Terranes accreted south of the Liberty - Dog Bay - Navan - Solway line

#### 5.4.1. Liberty – Dog Bay – Navan – Solway line

The foregoing terranes, all assigned to Ganderia (e.g. van Staal and Barr, 2012; van Staal et al., 2012) lie to the north of a belt of Silurian

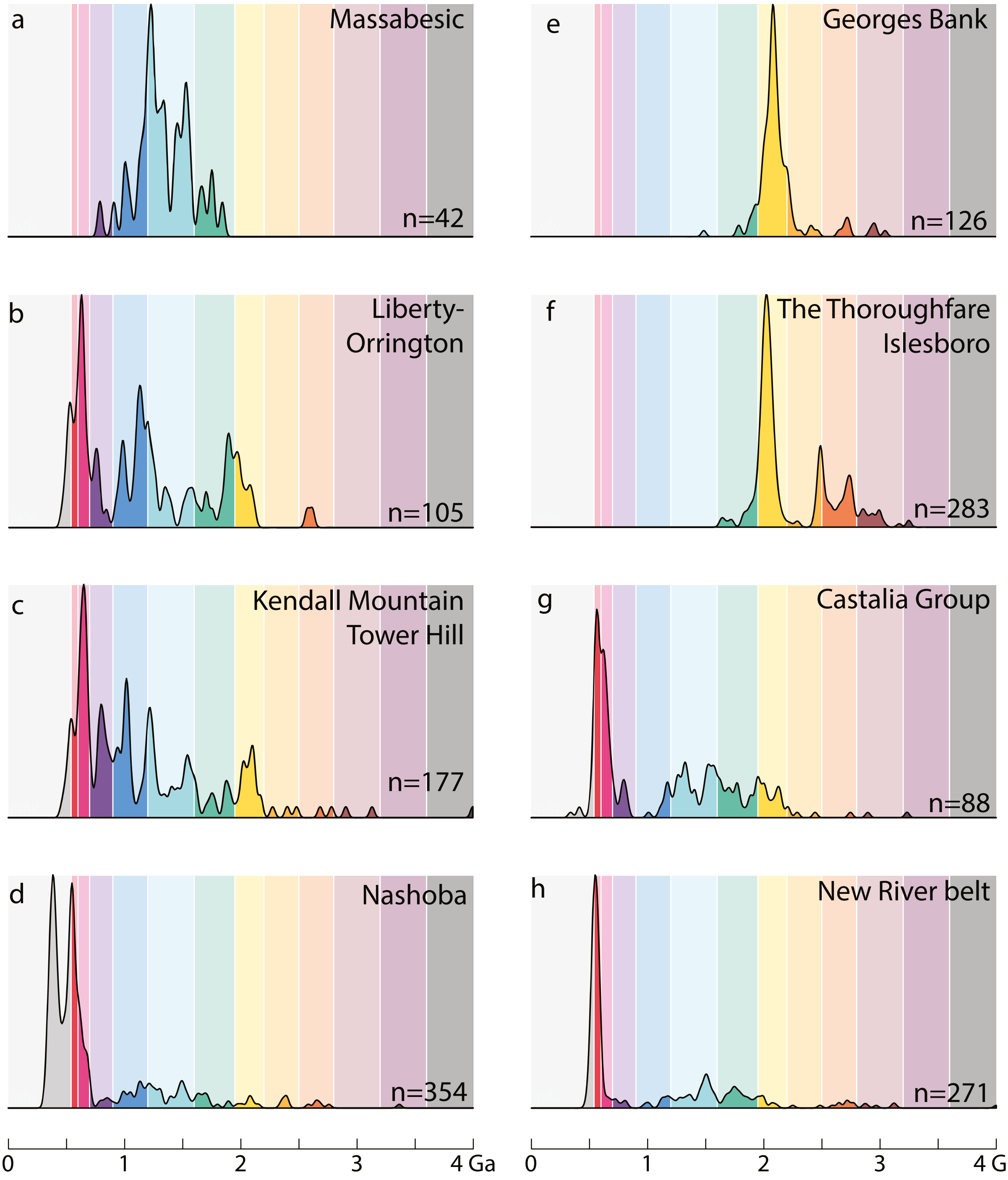


**Fig. 17.** Detrital zircon data from non-Avalonian terranes in SE New England and New Brunswick, showing evidence for diverse sources (Fyffe et al., 2009; Dorais et al., 2012a; Barr et al., 2014b, 2019; Kuiper et al., 2017; Ludman et al., 2017, 2018; Johnson et al., 2018; Reusch et al., 2018; Cartwright et al., 2019; Hepburn et al., 2021; Walsh et al., 2021). (a) Massabesic paragneiss. (b) Liberty-Orrington belt, Casco Bay Group. (c) Inferred post-Penobscottian units at NW margins of Nashoba and St. Croix terranes: Kendall Mountain and Tower Hill formations (d) Nashoba Terrane. (e) Offshore Georges Bank. (f) Precambrian quartzose sandstones in Islesboro slice of St. Croix terrane, and Grand Manaan Island. (g) Combined Castalia Group, Grand Manan Island; (h) New River belt.

Llandovery to Wenlock metasedimentary rocks in the Merrimack–Bucksport–Fredericton (MBF) or "Merribuckfred" (Hussey et al., 2010) trough (Fig. 7, Fig. 8). Detrital zircon data (Fig. 18) from the northern part of the MBF belt in New Brunswick show Laurentian input throughout the Rhuddanian to Sheinwoodian (~444–430 Ma) interval, but the Sheinwoodian sample shows mixed provenance, interpreted to record input from the exhumation of the Miramichi terrane to the north (Dokken et al., 2018). In the south of the trough (Digdeguash Formation), Rhuddanian rocks contain no trace of Laurentian input, being dominated by ~620 Ma Ediacaran zircon, suggesting a Gondwanan source that is nonetheless distinct from GCS1 in the Miramichi terrane. The population is similar, however, to that from the fine-grained Calais Formation (Fig. 4) that lies at the top of GCS1 in the St. Croix terrane to the south (Fyffe et al., 2009). Overlying undated turbidites (Flume Ridge Formation), that are cross-cut by the ~422 Ma Pocomoonshine pluton, contain abundant late Mesoproterozoic zircon grains suggesting a Laurentian source. The upward transition from Gondwanan to Laurentian provenance is interpreted as recording the closure of a late remnant of the Iapetus Ocean (Reusch and van Staal, 2012; Dokken et al., 2018; West et al., 2021)

To the SW, in New England, additional samples (Ludman et al., 2017) from the MBF trough (Fig. 18) show the same dichotomy between Gondwanan and Laurentian sources, although the divide does not correspond to mapped formation boundaries. Lack of fossils due to higher metamorphic grade impedes interpretation of the timing of trough closure in this region.

In Newfoundland (Fig. 9) sedimentary rocks along the Dog Bay Line (Williams et al., 1993; Pollock et al., 2007; Reusch and van Staal, 2012) are probably equivalent to those of the MBF trough. Equivalent rocks in Britain and Ireland (Fig. 10) occur in the central and southern belts of the Southern Uplands, dominated by Laurentian zircon (Waldron et al., 2008), the southern border of which is traditionally marked as the Iapetus suture along the Navan Line in Ireland and the Solway Line in northern England (McKerrow et al., 1977; Leggett et al., 1979; Bluck et al., 1992).

In Ireland, relations at the southern margin of the Southern Uplands terrane are complicated by the presence of the Grangegeeth terrane (Fig. 10), which contains an older, Ordovician arc with detrital zircon of Laurentian aspect, suggesting complexities in the relatively simple picture of subduction. Possibilities include sinistral strike-slip motion along the Laurentian margin (McConnell et al., 2010) or the presence of a second Ordovician arc isolated (McConnell et al., 2019) within the Iapetus Ocean.

In the Leinster–Lakesman terrane (Fig. 10) to the south, Laurentia-derived zircon grains first arrived in the Wenlock (Waldron et al., 2014a). Therefore, despite their assignment to the domain Ganderia, this terrane arrived at the Laurentian margin significantly later than Ganderian fragments assigned to the Miramichi, Bronson Hill, and Moretown terranes (Waldron et al., 2019b).

### 5.4.2. Putnam–Nashoba terrane

The *Putnam–Nashoba terrane* of southern New England (Fig. 7, NSH), recognized as part of the Gander zone by Williams (1978b, 1978a), lies outboard of metasedimentary strata assigned to the Central Maine and Merrimack belts (Fig. 3, Fig. 7). Both belts were deformed and metamorphosed at amphibolite facies in the Devonian to Carboniferous Acadian and Quaboagian events, which in many cases have generated young metamorphic rims on older magmatic and detrital minerals (Wintsch et al., 2007; Kay et al., 2017; Walsh et al., 2021; Hepburn et al., 2021). This creates challenges in interpreting both the depositional age and the provenance of published detrital zircon populations, leading to contrasting tectonic interpretations. The terrane itself is characterized by generally mafic high-grade metavolcanic rocks (Marlboro Formation and equivalent Quinnebaug Formation of Connecticut) with crystallization ages from latest Ediacaran (~543 Ma) to Miaolingian (~499 Ma) and possibly younger (Hepburn et al., 1995; Kay et al., 2017; Walsh et al., 2021). A stratified succession in Massachusetts, the Nashoba Schist, which is dominantly igneous at the base but passes up into pelitic schist, is interpreted to be younger. The igneous rocks of both the Marlboro and Nashoba formations were interpreted by Kay et al. (2017) to represent arc to backarc environments developed over strongly attenuated continental crust. Notably, although the Nashoba terrane is commonly assigned to the domain Ganderia, the Marlboro Formation has little resemblance to the Albee / Dead River and Moretown formations of GCS1 that, in most interpretations, span approximately the same time interval and characterize the Bronson Hill and Moretown terranes farther west.

Traced southward into Connecticut, the Nashoba Formation is laterally equivalent to the Tatnic Hill Formation, from which Wintsch et al. (2007) reported detrital Silurian zircon at least as young as ~426 Ma (Ludlow), interpreting that the post-volcanic succession continues into the Silurian. Furthermore, the zircon data set presented by Wintsch et al. was devoid of the ~1 Ga "Grenville" population that characterizes many Silurian and younger rocks in the Merrimack and Central Maine belts to the NW, suggesting to Waldron et al. (2019b) that in contrast to those belts, the Nashoba terrane had not collided with composite Laurentia by Ludlow time ~426 Ma. However, recent publications (Hepburn et al., 2021; Walsh et al., 2021) have interpreted younger zircon dates in other parts of the Tatnic Hill Formation as metamorphic, placing its deposition before metamorphism at ~428 Ma, and probably in the Ordovician.

Walsh et al. (2021) identify a younger unit, formerly interpreted as the Black Hill Member of the Quinebaug Formation, in which they interpret detrital grains as young as 371 Ma, and detect no "Grenville" grains at ~ 1 Ga. Despite this new result, the uncertainties resulting from metamorphic overprints and poor constraints on depositional age continue to cast doubt on the time of accretion of the terrane.

Kay et al. (2017) and Walsh et al. (2021) considered possible correlatives of the Nashoba terrane and point out a close comparison with terranes attributed to Ganderia but lacking GCS1, farther NE in the Appalachians. They noted comparable Sm/Nd model ages (in the range 1.2–1.8 Ga) that are significantly older than typical Avalonian values. In particular, they highlighted a close comparison with the Annidale terrane and New River belt of southern New Brunswick (Kay et al., 2017), and with the Ellsworth terrane of coastal Maine (Walsh et al., 2021) citing comparable timing and range of arc to backarc geochemistry in the volcanic rocks.

### 5.4.3. Coastal Maine and southern New Brunswick

South of the Dog Bay – Liberty line in Maine and adjacent New Brunswick (Fig. 8), a plethora of terranes, reviewed by Fyffe et al. (2009, 2011), has been assigned to Ganderia (van Staal et al., 2021). Many of these terranes carry an extensive record of Silurian arc or backarc magmatism, which distinguishes them from terranes both to the northwest and to the southeast (section 5.4.6) that lack this Silurian magmatic record.

Within this belt is the St. Croix terrane, characterized by a metaclastic succession assigned to GCS1 by van Staal et al., 2021. Predominantly mafic and bimodal igneous slices of Cambrian age, assigned to the Ellsworth and Annidale terranes, are interpreted to have been thrust NW over the St. Croix terrane during Penobscottian deformation between 490 and 479 Ma (Pollock et al., 2022). To the SE, multiple fault slivers of the New River belt (Fig. 4) (Johnson and McLeod, 1996) are separated by Carboniferous faults which display a cumulative dextral strike slip estimated at ~250 km (Waldron et al., 2015). These slivers are here interpreted mainly as slices of the surrounding terranes. Southeast of the New River belt, the adjacent Kingston terrane represents a Silurian arc, interpreted to have been developed above a NW-dipping subduction zone (Barr et al., 2002b; White et al., 2006). It has been suggested that the Kingston arc was paired with the Mascarene backarc, but any such correlation must take into account the Carboniferous strike-slip faults that currently separate the two.

*5.4.3.1. St Croix terrane.* In the Penobscot Bay region of the central Maine coast, the St. Croix terrane (Fig. 7, SCX) and the adjacent Islesboro block include clearly continental Precambrian rocks of the Rockport and Islesboro successions, separated by the steep Turtle Head Fault. Both successions include units of clean quartzite and laminated shelf limestone presumed to be of Ediacaran or older age (Reusch et al., 2018). Quartzite of the Hutchins Island Formation contains no zircon younger than 1.8 Ga and is dominated by 1.95–2.2 Ga zircon, consistent with a source in the Eburnean Orogen of West Africa. East of the Turtle Head Fault, the Proterozoic rocks are overlain by greywacke constrained between youngest detrital zircon ~515 Ma and inferred late Llandovery (~435 Ma) cover. West of the fault, in the Camden Hills, a thick succession of assumed Cambrian rocks is assigned to the lower part of Cookson Group (Fig. 4), corresponding to GCS1 (van Staal et al., 2021). The succession comprises a basal conglomerate and sandstone unit (Simonton Corners Formation) overlain by a succession (Megunticook Formation) that fines upward from thick, distinctive conglomerate to cross-bedded clean quartzite and mixed pelite–quartzite including minor calc-silicate and coticule (Mn-garnet-bearing) beds (Osberg and Berry, 2020). An overlying thick unit of black shale, the Penobscot Formation, contains blocks or beds that have been attenuated by boudinage, including limestone, quartzite, and volcanic rocks. A volcanic unit near the base has been dated at 503 Ma (Tucker et al., 2001), but higher in the formation the Gushee volcanic member, of island arc affinity, is dated at ca. 490–487 Ma (Berry et al., 2016), and the correlative Calais Formation, along strike in New Brunswick, contains Tremadocian graptolites, suggesting that the black shale unit contains material spanning at least 20 Myr. However, the Penobscot Formation may not be intact; some outcrops resemble mélanges, similar to those that have been described in inliers of Cambrian–Ordovician rock in northern Maine.

The above succession is thrust over younger clastic units of the Benner Hill succession of Maine, correlative with the upper Cookson Group (Fig. 4) in New Brunswick, from which Ordovician fossils have been recovered in both areas. These units correspond to GCS2 (second Ganderia cover succession) in the terminology of van Staal et al. (2021). Although the unexposed lower contact of the upper Cookson Group has been interpreted as conformable (Fyffe and Riva, 1990), it was interpreted by van Staal et al. (2021) as an unconformity representing the Penobscottian event that affected much of Ganderia in the Early Ordovician. Within the succession, quartzite assigned to the Kendall Mountain Formation displays a unique detrital zircon signature (Ludman et al., 2017; confirmed by our unpublished data) that contains a range of Mesoproterozoic zircon including peaks at 1 and 1.2 Ga that resemble the "Grenville" peaks of Laurentian samples (Fig. 17). However, the unit overlies typical "Ganderian" rocks, and contains typically Gondwanan populations of zircon in the Ediacaran and in the "Eburnean" interval of the Paleoproterozoic. In addition to these familiar populations, the Kendall Mountain sample contains significant zircon in the ~800 Ma range, an age that is otherwise scarce in the northern Appalachians, suggesting that the St. Croix portion of Ganderia came into contact with a unique source of zircon during or immediately after the Penobscottian event (see also Riggs et al., 2022).

At its top the Cookson Group is in turn truncated by an unconformity, below Silurian volcanic and clastic rocks (Fig. 4), previously included in the Coastal Maine Magmatic province (Hogan and Sinha, 1989) or Coastal Volcanic belt (e.g. Piñán Llamas and Hepburn, 2013). Recognizing that this belt includes both volcanic and intrusive rocks, and extends into New Brunswick (Mascarene Basin; Fig. 4) and beyond, we here refer to it as the *coastal igneous belt* (CIB). Relationships at the N margin of the St. Croix terrane are unclear. Adjacent Llandovery turbidites of the Kingsclear Group (Digdeguash Formation) in the Fredericton trough, although clearly non-Laurentian, show a detrital zircon population dominated by Ediacaran grains, lacking the Meso- and Paleoproterozoic populations of the St. Croix terrane to the south. The Fredericton trough also contrasts strongly in facies with similar-age rocks of the CIB in the Mascarene basin that unconformably overlie the St. Croix terrane only ~ 5 km to the S. The St. Croix terrane arrived in proximity to composite Laurentia before the end of the Silurian as it is stitched to the Fredericton trough by the 421.9 ± 2.4 Pocomoonshine pluton (West et al., 1992; Ludman et al., 2018), which cuts a younger unit of the Kingsclear Group (Flume Ridge Formation) that contains Laurentian detrital zircon (Ludman et al., 2017; Dokken et al., 2018).

*5.4.3.2. Ellsworth terrane.* Contrasting with the St. Croix terrane, and lying mainly to the southeast, the Ellsworth terrane (Fig. 7, ELS) is dominated by mafic (enriched mid-ocean ridge basalt or EMORB) and felsic Cambrian oceanic to rift-related volcanic rocks of the Ellsworth Schist and North Haven Greenstone and the slightly younger Castine Formation. Available ages from these rocks are entirely Cambrian (Miaolingian, 509–500 Ma) and, in contrast to most of Ganderia, they show relatively juvenile $\varepsilon_{Nd}$ values. These successions were interpreted by Schulz et al. (2008) as representing a juvenile oceanic basin analogous to the modern Gulf of California, Red Sea, or Tasman Sea. The local presence of tectonite harzburgite at the base of the succession suggests the presence of exhumed lithospheric upper mantle (Reusch and Rust, 2001; Pollock et al., 2022). Few detrital zircon data are available for the Ellsworth terrane: the only dated sample (Fyffe et al., 2009), from an atypical clastic facies, shows Ganderian provenance.

The mafic rocks of the Ellsworth terrane, as well as the 492 Ma Lamoine Granite (Pollock et al., 2022), are variably deformed but show an abundance of shear fabrics, including mineral lineations and rotated porphyroclast systems (Reusch, 2003; Pollock et al., 2022) indicative of top-to-the-northwest transport. Although these fabrics remain undated, they are overprinted by static metamorphic aureoles of Silurian plutons associated with the CIB. In addition, in the area of Lords Cove (Fig. 7a), rhyolite of the Ellsworth terrane is thrust over Penobscot Formation black shale of the St. Croix terrane (Lord's Cove window; Reusch et al., 2018 and references therein); both units are folded by presumed Acadian folds. This relationship strongly suggests that the Ellsworth and St. Croix terranes were juxtaposed by NW-directed thrusting (present-day coordinates) in the Early Ordovician Penobscottian event.

*5.4.3.3. Annidale terrane.* Traced NE, the Ellsworth terrane disappears beneath the Mascarene basin of the CIB. Along strike to the NE, in New Brunswick, the Annidale terrane (Fig. 8, ANI) is a NW-verging thrust belt of comparable, dominantly mafic igneous and volcaniclastic rocks described in detail by McLeod et al. (1992) and Johnson et al. (2012). The ages of dated volcanic units are somewhat younger than those in the Ellsworth terrane, falling in the Furongian (500–490 Ma), and the units show consistent arc geochemistry, in contrast to the extensional environments inferred for the Ellsworth terrane. Intrusive igneous activity continued into the Early Ordovician; the 479 Ma Stewarton Gabbro stitches the contact with the Almond Road Formation of the New River belt to the SE, showing that the terranes were deformed and joined as a consequence of Penobscottian convergence.

*5.4.3.4. Coastal igneous belt and Mascarene basin.* Both the St. Croix and Ellsworth terranes are penetrated by abundant Silurian plutons of the CIB that probably represent sources for the unconformably overlying volcanic rocks (Mascarene Group: Fig. 4), beneath which the Ellsworth terrane becomes buried as it is traced eastward. The Mascarene Group contains a succession of volcanic and sedimentary rocks, ranging from marine to terrestrial, and extending from Llandovery to Přídolí (Miller and Fyffe, 2002; Churchill-Dickson, 2004; Piñán Llamas and Hepburn, 2013). In Maine, the magmatic rocks are interpreted as representing arc environments in the early part of the succession, transitioning to backarc basin in the later Silurian (Piñán Llamas and Hepburn, 2013), whereas the volcanic rocks in New Brunswick are interpreted as representing predominantly backarc environments (Van Wagoner, 2002). Although the belt is divided by faults, all those working on these rocks have agreed that the Silurian volcanic basin is continuous. It therefore represents an important overlap unit linking the terranes that it overlies, including the St. Croix, Ellsworth, Annidale, and parts of the New River belt (see below, section 5.4.3.5). Additionally, the ~422 Ma Pocomoonshine pluton (West et al., 1992; Ludman et al., 2018) cuts Laurentia-derived sediments of the Fredericton trough.

*5.4.3.5. New River belt.* The geology of the New River belt (Fig. 8, NRV) is summarized in a series of publications by Johnson (2001, Johnson and McLeod, 1996; Johnson et al., 2018). The belt is subdivided by NE-SW-striking steep faults, many of which were active in the Carboniferous (Waldron et al., 2015), showing contrast in stratigraphy (Fig. 4) between adjacent fault blocks.

The *Pocologan River* slice (Fig. 8, NRVP), in the SW of the belt, displays plutonic rocks of the Ragged Falls Suite (550–560 Ma), and overlying Neoproterozoic to earliest Cambrian volcanic rocks (Leavitts Harbour and Simpsons Island formations) with chemistry suggesting origin in an extensional setting (Barr et al., 2003a). A younger volcanic succession (Mosquito Lake Road Formation ~515 Ma) is either overlain (Johnson, 2001) or underlain (Johnson et al., 2018) by sandy metaclastic rocks of the Matthews Lake Formation, that resemble the Megunticook Formation of the St. Croix terrane. An additional link to the St. Croix terrane is provided by a Late Ordovician sedimentary succession with conodonts indicating mixed Laurentian mid-continent and Atlantic affinities (Nowlan et al., 1997).

The *Almond Road* slice (Fig. 8: NRVA) displays basal volcanic-dominated successions (Belleisle Bay Group) that also straddle the Ediacaran–Cambrian boundary and display arc-related chemistry (Johnson and Barr, 2004). They are overlain by a clastic succession (Almond Road Group) hypothesized to be deeper-water offshore equivalents of the trilobite-bearing shelf clastic succession that characterizes the third region.

The *Long Reach* slice (Fig. 8, NRVL) lies adjacent to the Belleisle Fault. Here, formation-level subdivisions of the Saint John Group are recognized, starting with a quartzose sandstone unit identified as the Glen Falls Formation, overlain by trilobite-bearing (Boyce and Johnson, 2004) sandstone and shale correlated with the Hanford Brook Formation. These units highlight a resemblance to the Brookville and Caledonia terranes to the SE. However, an interpreted maximum deposition age of ca. 487 Ma for a quartz arenite higher in the succession (Barr et al., 2019) suggests that the sampled unit may be time-equivalent to younger parts of the Saint John Group in the Caledonia terrane. The presence of 630–620 Ma arc plutons reinforces this resemblance although isotopic characteristics suggest that they may have different sources (Barr et al., 2003a).

A fourth slice at *Buckmans Creek* (Fig. 8, NRVB) also displays thin, fossiliferous Cambrian units assigned to the Saint John Group (Landing et al., 2008) but these rocks appear to be in faulted contact with an unfossiliferous Cambrian section with volcanic rocks (Barr et al., 2019).

Well to the southwest of the main outcrop of the New River belt, rocks on the island of *Grand Manan* (Fig. 8, GMN) have also been included in Ganderia (Fyffe, 2014 and references therein) and more specifically with the New River belt. This correlation is based on the presence of a succession of volcanic and sedimentary rocks (Castalia Group) approximately contemporary with the Bellisle Bay Group, overlying older clastic and carbonate successions of the Grand Manan Group. However, the Grand Manan Group also includes quartzite and carbonate units (The Thoroughfare and Kent Islands formations, respectively) that have been correlated with units in the Islesboro block (Fig. 4), usually assigned to the St. Croix terrane (Reusch et al., 2018; Barr et al., 2019; Cavagnaro et al., 2019). This correlation is strengthened by the presence of Neoproterozoic granitic pegmatite clasts, similar in age to pegmatite in the Islesboro block, in conglomerate of the Castalia Group (Barr and Mortensen, 2019).

Most detrital zircon data sets from the Cambrian rocks of the New River belt (Fig. 17 g–l) show similar successions to those in adjacent Ganderian terranes. However, the lowest unit in the Grand Manan Group, The Thoroughfare Formation, displays a purely Precambrian distribution with a large Eburnean peak (Barr et al., 2019), closely resembling that of the Hutchins Island Formation in the Islesboro block of Maine.

*5.4.3.6. Kingston terrane.* A major Carboniferous fault, the Belleisle fault, separates the New River belt from the Kingston terrane (Fig. 8, KNG) to the SE. Though formerly interpreted as a Precambrian dyke complex (Nance and Dallmeyer, 1993), the Kingston terrane is now known to expose largely Silurian (442–435 Ma) arc-related volcanic and minor sedimentary rocks, intruded by co-magmatic granitoid plutons and younger mafic sheets (Doig et al., 1990; Barr et al., 2002b), indicating that it is part of the CIB. In contrast to rocks of the Mascarene basin to the north, which are largely unmetamorphosed, rocks of the Kingston terrane are metamorphosed to upper greenschist and lower amphibolite facies, recording pressures up to ~0.4 GPa and temperatures ~460–470°C. A sliver along its SE boundary, the Pocologan metamorphic suite (White et al., 2006; Massonne et al., 2018), yields similar primary igneous ages (433.5 Ma) but much higher metamorphic pressures around 0.9 GPa at 590°C, incurred around 417 Ma, with a possible later episode of metamorphism associated with strike-slip mylonitization at ~390 Ma.

On its SE side, the Pocologan metamorphic suite is bounded by another major Carboniferous dextral strike-slip fault, the Kennebecasis fault (Fig. 8). The Kingston terrane is thus entirely bounded by younger, Carboniferous dextral strike-slip faults. Nonetheless, the similarity in protolith age and lithology with rocks of the Mascarene basin is striking, and the Kingston terrane has been interpreted to represent an arc paired with the Mascarene backarc basin, suggesting NW-dipping subduction during convergence between Avalonia and Ganderia. This association is subject to considerable uncertainty because Waldron et al. (2015) suggested many tens of kilometres of Devonian–Carboniferous dextral slip on both the bounding faults. However, NW-dipping subduction is supported by the Pocomoonshine pluton, that stitches the St. Croix terrane to Laurentia-derived sedimentary rocks of the Fredericton trough (Dokken et al., 2018) at ~422 Ma (West et al., 1992; Ludman et al., 2018).

### 5.4.4. *Aspy belt*

The pre-Silurian basement of the Kingston terrane is unknown, but, traced into Cape Breton Island, it correlates broadly with the *Aspy belt* (Fig. 8), which shows a varied pre-Silurian record, albeit highly deformed and modified by Acadian tectonism (e.g. Slaman et al., 2017). Like the St. Croix and Kingston terranes, the Aspy belt is distinguished from terranes to the SE by a Silurian history of arc magmatism, indicating that it is part of the CIB, and suggesting that the older Aspy belt rocks may be representative of the unexposed basement of the Kingston terrane. Silurian magmatism was closely followed, between ~415 and ~380 Ma, by Acadian Barrovian metamorphism, which locally produced kyanite-bearing gneiss.

Some authors (Keppie, 1993; Shellnutt et al., 2020 and references therein) have interpreted the Aspy belt, together with the Blair River Complex (Fig. 8) to the north, as parts of Avalonia. We disagree with this interpretation because of strong stratigraphic, isotopic, geochronologic and provenance links with those parts of Ganderia in coastal Maine, southwest New Brunswick, and southern Newfoundland that are overprinted by Silurian magmatism and Acadian deformation.

In the northwestern Cape Breton Highlands, the *Faribault Brook block* (Fig. 4; Fig. 8, ASPF) contains metamorphic rocks formerly assigned to the Jumping Brook Metamorphic Suite that include two contrasting units. An undated succession of metavolcanic rocks (Faribault Brook Formation) is intruded by 490–480 Ma diorite and tonalite and tectonically interleaved with a clastic succession (Dauphinee Brook

Formation) that contains younger late Ordovician (455 Ma) detrital zircon (McCarron, 2020). These relationships are comparable to those seen in the Victoria and Gander terranes of Newfoundland, where clastic successions (Badger and Davidsville Groups) of GCS2 (van Staal et al., 2021) unconformably overlie arc volcanic rocks that contain mineral deposits similar to those in the Faribault Brook Formation (Buschette and Piercey, 2016; Lode et al., 2017). We therefore infer that the Dauphinee Brook Formation was originally unconformable on the Faribault Brook Formation, and that the two were interleaved during Early Devonian deformation and metamorphism (White et al., 2016b and references therein).

In the adjacent *Pleasant Bay Complex* (Fig. 8, ASPP) a clastic metasedimentary succession (Fishing Cove River Formation) contains detrital zircon that displays a typical GCS1 distribution and shows a maximum depositional age around 545 Ma (McCarron, 2020).

Farther east, in the *Central Highlands block* (Fig. 4, Fig. 8, ASPH), more varied successions of inferred Ordovician age (e.g. Cape North and Middle River groups) probably overlie fault-bounded Ediacaran metaleucotonalite. These rocks are in turn overlain by a thick, well dated Silurian succession of metavolcanic and metasedimentary rocks (Sarach Brook Formation and laterally equivalent Money Point Group and correlative units), containing numerous contemporary intrusions, overprinted and transposed by Devonian metamorphism (Dunning et al., 1990b; Lin et al., 2007; Barr et al., 2018; White et al., 2018a). The earliest meta-intrusive unit (Belle Cote Road Orthogneiss) is also present in the Pleasant Bay Complex and serves to stitch the Pleasant Bay Complex and Central Highlands units at ~443 Ma (Price et al., 1999; Horne et al., 2003). The Sarach Brook and Money Point groups are considered correlative with the Kingston arc terrane of southern New Brunswick; the older Cape North and Middle River groups and associated Ordovician intrusions may be representative of the otherwise hidden substrate of the CIB in the Kingston terrane. These units display mainly high-grade Acadian metamorphism; for example, kyanite-bearing gneiss in the Pleasant Bay Complex records conditions estimated at 0.8 to 1.0 GPa and 700–750°C (Plint and Jamieson, 1989). The timing of peak metamorphism is bracketed by the youngest protolith ages (~415 Ma), post-metamorphic plutons at ~380 Ma, monazite metamorphic ages from ~411 to ~399 Ma (Barr and Jamieson, 1991; White et al., 2016b), and cooling ages of ~380–370 Ma from apatite, amphibole, and muscovite (Reynolds et al., 1989; Price et al., 1999; McCarron, 2020).

The *Cheticamp block* (Fig. 8, ASPC), located southwest of the Faribault Brook block, contains a mixed succession of Precambrian clastic and carbonate units that are intruded by Ediacaran (~567 Ma) plutons and younger, Silurian, intrusive units that provide a clearer link with the CIB of the Pleasant Bay and Central Highlands blocks (Slaman et al., 2017). These Ediacaran plutons and their host rocks are similar to units of the same age in the Bras d'Or terrane which led previous workers to infer that the Aspy belt was built on Bras d'Or terrane crust (Lin et al., 2007; Slaman et al., 2017)

In the southwestern part of the Aspy belt, the *Mabou Highlands block* (Fig. 8, ASPM) contains mixed metavolcanic and metasedimentary rocks of Neoproterozoic age, and leucotonalite similar to that in the Central Highlands block. The Neoproterozoic rocks are overlain by an undeformed and undated volcanic-sedimentary succession shown in recent map compilations as Silurian (Barr and White, 2017), though previously interpreted as Devonian (Barr and MacDonald, 1989). Small outcrop areas of unmetamorphosed Silurian fossiliferous sedimentary rock have also been reported in the Mabou Highlands block but are not well documented (Barr and MacDonald, 1989 and references therein).

#### 5.4.5. *Newfoundland*

In Newfoundland (Fig. 1, Fig. 5, Fig. 9), Ganderia is represented by the Gander zone or terrane (GAN) (Williams, 1979; Williams and Hatcher, 1982) that displays a thick metaclastic succession (Gander Group) assigned to GCS1 (van Staal et al., 2021). The Gander zone was subdivided (Williams et al., 1988) into an original 'type' Gander Lake subzone, and subzones to the west (Mount Cormack, and Meelpaeg) where GCS1 metaclastic rocks are surrounded by volcanic units assigned to the Exploits subzone of the Dunnage zone. However, these subzones were identified (Williams et al., 1988) as inliers or fenster of the Gander Lake subzone, and are therefore here included in the Gander Terrane. To the south, a region known as the Hermitage flexure (Dunning and O'Brien, 1989), and here termed the Hermitage belt, is dominated by Devonian granitoids, and a thick Silurian succession of volcanic and sedimentary rocks, an apparent continuation of the CIB of the Aspy belt (Barr et al., 2014a). Enclaves of Neoproterozoic and early Paleozoic units have similarities with both the Aspy and Bras d'Or terranes of Cape Breton Island.

*5.4.5.1. Gander terrane.* Ganderia takes its name from the Gander Zone, one of five original zones defined in Newfoundland and correlated throughout the orogen (Williams, 1979), in turn named for the Gander Group, a thick succession of metaclastic rocks in east-central Newfoundland. The Gander Group is dominated a metamorphosed succession of generally quartzose psammites and pelites (GCS1) interpreted as turbidites. Its detrital zircon populations (Willner et al., 2014; Henderson et al., 2018) show youngest grains around 496 Ma, suggesting that the unit is Cambrian, though stratigraphic relationships (Fig. 5) allow it to extend into the Early Ordovician. Older detrital grains include a broad range of Mesoproterozoic zircon extending back to 2.2 Ma, typical of GCS1. Correlatives of the Gander Group extend in a belt across the island of Newfoundland, but appear to be cut out against the younger Cabot Fault (Fig. 9), so that no clear equivalents are found in Cape Breton Island. However, the Gander Group has been widely compared to similar, grey-green, "pinstriped" metaclastic units of GCS1 that occur in the Miramichi, Bronson Hill, and Moretown terranes to the SW, and with rocks in the Cahore Group in Ireland and the Holy Island Group in N Wales (e.g. Kennedy, 1979; Waldron et al., 2014a; van Staal et al., 2021).

The Gander Group is tectonically overlain in its type area by a fragmented ophiolite package forming the "Gander River ultrabasic belt" or GRUB, emplaced in a Penobscottian "soft" collision (van Staal and Zagorevski, 2020) during the Early Ordovician.

Relations at Mount Cormack (Fig. 9) (Colman-Sadd et al., 1992) are critical in understanding the Penobscottian history of the Gander terrane. Thrust above the Gander Group are ophiolitic rocks assigned to the Pipestone Pond, Coy Pond, and Great Bend complexes, that include peridotite, gabbro, basalt, and trondhjemite dated at 494 +3/-2 Ma (Furongian). The contact is sealed by a granitoid pluton (Partridgeberry Hills) dated at 474 +6/-3 (Floian) showing that ophiolite emplacement occurred in a Penobscottian event around 480 Ma, providing a tighter constraint on the Penobscottian event than at the GRUB.

Both the Gander Group and the overlying ophiolitic rocks are unconformably overlain (Currie, 1995) by a younger Ordovician to Silurian cover succession (Bay du Nord, Davidsville and Indian Islands groups; Fig. 5) corresponding to GCS2 of van Staal et al., 2021. This succession was included in the Exploits subzone or terrane by Williams et al. (1988) and most subsequent authors. However, because its position depositionally above the Gander Group distinguishes it from western parts of the Exploits subzone (where there is no record of GCS1) we here include it in the Gander terrane as a cover succession (GAC in Fig. 9). Parts of the "Exploits subzone" west of the Dog Bay line are here assigned to the Victoria terrane (section 5.3.4) which is thrust over the Gander terrane cover along the Dog Bay Line, although poorly understood intermediate structural slices assigned to the Duder Complex and the Hamilton Sound Group occur adjacent to the Dog Bay line in NE Newfoundland (not shown in Fig. 5 for reasons of space).

At the top of the Gander Group, east of the GRUB, a thin fossiliferous unit, the Indian Bay Big Pond Formation, with Middle Ordovician shelly fossils is commonly interpreted as conformable with lower parts of the

Gander Group (Wonderly and Neuman, 1984). However, if it is treated as part of the Gander Group, its age is difficult to reconcile with relationships at Mount Cormack, where the Gander Group had already been over-ridden by ophiolites and intruded by granite at ~474 Ma. It seems more likely, therefore, that the Indian Bay Big Pond Formation is an outlier of the basal Davidsville Group cover succession, separated from the Gander Group by an unexposed Penobscottian unconformity.

*5.4.5.2. Hermitage belt.* A region of southern Newfoundland lies tectonically between the Avalon terrane and terranes assigned to Ganderia. The region is typically described as the "Hermitage Flexure" on the basis of its E–W trend, that contrasts with much of the Newfoundland Appalachians. We here refer to it as the Hermitage belt (Fig. 9). Although it was included in the review of Avalonian terranes by O'Brien et al. (1996), subsequent authors (Barr et al., 1998; Lin et al., 2007; Barr et al., 2014a) have drawn attention to close correlations of parts of the belt with both the Aspy and Bras d'Or terranes of CBI, included in Ganderia. The belt is characterized by a history of repeated intrusion and deformation over a long history from Cryogenian to Devonian.

Lin et al. (2007) recognize two successions with contrasting history in the Hermitage belt. In the *La Poile Bay block* (Fig. 9, HER) in the west, the oldest rocks (Fig. 5) are Cryogenian (690-670 Ma) ortho- and paragneiss (Cinq Cerf gneiss) (O'Brien et al., 1993, 1996; Valverde-Vaquero et al., 2006b). The Cinq Cerf gneiss was deformed prior to deposition of an Ediacaran cover succession of clastic sedimentary rocks and tuff (Whittle Hill and Third Pond formations) at ~585 Ma. Further intrusions (Roti Granite Suite and related rocks, 578 ± 10 Ma) were followed by deformation in an environment of obliquely convergent dextral shear (O'Brien et al., 1993). Further intrusive episodes (Wild Cove Granite) occurred towards the end of the Cambrian. No Ordovician stratified units are present, and mylonitic rocks along the Grand Bruit Fault (O'Brien et al., 1993) record dextral shear prior to development of a thick succession of volcanic and sedimentary rocks, the La Poile Group, which was deposited, probably in extensional half-graben, between 430 and 420 Ma in the Silurian, forming the NE extremity of the CIB in Canada. The terrane was deformed again, this time in sinistral shear, prior to intrusion of the Otter Point Granite at 419 ± 2 Ma. Further dextral shear preceded intrusion of the largely undeformed Chetwynd Granite at 390 ± 10 Ma.

The *Grey River block* in the east (Fig. 9, GRV) is separated by the Silurian Burgeo Granite from the La Poile Bay block; however, it appears not to have been metamorphosed by the granite. The oldest rocks are Cryogenian ortho- and paragneiss (Grey River Gneiss) comparable to the Cinq Cerf Gneiss (O'Brien et al., 1996). As in the west, stratified rocks, including sandstone and tuff, overlie the gneiss, but these are younger, dating from near the end of the Ediacaran (544 Ma). The area largely escaped the Silurian deformation and metamorphism that affected the La Poile Bay block (Lin et al., 2007) suggesting that the unnamed fault that juxtaposes the two blocks is post-Silurian.

Overall, the Hermitage belt contrasts with the Avalon terrane of Newfoundland (with which it was formerly included; e.g. O'Brien et al., 1996) in the presence of high-grade metamorphic rocks, absence of a distinctive thin Cambrian shelf succession, and a preponderance of negative (evolved) $\varepsilon_{Nd}$ values, features in common with the Bras d'Or terrane and Aspy belt of Cape Breton Island. In the La Poile Bay block, the presence of a thick, volcanic-dominated Silurian succession (La Poile Group) which was subsequently overprinted by Přídolí–Lokhovian metamorphism, provides a link to the Aspy belt and thence to the Kingston terrane, the Mascarene basin and Coastal Maine volcanic belt of New Brunswick and Maine (Barr and Jamieson, 1991; Lin et al., 2007). We here assign all these units to the *coastal igneous belt* (CIB). In contrast, the lack of post-Ediacaran, pre-Devonian deformation and igneous activity in the Grey River block led Lin et al. (2007) to correlate it with the Bras d'Or terrane of Cape Breton Island. This interpretation is supported by geophysical interpretations of the intervening Cabot Strait (Barr et al., 1998; Lin et al., 2007; Barr et al., 2014a).

*5.4.6. Brookville – Bras d'Or*

The Brookville terrane in New Brunswick and the Bras d'Or terrane of Cape Breton Island (Fig. 8a) are distinguished from surrounding terranes by several characteristics: a Precambrian sedimentary record including quartzite and stromatolitic marble, with highly variable grades of metamorphism (low-pressure migmatitic paragneiss is interpreted to be the high-grade equivalent of the lower-grade rocks); by late Ediacaran to Cambrian arc volcanic and intrusive activity; by evolved isotopic signatures and Mesoproterozoic crustal model ages similar to Ganderia; by a narrow fault-bounded belt in Bras d'Or terrane of unmetamorphosed Cambrian volcanic rocks and fossiliferous shale that show some similarity to those in Avalonia; and by an almost complete absence of the Silurian volcanic activity that characterizes the now adjacent Kingston terrane.

In addition, the eastern part (Grey River area) of the Hermitage belt of southern Newfoundland shares many of these characteristics, suggesting it may be correlated with the Brookville and Bras d'Or terranes (Lin et al., 2007; Barr et al., 2014a)

*5.4.6.1. Brookville terrane.* The Brookville terrane of southern New Brunswick (Fig. 8, BRK) contains a Neoproterozoic metasedimentary successions (Fig. 4 containing quartzite and carbonate of probable shelf origin (Green Head Group) that contrasts with a high-grade succession (Brookville Gneiss) of para- and orthogneiss deposited over approximately the same time interval from late Cryogenian to mid-Ediacaran, prior to intrusion of tonalitic sheets, now preserved as orthogneiss in the Brookville Gneiss, at ~615 Ma. Regional metamorphism and deformation of the gneiss was followed by intrusion, into both high-grade and low-grade units, of the subduction-related Golden Grove plutonic suite between 555 and 525 Ma; contemporary Dipper Harbour volcanic rocks were extruded at ~553 +/- 3 Ma. Several small, fault-bounded patches of unmetamorphosed fine grained shale with interbedded concretionary limestone are assigned mainly to the King Square Formation of the Saint John Group; they closely resemble strata of the same age in the Caledonia terrane to the SE and their depositional relationship to Brookville terrane rocks cannot be demonstrated. An anorthositic body in the subsurface about 100 km along strike to the NE of the main outcrop was dated at 975 ± 2.3 Ma (Miller et al., 2018), an age more typical of the Grenville Orogen, leading to the suggestion that this portion of Ganderia is sourced from the equivalent Sunsas Orogen in Amazonia (Miller et al., 2018)

Detrital zircon populations from the Brookville terrane (Fig. 20) appear typically "Ganderian" with a broad distribution of Meso- and Paleoproterozoic zircon from 1.2 to 2.2 Ga, but vary in the amount of Ediacaran zircon. In some quartzite samples, notably from carbonate-dominated parts of the Green Head Group, the Ediacaran component is entirely absent, leading to suggestions that these units represent pre-Ediacaran basement, despite being apparently laterally equivalent to other, less quartzose clastic units (e.g. Martinon Formation) that show large peaks in the zircon distribution around 650 Ma (Barr et al., 2014b). However, results from the Bras d'Or terrane (van Rooyen et al., 2019) suggest that in clastic successions of variable maturity, it is common for the most mature arenites to represent old source areas, whereas interbedded immature sands preserve zircon from more labile sources that are closer to the depositional age.

*5.4.6.2. Bras d'Or terrane.* The Bras d'Or terrane of Cape Breton Island (Fig. 8, BDR) is one of several terranes identified by Barr and Raeside (1989) that are attributed to the domain Ganderia (Hibbard et al., 2006; White et al., 1994; Palacios et al., 2012; van Rooyen et al., 2019). The terrane includes diverse Precambrian metasedimentary rocks — pelite, quartzitic psammite, quartzite, and metacarbonate. Different suites (Bras d'Or and George River) have been identified based on contrasting metamorphic grade, but based on overall lithology, provenance, chemical and isotopic characteristics, and the ages of cross-cutting plutons, they are interpreted to represent related successions deposited between ~ 640 and 590 Ma (Barr et al., 2013), analogous to the Green Head Group and Brookville Gneiss in the Brookville terrane. Quartzite units lacking abundant Neoproterozoic zircon have been speculated to be older, but recent work suggests that, as in the Brookville terrane, the lack of younger grains in the quartz-rich psammites is an artifact of maturity contrasts. The metasedimentary rocks are intruded by multiple generations of plutons, and then were metamorphosed around 550 Ma. Younger, less deformed plutons (509 ± 2 Ma; White et al., 1994) are contemporary with a Cambrian to earliest Ordovician succession (Bourinot belt in the Boisdale Peninsula) that starts with ~510–505 Ma bimodal volcanic rocks and passes up into fossiliferous clastic sedimentary rocks with tuffaceous intercalations in their lower part that span the interval from Drumian to Tremadocian, although disconformities are postulated (in somewhat different interpretations of the stratigraphy) by Landing (1996) and Palacios et al. (2012). Elsewhere in the terrane, plutons (Kellys Mountain, Cape Smokey) between 515 and 490 Ma (Furongian) testify to continued intrusive activity that seems at odds with the shale-dominated sedimentary succession, suggesting that the terrane incorporates regions that had contrasting Cambrian histories.

Detrital zircon distributions (Fig. 20) are similar to those of the Brookville terrane. Ediacaran zircon is much less abundant than in the adjacent Mira terrane, but the pre-Ediacaran populations of Brookville and Bras d'Or (Barr et al., 2003b, 2012) are closely similar to those of Caledonia and Mira (Fig. 20 g–j).

The low metamorphic grade of the Cambrian volcanic and sedimentary rocks of the Bourinot belt, exposed in a NE-trending regional syncline, presents an opportunity for paleomagnetic study, and these rocks were investigated by Johnson and Van der Voo (1985). Although the volcanic rocks were emplaced mostly subaerially, the uppermost basaltic flows are intercalated with marine sediments bearing the trilobite *Paradoxides bennetti*, constraining the biostratigraphic age within the Miaolingian at ~506 Ma, consistent with a similar U-Pb zircon age from a rhyolite flow (White et al., 1994). Nine sites from flows on both limbs of the syncline provided well-defined ChRM directions which clustered into two steep-inclination, opposite polarity groups upon bedding correction, passing a fold test (Table 2). The synclinal folding affected both the Bourinot belt and mid-Devonian arkose and conglomerate of the McAdams Lake Formation that rests on the adjacent Mira terrane to the south (White and Barr, 1998), but not Early Carboniferous Horton Group clastic sedimentary rocks, thus making the remanence older than Acadian folding. Johnson and Van der Voo (1985) argued for primary magnetization for the volcanic flows, as the remanence is found in both magnetite and hematite, with consistent polarity in each flow where both occur. Magnetizations in the intercalated and overlying sedimentary units are more complex, typically requiring great-circle directional analysis to unmix the steep directions from shallow, likely Early Carboniferous overprint magnetization directions, leading the authors to report two parallel paleomagnetic results: one for the volcanic rocks and one for the sedimentary rocks (Johnson and Van der Voo, 1985) which are nevertheless statistically indistinguishable after structural corrections for bedding and locally for syncline plunge. The steep primary directions imply a high paleolatitude for the Bras d'Or terrane at 506 Ma of 49° ± 11° S, but the ESE declination also suggests that the terrane underwent significant rotation between the time of remanence acquisition and the folding which produced the NE-trending regional syncline.

### 5.4.7. *Leinster–Lakesman terrane*

The *Leinster–Lakesman terrane* (Fig. 10 LLM) extends from the Leinster massif of southeast Ireland, northeastward through the Isle of Man and continues in the English Lake District (Fig. 10). Precambrian basement is unknown; the oldest exposed rocks are sandy turbidites of the Bray Group (Fig. 6), dated as early (Series 1–2, possibly early 3) Cambrian by the presence of the trace fossil *Oldhamia* (Herbosch and Verniers, 2011). The Bray Group apparently passes up into interbedded slate and sandstone, with local volcanic rocks, of the Ribband Group which extend into the Middle Ordovician (early Darriwilian). Correlative, though coarser, clastic turbidites are found in the Skiddaw Group of the English Lake District (Fig. 10), where they are laterally equivalent to thick debris-flow deposits that indicate syndepositional instability. The Bray and Skiddaw Groups have detrital zircon populations (Fig. 16) that are closely similar to those of the Gander Group and other Cambrian Ganderian successions in the Appalachians (Waldron et al., 2014a). Both successions were deformed, but not metamorphosed, prior to the deposition of overlying volcanic-dominated units. In Ireland this deformation is tightly bracketed at ~465 Ma between the early Darriwilian rocks of the Ribband Group and the unconformably overlying late Darriwilian Tramore Group at the base of the volcanic succession (Graham and Stillman, 2022).

Above the Darriwilian unconformity, arc and rifted-arc volcanic edifices dominate the Sandbian to early Katian succession (Fig. 6) in both Britain (Borrowdale Volcanic Group) and Ireland (Duncannon Group). Succeeding these volcanic rocks, a thin but well dated succession of shale dominates the upper Katian through Wenlock. A thin Hirnantian sandstone unit shows Gondwanan detrital zircon provenance (Waldron et al., 2014a). A diachronous influx of coarse clastic turbidites in the Wenlock is interpreted to reflect collision with the Laurentian margin at the NW-dipping subduction zone represented in the Southern Uplands (King, 1994; Waldron et al., 2014a). Laurentian sources dominate the provenance of these sandstones. The only significant Silurian volcanic rocks occur in western Ireland (Dunquin Group) suggesting a possible continuation of the CIB. Subsequently, during the Early Devonian, the terrane was intruded by major granitoid plutons dated between 405 and 395 Ma. Related Early Devonian volcanic rocks are mainly andesite and trachyte (Stone et al., 2010). Structures in the Leinster–Lakesman terrane trend predominantly NE–SW, but are reoriented in the extreme SW of Ireland by overprinted Variscan structures, which have a more E–W orientation.

The Leinster–Lakesman terrane is represented by three paleomagnetic results of Ordovician through Silurian age (Table 2). These allow useful comparisons within the terrane and with other peri-Gondwanan elements.

The Darriwilian Tramore Formation in Ireland consists predominantly of tuff, andesitic flows, and sills with intercalated sedimentary rocks. The sills were interpreted to have intruded wet sediment subhorizontally, and are now exposed with nearly vertical orientation, requiring a large structural correction. Deutsch (1980) reported paleomagnetic results in which 16 sites retained a stable ChRM that passed a (Caledonian) fold test. A distinctive fossiliferous limestone provided a Darriwilian marker horizon, separating the paleomagnetic result into an older group (6 sites) in sills retaining steep reversed-polarity ChRM, and a younger group (10 sites) in flows and tuff with steep normal-polarity ChRM (Table 2). The SSE declination projects to a paleopole well away from contemporaneous poles (Deutsch, 1980). The result implies that the Leinster–Lakesman terrane lay 1500 to 4000 km south of the contemporary margin of Laurentia at 44° ± 10° S at ca. 462 Ma, significantly clockwise of its present-day orientation, though roughly parallel to the Laurentian margin which lay more E–W at the time.

Younger paleomagnetic results from the Stockdale (Channell et al., 1993) and Dunquin groups (Mac Niocaill, 2000) represent the Leinster–Lakesman terrane in the Silurian, and bear on possible terrane rotation. Both paleomagnetic results are derived from clastic sedimentary rocks, which likely experienced some degree of inclination shallowing during compaction. Inclination shallowing affects the calculation of paleolatitude, but leaves the declination unaffected. The Dunquin Group lies within an area (Dingle Peninsula) affected by Variscan folding, in which regionally NE–SW-oriented Caledonide folds swing about 20° clockwise (CW) into an WNW-WSW orientation. We infer that they may have undergone ~20° of clockwise rotation during Variscan dextral transpression (e.g. Bresser and Walter, 1999)

The Browgill Formation in the Stockdale Group (Fig. 6) of NW England contains an anomalous hematite-bearing series of lenticular red mudstones in marine shale, well constrained to the Llandovery *Monoclimacis crenulata* biozone (~436 Ma) (Channell et al., 1993). The Acadian Orogeny deformed the Browgill Formation about NE-trending folds (locally E–W), and further Variscan folding affected some sampling localities. Twelve sites provide stable ChRM directions carried by hematite in two polarities (8 normal and 4 reversed), sometimes in both polarities within-site, passing a reversal test. Site mean directions show declination scatter, but still pass a fold test, indicating that the ChRM likely predated Acadian folding (Channell et al., 1993). Correcting for inclination shallowing assuming a flattening factor of $f = 0.6$ (Domeier, 2016) improves the clustering of tilt-corrected site means, but the declination scatter persists and possibly reflects unrecognized complexity in local structural corrections due to the superposition of Variscan folding and/or faulting. With correction for inclination shallowing, the dual-polarity Browgill Formation paleolatitude is 20° ± 10° S at 436 Ma (Table 2).

In SW Ireland, red/purple siltstones and mudstones bearing Homerian fauna (~429 Ma) of the Dunquin Group (Fig. 6) provided two-component magnetizations in 12 sites, one unblocked in the laboratory at intermediate demagnetization temperatures and a ChRM at high unblocking temperatures representing hematite (Mac Niocaill, 2000). An intraformational conglomerate test on agglomerate mudstone clasts shows the ChRM to be primary and the intermediate-temperature magnetization to be an overprint, likely Carboniferous. The fold test is inconclusive, due to the limited range of bedding attitudes that could be sampled and the coincidence of the reversed polarity ChRM site mean directions with the SW–NE orientation of the fold hinges. Assuming a flattening factor of $f = 0.6$ (Domeier, 2016) to correct for inclination shallowing, the Dunquin Group paleolatitude is 19° ± 6° S at 429 Ma (Table 2).

Notably, the two Silurian primary paleomagnetic results from the Browgill Formation and Dunquin Group, separated by ~400 km along the strike length of the Leinster–Lakesman terrane, are remarkably similar in placing the terrane at low paleolatitude and with a similar paleo-orientation (Channell et al., 1993; Mac Niocaill, 2000). If the Leinster-Lakesman terrane is taken to be a tectonically coherent block — as these paleomagnetic results suggest — then the older Tramore Formation paleomagnetic result from the Waterford region (Deutsch, 1980) suggests that the terrane not only moved from ~44° S to ~20° S between ~462 Ma and 436 Ma, but that it also had an apparent CCW rotation of ~75° during that time. Subsequently, ~30–45° of CW rotation, during the closure of the intervening Iapetus Ocean and subsequent Variscan deformation, brought the terrane into its present-day orientation with respect to Laurentia (which rotated ~45° CCW during the same interval).

### 5.4.8. Monian belt

Farther south in the British Isles, rock units variously termed the Mona Complex (Greenly, 1919) or Monian Composite terrane (Gibbons and Horak, 1990) of Anglesey (Fig. 10), are here referred to as the *Monian belt* (Fig. 10, MON). The belt contains diverse tectonic slices with contrasting stratigraphies, some of which appear to contain thick Cambrian clastic successions with facies and detrital zircon provenance similar to GCS1 (van Staal et al., 2021). The Monian belt includes some of the first identified examples of mélange (Greenly, 1919) and blueschist (Gibbons and Mann, 1983) in the Appalachian–Caledonide system. Correlative rocks (Cahore Group and Rosslaire Complex) are found in the extreme SE of Ireland (Tietzsch-Tyler and Phillips, 1989).

A broad correlation of the Monian rocks with the Gander terrane and Ganderia generally has been noted by many authors (Kennedy, 1979; Kennan and Kennedy, 1983; van Staal et al., 1998). Several distinct terranes were identified within the complex by Gibbons and co-workers (Gibbons, 1987; Gibbons and Horak, 1990). A summary of recent work was provided by Schofield et al. (2020) who identified at least five terranes on the island, in addition to the Arfon terrane in NW Wales (Fig. 6, Fig. 10). We here refer to these terranes as slices, because of their small size, comparable to similar fault-bounded tectonostratigraphic entities in the New River belt of Atlantic Canada (Fig. 8). Each slice is characterized by different stratigraphy, without clear correlation into adjacent slices until after an early Ordovician event, approximately at the Tremadocian–Floian boundary, known as the Monian Orogeny, roughly correlative with the Penobscottian event in the Appalachians.

The *Amlwch slices*, in the NW (Fig. 10, MONU; Fig. 19 b) consists of a succession of mixed metaclastic and metavolcanic rocks (Llanfachel Group) thrust over an undated unit (MONL) of mainly metaclastic rocks that are assumed to be younger (Schofield et al., 2020). Two detrital zircon data sets (Asanuma et al., 2017) show somewhat contrasting provenance. A diverse sample shows a typical “Ganderian” spectrum with varied Mesoproterozoic zircon but a large Cambrian peak at ~530 Ma. The other is restricted to a single peak at ~570 Ma.

The *Porth y Felin slice* (Fig. 10, MONF) includes a well-known Cambrian psammitic succession of the Holy Island Group (Schofield et al., 2020), which is overlain by the finer-grained Rhoscolyn Formation, that includes calc-silicate and metabasic units, that has been interpreted as a mass-transport deposit (Phillips, 1991). The rocks are folded by early NW-vergent folds and at least two generations of younger SE-vergent structures. Of all the Monian slices the Porth y Felin has the most data on detrital zircon provenance (Collins and Buchan, 2004; Asanuma et al., 2017). A majority of samples show typical “Ganderian” distributions with abundant and diverse Mesoproterozoic zircon (Fig. 19 c). The proportion of Paleoproterozoic “Eburnean” (1.9 - 2.2 Ga) zircon tends to vary in inverse relationship with Ediacaran zircon, which shows peaks at either ~550 or ~620 Ma, or both.

Comparable rocks to those of the Porth y Felin slice are found in SE Ireland (Fig. 6, Fig. 10) where the Cahore Group is broadly correlated with the Holy Island Group (Tietzsch-Tyler and Phillips, 1989). This correlation is confirmed by the similarity of their detrital zircon populations (Waldron et al., 2014a) (Fig. 19 a).

The *Coedana slice* (Fig. 10, MONC) in the central part of Anglesey is dominated by early Ediacaran (613 ± 4 Ma) calc-alkaline granite intruded into gneiss, which was deformed at 666 ± 7 Ma (Strachan et al., 2007), and overlying metasedimentary rocks which were deposited between these two events. Despite previous correlations with Avalonia, a single detrital zircon data set (Asanuma et al., 2017) displays a population rich in Mesoproterozoic zircon between 1.1 and 1.9 Ga with relatively small amounts of both Ediacaran and “Eburnean” zircon (Fig. 19 d).

The *Aberffraw slice* (Fig. 10, MONA) comprises highly sheared metaclastic rocks with subordinate metacarbonate and amphibolite, from which Asanuma et al. (2017) interpreted an Ediacaran maximum depositional age (585 ± 30 Ma) overprinted by metamorphism dated by phengite at 578 ± 11 and 575 ± 11 Ma. An unconformably overlying unit of megaconglomerate “mélange” contains late Ediacaran detrital zircon (550 ± 24 Ma) suggesting a possible Cambrian age. The entire succession is folded in NW-vergent folds. The detrital zircon data of Asanuma et al. (2017) are difficult to locate with certainty in the stratigraphy of Schofield et al. (2020) but appear to represent a mixture of distributions resembling, respectively, the Coedana and Porth y Felin slices, suggesting either tectonic or sedimentary mixing of these sources Fig. 19 e).

In the extreme SE of Ireland, metasedimentary rocks and amphibolite of the Rosslaire Complex have been compared with rocks now included in the Coedana and Aberffraw slices of Anglesey. No published detrital zircon data are available.

The *Penmynydd slice* (Fig. 10, MONP) comprises mixed metasedimentary and mafic metavolcanic units some of which show blueschist facies metamorphism. The protoliths are interpreted as Ediacaran (590-580 Ma), and metamorphism followed between 570 and 555 Ma. A structurally higher unit of greenschist facies rocks overlies the blueschists. Like the Aberffraw slice, the latest folds in the Penmynnydd slice are NW-vergent. Two detrital zircon data sets (Asanuma et al., 2017) are dominated by Ediacaran (~620 Ma) grains, suggesting that this slice is relatively juvenile in provenance (Fig. 19 f). A blueschist unit in the Llyn Peninsula of mainland Wales, correlated with the Penmynydd slice by Asanuma et al. (2015), shows a contrasting distribution more similar to the Coedana sample, suggesting that blueschist metamorphism is not limited to the Penmynydd slice.

The above slices are overlain by a Floian and younger shale succession that postdates their amalgamation. A brief volcanic interval is recorded in the Llandovery at 436 Ma. Younger but undated redbeds are associated with south-vergent thrusting at the Carmel Head thrust Fig. 10), which could be related either to the Silurian (Salinian/Scandian) collision of northern England with Laurentia, or could, alternatively, be a Devonian (Acadian) event.

Anglesey is bounded to the SE by the Menai Strait, which give its name to the NE–SW Menai Strait Fault System (Fig. 10), branches of which bound the Penmynydd slice. Deformation is inferred to have been mainly sinistral during juxtaposition of the various slices during Early Ordovician Monian–Penobscottian deformation (Schofield et al., 2020). Additional strands of the fault system cut mainland Wales to the SE, where they are overstepped by a regional post-Tremadocian unconformity. On the Llyn Peninsula (Fig. 10, MONW) mélange units and Ediacaran granitoids (Sarn Complex) are comparable to those in the Aberffraw and Coedana slices and may represent strike-slip fault repetitions of those units. Farther SE, the distinctive Arfon succession includes thick Ediacaran tuff and related intrusions dated at ~615 and ~575 Ma, overlain by Cambrian shale units with provenance almost entirely restricted to a single mode at ~550 Ma (Pothier et al., 2015a).

### 5.5. *West Avalonia*

Avalonia takes its name from the Avalon terrane, characterizing the Avalon Peninsula and adjacent areas of SE Newfoundland (Fig. 9, AVN), and its predecessor the Avalon Zone, identified through the northern Appalachians and into Britain, Ireland, and continental Europe in early syntheses of the orogen (Williams, 1978a, 1979). The domain was initially recognized on the basis of thin but laterally extensive shelf sedimentary rocks, mostly fine-grained clastic rocks, containing locally abundant Cambrian faunas representing the Acado-Baltic province, contrasting with contemporary faunas on Laurentia. This distinction enabled Wilson (1966) to identify an "Atlantic Faunal Realm" extending from Baltica to southeast New England. The Cambrian successions typically overlie thick piles of Cryogenian to Ediacaran volcanic rock, within which unconformities record a succession of deformational events. European segments of Avalonia have become known as "East Avalonia" (following Pickering et al., 1988) while the portions in the Appalachians are distinguished as "West Avalonia".

The development of Sm–Nd isotopic analysis led to a second defining characteristic for Avalonia: Avalonian rocks, particularly in the Avalon terrane, were found to be isotopically juvenile (Barr and Hegner, 1992; Nance and Murphy, 1994; Kerr et al., 1995), a feature which has come to be used as a defining characteristic of Avalonia, distinguishing it from Ganderia which is more isotopically evolved. Young (<1 Ga) model ages for most rocks in the Avalon terrane of Newfoundland suggest that it was not part of the supercontinent Rodinia, but that it came into existence perhaps as an arc or oceanic plateau during the Neoproterozoic (e.g. Murphy et al., 2008). However, as increasing amounts of Sm–Nd data have been collected within other terranes assigned to Avalonia, the distinction has become less clear-cut. For example, data from the SE New England terrane (Thompson et al., 2014) and from Britain (Schofield et al., 2016) show more evolved isotopic compositions, in some cases overlapping with those of Ganderia.

A recent review (van Staal et al., 2020) focussed on the Tonian to Ediacaran evolution of West Avalonia, drawing together some of the widely dispersed literature on its constituent terranes, and on the many proposals for Avalonia's original location. In contrasting interpretations, (Landing et al., 2022; van Staal et al., 2020) nonetheless both place Avalonia on the margin of Baltica during the Neoproterozoic.

Discussions of Avalonia have been beset by disagreements on what should be included in the domain. Some authors (e.g. Keppie, 1993; Landing, 1996; Cocks et al., 1997; Landing et al., 2022) have included all or most of those terranes here reported under Ganderia (section 5.1 to 5.4), interpreting Ganderia as the deep-water margin of Avalonia. In some publications (e.g. Landing, 1996) individual formation names have been extrapolated between terranes that are widely separated at the present day, in support of these correlations. In this paper we follow the more cautious route in restricting formation names to the terranes where they were defined. This approach has advantages when working with maps produced by individual state and provincial geological surveys, and it allows clarity in discussing whether or not particular units could be correlative.

#### 5.5.1. *SE New England terrane*

"Avalonian" rocks in SE New England (Fig. 7, SEN) have been identified as foreign to Laurentia since the work of Wilson (1966) although the name applied to this terrane has varied. Names used include "Milford–Dedham Zone" (Zen, 1983), "Esmond–Dedham terrane" (Skehan and Rast, 1990), and "Avalon terrane of southern New England" (Socci et al., 1990). The latter usage blurs the distinction between the broader domain Avalonia and the Avalon terrane (of Newfoundland) itself. Hence, we here refer to the region as *Southeastern New England terrane* or SNE (following Thompson et al., 2022). Authors have also differed as to whether or not a region of gneisses straddling the Rhode Island – Connecticut border should be regarded as a separate "Hope Valley Terrane" (e.g. Skehan and Rast, 1990); we here treat the Hope Valley Gneiss as part of the Southeastern New England terrane.

A relatively complete account of bedrock units was given by Skehan and Rast (1990), but advances in stratigraphy and geochronology have resulted in significant revisions to the terminology of units (Thompson et al., 2010a, 2010b, 2014, 2018). The oldest rocks in the terrane are isolated regions of quartzose sandstone (Westboro Formation) which have yielded zircon grains with a minimum age of ~912 Ma (Thompson et al., 2012). Much of the area of the terrane exposes variably deformed Neoproterozoic intrusive rocks with ages between 615 and 599 Ma, which are overlain by a thick succession of Neoproterozoic stratified rocks in the Boston Basin (Fig. 7). These include 597–593 Ma calc-alkaline arc volcanic rocks, overlain by conglomerate and by the thick (>3 km) Cambridge Argillite, the upper part of which is ≤ 552 Ma as indicated by zircons in a tuff horizon and by an ash layer dated at 551.22 ± 0.20 Ma (Thompson and Bowring, 2000; Thompson and Crowley, 2020).

A younger succession of much thinner (< 600 m) Cambrian sedimentary rocks of shelf facies (Fig. 3) is present in the terrane, directly overlying ~600 Ma granites, suggesting an episode of uplift or tectonism close to the Precambrian–Cambrian boundary that removed Neoproterozoic strata from parts of the terrane. The Cambrian rocks, although generally poorly exposed, are locally prolifically fossiliferous (e.g. Landing, 1988; Fletcher et al., 2005) and display classic Acado-Baltic faunas, ranging from at least late Terreneuvian (~526 Ma) to Drumian (~503 Ma), and correlative with terranes characterized as Avalonian farther NE in the Appalachians and Caledonides (Landing, 1996; Landing et al., 2022; van Staal et al., 2020). Skehan and Rast (1990) suggested that the succession may extend into the Ordovician, but intrusive relationships with the bimodal Nahant intrusive rocks (Thompson et al., 2010a), dated at 490–488 Ma (Furongian), that the stratified rocks are all Cambrian. The Nahant intrusive rocks record the first of a series of within-plate igneous events extending through the Silurian into the Devonian, and Thompson et al. (2010a, 2010b) suggested that they may record separation of the Southeastern New England terrane from Gondwana. Subsequent intrusive events occurred close to the Ordovician–Silurian boundary (~444 Ma), in the late Silurian (426–423 Ma) and in the Devonian (411 Ma and 378 Ma) (Thompson and Hermes, 2003; Thompson et al., 2018). The last of these events (Scituate Igneous Suite) is interpreted as a precursor to the opening of the Narragansett basin, which was eventually filled by thick coal-bearing clastic sedimentary rocks in the Pennsylvanian. Metamorphism and deformation, associated with both contraction and strike-slip motion, occurred in the Permian (~280 Ma), increasing in intensity westward toward the contact with the Putnam–Nashoba terrane.

The detrital zircon distributions (Thompson et al., 2012, 2014) of the older units in Southeastern New England are distinctive in displaying significant amounts of zircon in the 0.9–1.2 Ma range, otherwise relatively rare in non-Laurentian terranes, together with progressively declining densities of older Mesoproterozoic to Paleoproterozoic zircon, producing an asymmetric Proterozoic peak reminiscent of Laurentian samples (Fig. 21). The distribution differs from most Laurentian samples, however, in including a small amount of "Eburnean" zircon 1.9–2.2 Ga. Nonetheless, without further evidence, these distributions would be difficult to distinguish from Laurentian samples. Other basement units (Selden Neck Quartzite and Old Lyme Gneiss) are similar but lack the abundant 0.9–1.2 Ga grains. Younger units are more recognizably Gondwanan because the similar distribution of Meso- and Paleoproterozoic zircon is diluted with Ediacaran grains, recording "Panafrican" events. Despite this, the overall distribution of zircon ages in Southeastern New England (Fig. 21) is distinctly different from most other parts of West Avalonia, with the notable exception of the Cobequid belt of Nova Scotia (section 5.5.3). Consistent with this relatively extended provenance, the Southeastern New England terrane displays initial Sm/Nd isotopic ratios ($\varepsilon_{Nd}$ -2 to +2) that are more evolved than typical of the Avalonian terranes elsewhere, although still juvenile in comparison to Ganderia.

Paleomagnetic work and U-Pb geochronology on the Nahant intrusive suite by Thompson et al. (2010a, 2010b) provided an important constraint for Furongian Southeastern New England terrane paleogeography. Ten sites within mafic sills, a dyke and a gabbro dated at 488.5 ± 0.8 Ma, have stable ChRM directions carried by titanomagnetite, which cluster upon tilt correction using paleohorizontal sill attitudes and sheeting joints to give a very steep, two-polarity result (Table 2). The positive fold and reversal tests suggest that the Nahant ChRM is primary, acquired at 488.5 Ma, and is unlike younger overprint magnetizations in three sites which correspond with the expected late Silurian and Carboniferous directions for Laurentia (Thompson et al., 2012). The steep tilt-corrected ChRM indicates a Southeastern New England terrane paleolatitude of 65° ± 7° S, placing it most likely near the South Pole in the Furongian, adjacent to the West African margin of Gondwana. A location closer to the Arabian–Nubian Shield is also permissible, although that requires Southeastern New England to be located on the far side of the South Pole and to be rotated into an opposite orientation relative to the Gondwanan margin (Fig. 24).

### 5.5.2. Caledonia terrane

One of the most complete successions assigned to Avalonia in the Maritime Provinces lies in the *Caledonia terrane* (Fig. 8, CAL) of southern New Brunswick, where three Cryogenian to Ediacaran successions (Fig. 4) are dominated by volcanic and epiclastic rocks; each succession is associated with granitoid intrusions (Barr et al., 1994, 2002a; White et al., 1990; Barr et al., 2019, 2020b). The oldest of these is the Cryogenian Lumsden Group which, together with related plutons, is dated around 690 Ma. A similar but younger Broad River Group, and syn-volcanic plutons, range in age from ~630 to ~615 Ma. Both the Lumsden and Broad River groups, as well as the associated plutons, are calc-alkaline and represent continental-margin subduction-zone settings.

A small but significant sliver of high P/T metamorphic rocks (0.9 GPa at 580°C), the Hammondvale metamorphic suite, is preserved near the NW edge of the Caledonia terrane (White et al., 2001). These rocks consist of pelitic schist, calc-silicate rocks, impure marble, and rare quartzite, and are interpreted as part of the Caledonia terrane because they are intruded by the ca. 550 Ma granite that is widespread in the terrane. Muscovite $^{40}Ar/^{39}Ar$ ages suggest that metamorphism occurred at ca. 615 Ma but that the depositional age of the pelitic protolith is ≤650 Ma. They have been interpreted to represent the remnants of an accretionary prism (White et al., 2001; Reynolds et al., 2009; Satkoski et al., 2010; Barr et al., 2012). This subduction-related tectonism thus immediately preceded deformation and accompanying greenschist-facies metamorphism of the adjacent 630–615 Ma volcanic arc rocks of the Broad River Group. If interpreted as paired metamorphic belts the Hammondvale metamorphic suite and the Broad River Group suggest SE-dipping subduction around 615 Ma.

In contrast the younger Coldbrook Group (Fig. 4) and associated plutons span a short interval from ~560 (or younger) to ~548 Ma and represent a nonmarine extensional setting prior to the transition to a marine depositional environment by the end of the Terreneuvian (~520 Ma). Values of $\varepsilon_{Nd}$ in felsic igneous samples representing all three successions are mainly juvenile but include some negative values ($\varepsilon_{Nd}$ -2 to +4), showing that the igneous rocks are derived from crustal sources somewhat more mature than those in the eastern Avalon terrane of Newfoundland but similar to other parts of Avalonia.

The Coldbrook Group is overlain disconformably by a thin (~500 m) platformal succession of fossiliferous Cambrian to Early Ordovician strata (Fig. 4) that contain locally abundant fauna including trilobites. The succession consists entirely of shelf facies, and includes numerous disconformities. Landing (1996) correlated unconformity-bounded sequences from Newfoundland to New Brunswick. The nomenclature shown in Fig. 4 prioritizes lithologic boundaries, rather than those inferred on the basis of biostratigraphy or sequence stratigraphy, and mainly reflects the work of Tanoli and Pickerill (1988). This approach allows us to place the biostratigraphic and chronostratigraphic results of Landing (e.g. Landing, 1996; Landing et al., 1998; Landing, 2004) in the context of local geologic mapping, section measuring and isotopic dating. The highest strata are early Ordovician shales, possibly extending into the Floian.

Detrital zircon spectra from the Caledonia terrane (Fig. 21 d) show large, paired peaks in the Ediacaran to earliest Cambrian, reflecting derivation directly from the local volcanic units, and smaller populations of Meso- to Paleoproterozoic and minor Archean zircon. However, when the Ediacaran component is excluded, the distributions appear identical to those in adjacent parts of Ganderia, with peaks at ~1.5 and ~2.0 Ga, suggesting that the Brookville and Caledonia terranes may have had similar sediment sources in Gondwana during the Cambrian (Barr et al., 2019).

### 5.5.3. Cobequid belt and Antigonish terrane

"Avalonian" rocks in mainland Nova Scotia occur in an E–W belt in the Cobequid Highlands north of the Carboniferous Minas fault zone (Fig. 9), and farther east in the Antigonish Highlands (AGN). In both areas, Proterozoic to Devonian rocks occur as inliers surrounded by sedimentary rocks of the Carboniferous Maritimes Basin.

The Cobequid belt (Fig. 8) is divided into the Jeffers (COBJ), Bass River (COBB), and Mount Ephraim (COBE) blocks (White et al., 2022). The latter two blocks contain some of the oldest rocks in Avalonia (Fig. 4). In the Bass River block, quartzite, metawacke, and minor carbonate of the Gamble Brook Formation have a maximum possible depositional age of 945 ± 12 Ma based on detrital zircon. They are interlayered with undated subaqueous mafic volcanic rocks, siltstone, and ironstone of the Folly River Formation. Both formations are intruded by the 615 to 600 Ma calc-alkalic subduction-related Bass River plutonic suite. The detrital zircon distributions of the Gamble Brook Formation show a marked resemblance to those of the older units in the Southeastern New England terrane (van Staal et al., 2020) (Fig. 21 a, b). The age of the higher-grade and possibly correlative Mount Thom Formation in the Mount Ephraim block is constrained as >755 Ma by unconformably overlying volcanic rocks of the Dalhousie Mountain Group, and abundant plutons of the 752–725 Ma Mount Ephraim plutonic suite (White et al., 2022). In contrast, the larger Jeffers block that forms most of the Cobequid belt consists mainly of intermediate to felsic volcanic, epiclastic, and only minor plutonic rocks. U-Pb zircon ages from volcanic and plutonic rocks range from 630 Ma to 592 Ma. Poorly exposed Silurian sedimentary cover rocks (Wilson Brook and equivalent formations) are inferred to overlie the Jeffers block unconformably. The whole belt was affected by bimodal magmatism in the Early Carboniferous associated with the transtensional opening of the Maritimes Basin (Dunning et al., 2002).

The Antigonish terrane to the east (Fig. 8) is separated from the Cobequid belt by Carboniferous cover but appears most closely related to the Jeffers block. It contains a thick and varied succession of arc-related sedimentary and volcanic rocks known as the Georgeville Group, the minimum age of which is constrained by cross-cutting plutons with ages of ~618–603 Ma (Keppie and Murphy, 1988; White, 2017; White et al., 2022). The Georgeville Group is overlain by two other Ediacaran volcanic–sedimentary units and a small area of thin and poorly exposed early Paleozoic (Cambrian to Floian) sedimentary rocks that appear to have been juxtaposed by faulting (Keppie and Murphy, 1988; White, 2017; White et al., 2021). Fossils are comparable to those elsewhere in West Avalonia (Landing and Murphy, 1991). Detrital zircon samples of Cambrian and Ordovician age are dominated by Ediacaran zircon with only minor Meso- and Paleoproterozoic input (Fig. 21 c).

The Georgeville Group and related plutons are intruded by widespread and protracted ca. 495–460 Ma gabbroic to syenitic magmatism, producing the West Barneys River Plutonic Suite and related plutons (Escarraga et al., 2012; Archibald et al., 2013; White, 2017). They were interpreted to have been emplaced in an extensional setting (Archibald et al., 2013). However, bimodal volcanic rocks of the Dunn Point and McGillivray Brook formations (Fig. 4), of Darriwilian to Sandbian age (460–454 Ma), are interpreted to record arc to backarc environments (Jutras et al., 2020). These volcanic rocks are overlain unconformably by richly fossiliferous shallow marine shale and sandstone of the Arisaig Group that span most of the Silurian Period, and are overlain by thick, rapidly accumulated Lochkovian redbeds of the Knoydart Formation. Waldron et al. (1996) modelled the subsidence history of the Arisaig Group, concluding that it originated in a rift basin that was converted to a collisional foreland basin during the latest Silurian.

In the Silurian Arisaig Group the oldest samples show a bimodal detrital zircon age distribution dominated by Ediacaran and “Eburnean” (1.9–2.2 Ga) grains comparable to the Meguma terrane (section 5.7.1), but younger parts of the Group show diverse ages best explained as derived from a basement similar to that which supplied Southeastern New England. Values of $\varepsilon_{Nd}$ for the Cobequids span a wide range (-8 to +8) but the Antigonish highlands are consistently juvenile (+2 to +4) (Thompson et al., 2012; White, 2017; White et al., 2021).

Paleomagnetic results (Table 2, Fig. 9 b) have been obtained from the Ordovician Dunn Point Formation in the western Antigonish Highlands (Van der Voo and Johnson, 1985; Johnson and Van der Voo, 1990). The formation consists of steeply dipping to overturned basalt and rhyolite, tilted about mainly E–W axes. The rhyolite yielded a U-Pb zircon age of Darriwilian age of 460.0 ± 3.4 Ma (Hamilton and Murphy, 2004). Nineteen sites from oxidized flows provided ChRM directions carried predominantly by hematite that passed a fold test (Acadian), resulting in a steep upwards single-polarity mean direction upon tilt correction (Table 2). The paleolatitude of the Antigonish terrane at 460 Ma was 41° ± 5° S, and the declination indicates that the south pole lay towards the SSE (present-day coordinates). These results position the Antigonish terrane in roughly its present orientation relative to the margin of composite Laurentia, but 2000–3000 km farther south, in a mid-Iapetus position.

### 5.5.4. Mira terrane

Avalonian rocks in Cape Breton Island are assigned to the *Mira terrane* (Fig. 8, MIR) where three assemblages of Neoproterozoic, predominantly volcanic and epiclastic rocks, have been identified. The oldest rocks are assigned to the ~680 Ma (Cryogenian) Stirling Group and related plutons. Younger arc volcanic rocks (Fig. 4) of the East Bay Hills, Pringle Mountain, and Coxheath groups and associated plutons (~625–615 Ma) occur in separate belts within the Mira terrane, and are in faulted contact with the 575–570 Ma Fourchu and Main à Dieu groups that record both arc and extensional arc-related environments. It is not yet clear how large an age gap occurs between the uppermost redbeds and interlayered mafic volcanic rocks of the Main-à-Dieu Group and the disconformably overlying Cambrian succession (e.g. Barr et al., 2020a). The lowermost Cambrian units record a transition from nonmarine conglomerate and redbeds to shelf conditions in which were deposited highly fossiliferous shale and sandstone possibly extending into the earliest Ordovician. Trilobite and other fauna are similar to those in Avalonian successions in Southeastern New England, southern New Brunswick and Newfoundland, and lithostratigraphic units (Landing, 1996, 2004) have been correlated between the terranes. Subsequent work using acritarchs has shown important differences in timing of units (Palacios et al., 2009, 2011, 2018), although the facies and overall character of the faunas remain closely similar.

Detrital zircon distributions (Fig. 21 h) are closely similar to those of the Caledonia terrane, showing paired Ediacaran peaks at ~550 and 650 Ma and a diverse Mesoproterozoic to Archean record, with distinct early Mesoproterozoic and Eburnean peaks at 1.5 and ~2.05 Ga. The pre-Ediacaran distribution is also similar to those of the Bras d’Or terrane and, even more so the Brookville terrane, suggesting that these terranes shared a common source, probably in Amazonia. Perhaps surprisingly, in the light of this extended provenance and zircon inheritance back to the Archean (Bevier et al., 1993), granitoid plutons in the terrane mainly show relatively juvenile $\varepsilon_{Nd}$ values in the range +1 to +8, although some plutons have negative $\varepsilon_{Nd}$ (Barr and Hegner, 1992; Samson et al., 2000; Willner et al., 2013; Pollock et al., 2015).

### 5.5.5. Avalon terrane

The *Avalon terrane* in Newfoundland, including both the Avalon Peninsula and adjacent areas farther west (Fig. 9, AVN), represents the original ‘type’ Avalon Zone of Williams (1979). The terrane occupies a large area in SE Newfoundland, within which Fig. 5 shows considerable variability in the Neoproterozoic stratigraphy (O’Brien et al., 1996; Mills et al., 2021 and references therein). The overlying platformal Cambrian to Early Ordovician succession shows less lateral variation than the Neoproterozoic rocks, except in the SW of the terrane, where distinct units are present. The terrane is known to extend under the Grand Banks to the east, where the succession continues into the Silurian (King et al., 1986; Durling et al., 1987). Four stratigraphic columns are distinguished in Fig. 5, representing the eastern Avalon Peninsula, the Bonavista and Burin peninsulas farther west, and the Connaigre Peninsula adjacent to the boundary with the Hermitage belt (Fig. 9).

The oldest rocks (Tonian, ~764 Ma) occur in the Burin Peninsula (Fig. 9), where mafic volcanic and intrusive rocks of ophiolitic aspect are hypothesized (Murphy et al., 2008) to represent a juvenile oceanic arc, although minor involvement of older crust is possible. They are associated with clastic and carbonate sedimentary olistostromes or mélange (O’Brien et al., 1996) inferred to represent either oceanic island environments (Murphy et al., 2008) or a contemporary passive margin onto which the arc was emplaced (van Staal et al., 2020). Although of low metamorphic grade, they are possibly representative of the basement on which younger volcanic arcs, that dominate the terrane, were founded, as published plots of Sm–Nd isotopic data from Avalonia indicate that parts of the Avalon terrane are the most juvenile in Avalonia. Tonian (729 ± 7 Ma) intermediate to felsic tuff has been reported on the Avalon Peninsula (Israel, 1998). However, Cryogenian rocks occur in the Connaigre Peninsula, where mixed sedimentary and volcanic units of the

Tickle Point Formation (~683 Ma) are intruded by 673 ± 3 Ma granite (O'Brien et al., 1996). These rocks have been correlated with the Stirling belt of the Mira terrane, with which they share not only age but also negative $\varepsilon_{Nd}$ and other isotopic characteristics (Pollock et al., 2015).

Early Ediacaran (~635–605 Ma) arc successions (Fig. 5) occur throughout the Avalon terrane of Newfoundland, although major lateral facies variations occur between volcanic centres (Mills et al., 2021). The volcanic rocks were intruded by contemporary calc-alkaline plutons and surrounding basins were filled by volcanic-rich turbidites. A second, late Ediacaran major pulse of arc-related, increasingly within-plate alkaline volcanic rocks at ~ 575 Ma dominates all the successions except that in the St. John's area, where distal volcanic ash deposits contribute to preservation of the famous Ediacaran faunal site at Mistaken Point and elsewhere at 565 Ma (e.g. Wood et al., 2003). Another distinctive feature of the Avalon terrane is the widespread preservation of glacial deposits at ca. 580 Ma (Pu et al., 2016). Neither glacial diamictites nor Ediacaran fauna have been recognized in other parts of West Avalonia, with the exception of older (595–594 Ma) glaciogenic Roxbury deposits at Squantum Head in the Southeastern New England terrane (Thompson et al., 2014).

Latest Ediacaran to Cambrian successions (Fig. 5) are predominantly sedimentary, and include, on the Burin Peninsula, the international stratotype for the base of the Cambrian System (Narbonne et al., 1987; Landing, 1994). This part of the succession is missing at an unconformity farther east, but a widespread marker unit of shallow-marine quartz arenite, the Random Formation, occurs in most areas of the terrane. The overlying Cambrian succession is highly fossiliferous but conflicting lithostratigraphic schemes (e.g. Landing, 1996; Fletcher, 2006; Landing et al., 2017) have been used. Nonetheless, all these authors are agreed that similar stratigraphic units can be recognized across the Avalon, Bonavista, and Burin peninsulas; a less continuous stratigraphy, with sandstone in the Miaolingian, is recognized in the Connaigre Peninsula. The simplified version shown in Fig. 5 mainly reflects usage in publications of the Newfoundland Geological Survey (e.g. Fletcher, 2006). Thin, shaly fossiliferous units record most of the trilobite zones in Cambrian series 2–4, suggesting that thermal subsidence controlled sedimentation; laterally traceable unconformities may record mainly eustatic events.

The shallow-marine succession continues into the Ordovician on Bell Island (Fig. 9) (Pickerill and Fillion, 1983; Ranger et al., 1984), but is frustratingly poor in fossils. The youngest dated strata there are Floian. However, younger gently dipping sandstone and shale, loosely constrained by fossils from Late Ordovician to Ludlow in age, are recorded in offshore core samples tied to seismic reflection data (King et al., 1986; Durling et al., 1987).

Available detrital zircon data for the Avalon terrane (Pollock et al., 2009; Henderson et al., 2016) also show strong similarity between samples (Fig. 21 e). With one exception, populations are dominated by Ediacaran grains; typically, two populations can be discerned within this peak, respectively older and younger than 600 Ma, corresponding to the two major successions of volcanic rocks in the terrane. This dominance of "young" zircon corresponds to the isotopically juvenile character of most Avalon terrane igneous rocks ($\varepsilon_{Nd}$ +2 to +7), which have been interpreted to imply that the terrane was not part of the supercontinent Rodinia (Nance and Murphy, 1994; Murphy and Nance, 2002). The exception to this uniformity is a single sample (Fig. 21 f) from the Early Ordovician Redmans Formation on Bell Island, the youngest unit sampled by Pollock et al. (2009). In addition to the characteristic Ediacaran populations, this sample shows a range of Mesoproterozoic and Paleoproterozoic zircon including a significant "Eburnean" population between 2.0 and 2.3 Ga, resembling those obtained from Ganderian samples. Interestingly, Henderson et al. (2016) did not report a similar distribution from the Redmans Formation; their sample contains a single Ediacaran peak like those below it. Although the samples were not precisely located in a stratigraphic succession, we infer that Pollock et al. (2009) sample records an influx of older zircon part-way through the Redman's Formation. Though interpreted by Pollock et al. (2009) to represent *separation* of Avalonia from Gondwana, Waldron et al. (2014a) argued that the new appearance of Gondwana-sourced zircon in this sample more likely represents a *convergence* of the Avalon terrane with a Ganderian terrane.

As noted above and illustrated in Fig. 5, the Connaigre peninsula in the SW of the Avalon terrane is exceptional in a number of respects. Negative $\varepsilon_{Nd}$ values, the presence of Cryogenian volcanic rocks, a distinct Cambrian succession, and the presence of a Silurian intrusion (Kellett et al., 2014) all suggest possible links to other Avalonian terranes.

In the SW Avalon, Cambrian marine strata are intruded concordantly by the Cape St. Mary's gabbroic sills and feeder dykes, which yielded a U-Pb baddeleyite age of 441 ± 2 Ma (Greenough et al., 1993). The sills and host sedimentary rocks were deformed into open folds with nearly N–S-trending axes most likely during the Devonian Acadian Orogeny. Twelve paleomagnetic sites in the sills provide stable ChRM recorded by low-Ti magnetite, with site mean directions that cluster well in a single (normal) polarity after tilt-correction, passing the fold test (Hodych and Buchan, 1998). The resulting paleolatitude for the Avalon terrane at 441 Ma is 32° ± 8° S, and the declination indicates that the south pole lay towards the SSE (present-day coordinates; Table 2, Fig. 9 b). The 441 Ma Cape St. Mary's sills result is similar to that from the 460 Ma Dunn Point Formation in the Antigonish highlands (Table 2), despite differing structural corrections, suggesting that these present elements of Avalonia maintained a similar paleo-orientation with respect to the south pole, and the Laurentian margin, from 460 to 441 Ma, as Avalonia drifted to lower paleolatitude. The Cape St. Mary's result suggests that by 440 Ma it was ~1000 km south of its present position relative to the margin of composite Laurentia.

### 5.6. East Avalonia: Midland platform: Wrekin and Charnwood terranes

The stratigraphy of the Midland Platform of England (Fig. 6) resembles that of the Avalon terrane of Newfoundland, to the extent that it is commonly known as "East Avalonia" (Pickering et al., 1988). Available isotopic data suggest that despite the stratigraphic similarities, the crust beneath East Avalonia is more evolved than that of the Avalon terrane in Newfoundland (Schofield et al., 2016). However, because of the extent of post-Devonian cover, large areas of the underlying early Paleozoic and Precambrian rocks are unknown. Despite the small areas of exposed Precambrian rock, several terrane boundaries have been proposed within this area. However, the terrane names — Cymru, Wrekin, Charnwood, and Fenland — are strictly applied to Precambrian rocks (Pharaoh et al., 1989), and the boundaries between them are largely concealed beneath Ordovician and younger cover rocks. Most authors use the single name "East Avalonia" in descriptions of the Cambrian and younger history of England and Wales.

#### 5.6.1. Terranes

The *Wrekin terrane* (Fig. 10, WRE) extends between the Malvern line in the east and the Welsh Borderlands fault system in the west. Although the terrane is traditionally delineated at the Pontesford–Linley fault zone, we extend it as far as the Tiwi Lineament and Severn Valley fault zone Fig. 10) which mark a boundary between distinct Ordovician and Silurian successions of the Midland platform and the Welsh basin (Cave, 2008). The Wrekin terrane is characterized by Cryogenian basement in the ~710 Ma Stanner Hanter Complex (Schofield et al., 2009a) and the ~677 Ma Malverns Gneiss (Strachan et al., 2007). Above this basement, calc-alkaline early Ediacaran rocks are typically overlain by late Ediacaran within-plate volcanic rocks (Uriconian Supergroup, Fig. 6) that record arc rifting (McIlroy and Horak, 2006). Towards the western edge of the terrane a late Ediacaran graben was filled with clastic sediment (Longmyndian Supergroup) that was then deformed in sinistral transpression close to the Ediacaran–Cambrian boundary (Pauley, 1990). The east and west boundaries of the inverted, folded graben are marked by

**Table 3**
List of terranes utilized in map construction and labelling of detrital zircon and paleomagnetic data sets.

| Code | Terrane, block, or belt | Terrane (short name) | GPlates ID | Domain* |
|---|---|---|---|---|
| ASQ | Annieopsquotch accretionary tract | Annieopsquotch | 15692 | PLa |
| AGN | Antigonish | Antigonish | 10860 | WAv |
| ANI | Annidale | Annidale | 18489 | Gdr |
| ARF | Arfon | Arfon | 39202 | Gdr |
| ASP | Aspy belt (undifferentiated) | Aspy | 18497 | Gdr |
| ASPC | Aspy belt Cheticamp block | Aspy Cheticamp | 18444 | Gdr |
| ASPF | Aspy belt Faribault Brook block | Aspy Faribault Bk | 18443 | Gdr |
| ASPH | Aspy belt Central Highlands block | Aspy Central highlands | 18441 | Gdr |
| ASPP | Aspy belt Pleasant Bay block | Aspy Pleasant Bay | 18442 | Gdr |
| AVN | Avalon | Avalon | 10800 | WAv |
| BRB | East Avalonia of mainland Europe | Brabant | 31510 | EAv |
| BRD | Bras d’Or | Bras d’or | 18465 | Gdr |
| BRI | Blair River “inlier” | Blair River | 15694 | PLa |
| BRK | Brookville | Brookville | 18464 | Gdr |
| BRN | Bronson Hill | Bronson | 18463 | Gdr |
| BWS | Bellewstown | Bellewstown | 39270 | Gdr |
| CAL | Caledonia | Caledonia | 10865 | WAv |
| CHL | Chain Lakes, Maquereau, & overlying CVG belt | Chain Lakes | 15601 | PLa |
| CHN | Charnwood | Charnwood | 31570 | EAv |
| CMB | Unexposed basement of Cumberland basin | Cumberland | 10871 | WAv? |
| COBB | Cobequid belt - Bass River block | Cobequid | 10870 | WAv |
| COBE | Cobequid belt - Mt. Ephraim block | Mt Ephraim | 10872 | WAv |
| COBJ | Cobequid belt - Jeffers block | Jeffers | 10879 | WAv |
| CON | Connemara | Connemara | 33103 | PLa |
| CYM | Cymru | Cymru | 31572 | Meg |
| DSH | Dashwoods | Dashwoods | 15602 | PLa |
| ELM | Elmtree (slices above Miramichi) | Elmtree | 18456 | Gdr |
| ELS | Ellsworth | Ellsworth | 18487 | Gdr |
| ENG | Subsurface of eastern England | Fenland | 31560 | EAv |
| FDL | Fleur de Lys | Fleur de Lys | 15674 | PLa |
| FRN | Fredericton trough north | Fredericton Trough N | 18458 | Gdr |
| FRS | Fredericton trough south | Fredericton Trough S | 18475 | Gdr |
| GAC | Post-Penobscot cover on Gander | Davidsville | 18469 | Gdr |
| GAN | Gander terrane | Gander | 18400 | Gdr |
| GMN | Grand Manan slice of ?New River Belt | Grand Manan | 18477 | Gdr |
| GRA | Grampian | Grampian | 33102 | PLa |
| GRV | Hermitage Grey River block | Hermitage Grey R | 18466 | Gdr |
| GTH | Grangegeeth | Grangegeeth | 33161 | PLa |
| GUY | Guysborough | Guysborough | 10878 | ? |
| HEB | Hebrides | Hebrides | 15400 | Lau |
| HER | Hermitage La Poile Block | Hermitage | 18493 | Gdr |
| HUM | Humber zone of Newfoundland | Humber | 15500 | Lau |
| KNG | Kingston | Kingston | 18480 | Gdr |
| LBO | Liberty–Orrington bellt | LibertyOrrington | 18470 | Gdr |
| LLM | Leinster–Lakesman | LeinsterLakesman | 39281 | Gdr |
| LNA | Lough Nafooey Arc | Lough Nafooey Arc | 33150 | PLa |
| MAB | Aspy belt (Mabou block) | Mabou | 18498 | Gdr |
| MCK | Merrimack trough | Merrimack | 18485 | Gdr |
| MEG | Meguma main block | Meguma Main | 18382 | Meg |
| MEGE | Meguma East of Country Harbour fault | Meguma East | 18383 | Meg |
| MING | Mings Bight block of Fleur de Lys | Mings Bight | 15684 | PLa |
| MIR | Mira | Mira | 10873 | WAv |
| MON | Monian (undifferentiated) | Monian | 39285 | Gdr |
| MONA | Monian Abberffraw slice | MonianAberffraw | 39292 | Gdr |
| MONC | Monian Coedana slice | MonianCoedana | 39290 | Gdr |
| MONF | Monian Porth y Felin slice | MonianPorthyFelin | 39289 | Gdr |
| MONL | Monian Lower Amlwych slice | MonianAmlwchL | 39287 | Gdr |
| MONP | Monian Penmynydd slice | MonianPenmynydd | 39295 | Gdr |
| MONU | Monian Upper Amlwych slice | MonianAmlwchU | 39286 | Gdr |
| MONW | Monian West Llyn Peninsula | WestLlyn | 39288 | Gdr |
| MOR | Moretown | Moretown | 18455 | Gdr |
| MRM | Miramichi | Miramichi | 18459 | Gdr |
| MSB | Massabesic Gneiss | Massabesic | 18484 | Gdr |
| MVS | Midland Valley of Scotland | Midland Valley | 33151 | PLa |
| NHI | Northern Highlands | Northern Highlands | 33101 | Lau |
| NOD | Notre Dame | Notre Dame | 15690 | PLa |
| NRV | New River belt (undifferenticated) | New River | 18490 | Gdr |
| NRVA | New River belt (Almond Road slice) | NewRiverAlmondRd | 18492 | Gdr |
| NRVB | New River belt (Buckmans Creek slice) | NewRiverBuckmansCreek | 18495 | Gdr |
| NRVL | New River belt (Long Reach slice) | NewRiverLongReach | 18494 | Gdr |
| NRVP | New River belt (Pocologan River slice) | NewRiverPocologanR | 18491 | Gdr |
| NSH | Putnam-Nashoba terrane | Nashoba | 18496 | Gdr |
| POP | Popelogan | Popelogan | 18457 | Gdr |
| SCX | St. Croix | St. Croix | 18488 | Gdr |

(*continued on next page*)

**Table 3** (*continued*)

| Code | Terrane, block, or belt | Terrane (short name) | GPlates ID | Domain* |
|---|---|---|---|---|
| SEN | Southeastern New England west of Narangansett basin | SE New England | 10862 | WAv |
| SUP | Southern Uplands belt | Southern Uplands | 33160 | PLa |
| VIC | Victoria: Exploits subzone W of Dog Bay Line | Victoria | 18476 | Gdr |
| VSC | Cymru overprinted by Variscan | Variscan SW Wales | 31573 | Meg |
| VSE | Charnwood overprinted by Variscan | Variscan S England | 31571 | EAv |
| VSI | Leinster Lakesman overprinted by Variscan | Variscan S Ireland | 39284 | Gdr |
| VSW | Wrekin overprinted by Variscan | Variscan SW England | 31596 | EAv |
| WRE | Wrekin | Wrekin | 31595 | EAv |

| *List of Interpreted domains | Abbreviation |
|---|---|
| Laurentian | Lau |
| Peri-Laurentian | Pla |
| Ganderia | Gdr |
| West Avalonia | WAv |
| East Avalonia | EAv |
| Megumia | Meg |

the Church Stretton and Pontesford–Linley fault zones (Fig. 10). A Cambrian shelf succession, locally richly fossiliferous, is highly condensed and contains many internal disconformities (Brenchley et al., 2006 and references therein; Rushton et al., 2011). An overlying Tremadocian shaly succession that extends both east and west of the Longmyndian inlier shows dramatic thickness variations, suggesting deposition in a rift system that has been correlated with opening of the Rheic Ocean (Smith and Rushton, 1993). An Ordovician shelf succession, interleaved with rift-related volcanic rocks is preserved along the western margin of the terrane in the Shelve inlier. A regional unconformity separates it from an overlying Wenlock and younger shelf succession which is diachronously overlain by clastic non-marine sediments in the Pridoli to Early Devonian.

The *Charnwood terrane* (Fig. 10, CHN) is largely concealed beneath late Paleozoic and Mesozoic cover. Pre-Silurian successions are known from small inliers, notably at Nuneaton and Charnwood Forest (Fig. 10), and from boreholes. These inliers lack true basement rocks, but display thick Ediacaran calc-alkaline volcanic successions interbedded with sedimentary units famous for the first documentation of Ediacaran fossils (McIlroy and Horak, 2006 and references therein). Sandstone representing the Terreneuvian to Cambrian Series 2 is overlain by a relatively thick (>600 m) muddy succession that contrasts with the very condensed Cambrian in the Wrekin terrane. The Tremadocian succession is also fine-grained, and like that in the Wrekin Terrane shows large thickness variations due to the development of extensional half-graben features that were subsequently inverted (Smith and Rushton, 1993), possibly during Late Ordovician collision between East Avalonia and Baltica along the Tornquist line. Locally preserved Silurian successions represent shelf environments similar to those of the Wrekin terrane.

Farther east, a boundary with a *Fenland terrane* (Fig. 10 ENG) has been proposed on the basis of scattered borehole information, coupled with geophysical interpretation. Dated igneous rocks recovered from boreholes (Noble et al., 1993) include Ediacaran tuffs at 612 ± 21 and 616 ± 6 Ma, and suite of late Ordovician calc-alkaline volcanics and intrusions dated between 457 and 442 Ma, interpreted as recording subduction of the Tornquist sea (separating East Avalonia and Baltica).

The only available detrital zircon data are from the Wrekin terrane (Murphy et al., 2004c; Waldron et al., 2019a) and are dominated by Ediacaran and Eburnean grains (Fig. 22 g), suggesting a close linkage with the Welsh basin, and therefore with the Meguma terrane and with the West African craton. No detrital zircon data are available for the Charnwood and Fenland terranes. However, many data sets have been reported from the extension of East Avalonia into the Variscan belt of mainland Europe (e.g. Stephan et al., 2019), beyond the scope of this review.

### 5.6.2. *Paleomagnetism*

Ordovician paleomagnetic results are reported from the Wrekin terrane (Table 2). The Darriwilian Stapeley Formation of the Shelve Inlier in the Welsh borderlands consists of interbedded basalt, rhyolite pyroclastic rocks and shale of the *Didymograptus artus* zone (~464.5 Ma), folded about NE-tending axes probably in the Late Ordovician, providing a well constrained fold test (McCabe and Channell, 1990). Eleven sites on different fold limbs retain a ChRM carried by titanomagnetite, with site mean directions that cluster well in a single (reversed) polarity following tilt-correction (Table 2). The steep tilt-corrected prefolding ChRM gives a paleolatitude of 51° ± 7° S, with a declination indicating that the south pole lay to the ESE (present-day coordinates).

A second Wrekin terrane inlier at Builth has been the subject of several overlapping paleomagnetic studies (Trench et al., 1991; McCabe et al., 1992) which documented somewhat contrasting results (see discussion in Channell et al., 1992). Northwest-dipping interbedded basalt, agglomerate, keratophyre, tuff and clastic sedimentary rocks primarily of the *D. murchisoni* zone (~462.5 Ma), along with concordant diabase intrusions, are exposed in the southwest of the inlier, with a decreasing volcanic component in the north. Intraformational agglomerate, and volcanic boulders in the unconformably overlying sandstone exhibited scattered stable ChRM directions, passing a conglomerate test, thus indicating that remanence carried by magnetite in underlying flows and diabase is primary (Trench et al., 1991; McCabe et al., 1992). Sites concentrated in the south of the inlier yielded tilt-corrected ChRM directions that are systematically shallower than those elsewhere in the inlier; hence two single-polarity results were reported (Channell et al., 1992): SW Builth (18 sites) and Builth North (6 sites). The tilt-corrected site ChRMs for SW Builth resulted in a paleolatitude of 34.5° ± 7.5° S, with a declination indicating that the south pole lay to the S (Trench et al., 1991); tilt-corrected site ChRMs for Builth North resulted in a paleolatitude of 54° ± 16° S, and south pole to the SE (McCabe et al., 1992). As discussed in Channell et al. (1992), it is unclear which result, if either, is representative of the surrounding area, because of difficulty in identifying true paleohorizontal surfaces. Failed paleomagnetic fold tests in the igneous rocks imply tilting and folding by volcanic processes prior to remanence acquisition, suggesting the presence of primary bedding tilts (Trench et al., 1991). Regional tilt correction, using unconformably overlying sandstone as a paleohorizontal, still resulted in inconsistent tilt-corrected ChRM directions (McCabe et al., 1992). One possible explanation for the inconsistency is that the units sampled in Builth were emplaced over too short a time to average paleosecular variation of the Earth's magnetic field, leading to an unrepresentatively result of single polarity (McCabe et al., 1992). However, the result from Stapeley, located only 50 km away in rocks of almost the same age, falls between the two Builth results. With these caveats, both Builth Inlier results are included in this review (Table 2), as they still represent primary Ordovician magnetizations that remain informative for the paleoorientation and paleolatitude of the Wrekin terrane. Taken together, the Stapeley, and Builth results imply that East Avalonia underwent a moderate apparent CCW rotation between ca. 462 Ma and 432 Ma as it moved from higher to lower paleolatitude, similar to the timing, latitudinal drift and degree of apparent CCW rotation inferred for the Leinster–Lakesman terrane, suggesting that these East Avalonia and Leinster–Lakesman terranes may have been on the same plate during this interval (Trench and Torsvik, 1991; Channell et al., 1992; Torsvik et al., 1993; Mac Niocaill, 2000).

In SW England, East Avalonia is represented by another paleomagnetic result from the East Mendips volcano-sedimentary sequence, south of the Variscan front. Early Wenlock andesite flows, bedded agglomerate, tuffs and red to green mudstone of the *Monograptus riccartonensis* zone (~432.5 Ma) were sampled over 250 m of section in two quarries in a small inlier of early Paleozoic rock (Torsvik et al., 1993). The inlier is mainly affected by asymmetric Variscan folds with E–W trend. Nine sites provided a high temperature ChRM carried by low-Ti magnetite and hematite (Table 2) as well as evidence for intermediate-temperature overprint magnetizations in some sites, likely acquired in the mid-Carboniferous during the Variscan Orogeny. The high temperature ChRM is demonstrated to be primary by positive intraformational agglomerate tests, and when tilt-corrected, the site ChRMs for East Mendips have a single (normal) polarity, indicating a paleolatitude of 13° ± 5° S, with a declination indicating that the south pole lay far to the W (Torsvik et al., 1993). This Sheinwoodian paleomagnetic result is quite different from the Darriwilian results from the Wrekin terrane, particularly in the paleoazimuth of the south pole, which implies that the East Mendips Inlier underwent a substantial Variscan CW rotation (~40°) between primary ChRM acquisition and the mid-Carboniferous overprint magnetizations, when compared with the contemporaneous paleopoles from Leinster–Lakesman terrane. In explaining this rotation, we note the Variscan CW rotations inferred from structures at Dunquin, just S of the Variscan front, and the position of the East Mendips inlier, well within the Variscan Orogen and surrounded by younger rocks. Substantial CW rotation would be consistent both with the prevalence of dextral transpression within the Variscan Orogen of Britain and Ireland (e.g. Bresser and Walter, 1999), and with oroclinal bending interpreted regionally in the Variscan Orogen to the south (e.g. Weil et al., 2010)

### 5.7. *Megumia*

The Meguma terrane of Nova Scotia (Fig. 8, MEG), originally the Meguma Zone (Williams, 1979), is the most outboard of the northern Appalachian terranes. It displays a distinctive Cambrian to Early Ordovician deep-water succession (Meguma Supergroup) with some similarities to Ganderia's GCS1, but lies to the south of the Avalonian Mira terrane, Antigonish terrane, and Cobequid belt in Nova Scotia.

Waldron et al. (2011) and Pothier et al. (2015a) noted similarity in stratigraphy (Fig. 4, Fig. 6) and detrital zircon provenance (Fig. 22) between the Meguma terrane and the Harlech Dome region in the Cymru terrane of North Wales (Fig. 10), and suggested that the two terranes, together with the Suwannee terrane of the Southern Appalachians, be included in a Cambrian domain "Megumia". It should be noted that Megumia was not conceived or intended as a single terrane that travelled independently; the extant parts of the domain were separated and dispersed into their present-day locations by Ordovician to Carboniferous plate movements. Subsequent work (Waldron et al., 2019a) has shown that the Cambrian platformal succession in East Avalonia, although contrasting in facies, displays a detrital zircon distribution similar to that of Megumia, suggesting that the Meguma terrane originated NW of East Avalonia, adjacent to the Cymru terrane in the Cambrian, but was transferred to its present location south of West Avalonia by the mid-Carboniferous (Waldron et al., 2015).

#### 5.7.1. *Meguma terrane*

The *Meguma terrane* of southern mainland Nova Scotia (Fig. 8, MEG) is named after a thick deep-water Cambrian to Early Ordovician metaclastic succession, the Meguma Supergroup, which is also extensive in offshore areas of the modern continental shelf. These rocks are mostly at low to medium metamorphic grade, although high-temperature metamorphic culminations occur in the E and SW parts of the onshore terrane.

A link with West Africa was originally proposed (Schenk, 1971, 1973), based on the position of the terrane adjacent to Morocco in reconstructions of Pangea. The resulting models supposed that the Meguma terrane remained attached to Gondwana throughout the Paleozoic until the amalgamation of Pangea. The Suwannee terrane of Florida, buried in the subsurface of the southern Appalachians, shows a similar detrital zircon profile (Mueller et al., 1994, 2013) and has also been regarded as a preserved portion of the Gondwanan margin that remained in North America during Atlantic opening. However, many other kinematic models have been proposed for the Meguma terrane, including some that have interpreted it as a deep-water margin of Avalonia, presumed to have travelled with West Avalonia throughout its history (Keppie et al., 2018; Landing et al., 2022).

The nature of the Precambrian basement is unknown — the "Liscomb Complex", previously interpreted as a basement core complex (Dostal et al., 2006), has been shown to be a product of contact metamorphism and assimilation during a major Late Devonian granitoid intrusion episode (Owen et al., 2010; Scallion et al., 2011; White and Scallion, 2011). The lower part of the succession (Fig. 4) the Goldenville Group, comprises quartzose sandy metaturbidites that become increasingly fine-grained and manganese-enriched towards the top (Waldron, 1992). They are overlain by an upper slate-dominated succession, the Halifax Group. Trilobite debris within this transition was determined by Pratt and Waldron (1991) to be of Miaolingian age, while the lower part of the overlying Halifax Group is Furongian (White et al., 2012). The Halifax Group extends into the Floian, where it is truncated by an unconformity; the overlying Rockville Notch Group includes bimodal volcanic rocks and fossiliferous shallow-marine sedimentary rocks spanning an interval from close to the Ordovician–Silurian boundary to the Early Devonian (White et al., 2018b).

The detrital zircon record of the Meguma terrane (Waldron et al., 2009, 2011; Pothier et al., 2015b; White et al., 2018b) shows a predominance of Ediacaran zircon in the oldest rocks, with increasing amounts of Eburnean zircon up-section. Minor amounts of younger Paleoproterozoic and Neoproterozoic zircon appear in the higher units but Eburnean peaks are the highest pre-Neoproterozoic peaks in most samples (Fig. 22 a,b). The up-section increase in older zircon is mirrored by an up-section fall in $\varepsilon_{\mathrm{Nd}}$ values, producing older model ages in younger rocks, attributed to derivation from a broader Gondwanan catchment area following rifting that was localized within an Ediacaran orogen (Waldron et al., 2009). None of the units sampled for detrital zircon show any clear indication of Laurentia-derived zircon. In addition, the faunal data, where available, suggest "Acado-Baltic", and "Rhenish" affinity from the Cambrian to the Early Devonian (Pratt and Waldron, 1991; Bouyx et al., 1997). These observations suggest that the Meguma terrane did not come into contact with composite Laurentia before 410 Ma.

The Meguma terrane was shortened, producing folds that trend ENE-WSW, and associated cleavage at 395–388 Ma (Hicks et al., 1999), commonly assumed to mark the accretion of the terrane to Laurussia. This deformation was simultaneous with Acadian deformation in the New England Appalachians but was distinguished as "Neo-Acadian" by van Staal (2005, 2007) because it occurred outboard (SE) of much less deformed West Avalonia, the accretion of which was seen as the driver of Acadian deformation. However, "Neo-Acadian" was used in a different sense in its definition (Robinson et al., 1998) and we recommend against the use of this term to describe deformation in the Meguma terrane.

Intrusion of granitoids and high-temperature, low-pressure metamorphism followed in the late Devonian. Subsequent deformation took place in the Carboniferous, and was associated with dextral strike-slip motion along the Minas Fault zone, which overprinted earlier structures in SW Nova Scotia (Culshaw and Liesa, 1997; Culshaw and Reynolds, 1997), and may have moved the Meguma terrane several hundred kilometres westward to its present position while causing the current oroclinal bend in fold axes and other structures within the terrane (Waldron et al., 2015; Warsame et al., 2021).

#### 5.7.2. *Georges Bank*

Basement samples from an offshore oil well on Georges Bank (Fig. 7), located approximately 200 km ESE of eastern Massachusetts, and 450 km SSW of the southern tip of Nova Scotia, were analysed by Kuiper et al. (2017). The samples showed a major peak in detrital zircon probability plots at ~2.1 Ga (Fig. 22 c). The youngest age population was ~1.9 Ga. Kuiper et al. compared these distributions with samples from the West African craton, and with the Paleoproterozoic components of samples from the Meguma terrane of Nova Scotia, and the Suwannee terrane of the southern Appalachians, showing them to be effectively identical. Subsequent work in the St. Croix terrane of Maine and on Grand Manan Island offshore of New Brunswick (correlated with the New River belt) has revealed other units characterized by large Paleoproterozoic peaks (Fig. 17 f), raising the possibility that the Georges Bank samples might be related to units included in Ganderia. However, a close examination of the distributions (Fig. 17 e,f) reveals a small but significant difference in age modes. It is therefore likely that the Georges Bank samples represent either basement to the Meguma terrane, or a fragment of the West African craton that was a source for the Meguma terrane, as suggested by Kuiper et al. (2017).

#### 5.7.3. *Welsh basin – Cymru terrane*

The Welsh basin, which overlies the *Cymru terrane* (pronounced, roughly, “Kum-ree”) (Fig. 10, CYM), is one of the most intensively studied regions of the orogen, and has had a remarkable influence on the history of biostratigraphy reaching back into the 19th century. Only a very basic summary is be given here and shown in four columns in Fig. 6. The complexity of the basin was summarized in Brenchley and Rawson (2006) and references therein. The Precambrian basement is known only from a borehole at the centre of the Harlech Dome, and is undated, but is assumed to be Ediacaran based on its similarity to rocks of the Arfon terrane to the NW, the Pebidian succession of SW Wales, and other exposed basement units along the boundary with the Wrekin terrane to the east.

Overlying rocks of the Cambrian succession in the Harlech Dome (Fig. 6) show stratigraphy and detrital zircon provenance remarkably similar to that of the Meguma terrane, which led Waldron et al. (2011) to suggest that the two terranes were contiguous in the Cambrian. To highlight this similarity, Waldron et al. (2011) assigned the Welsh basin and the Meguma terrane to the domain “Megumia”. However, the similarity extends only to the end of the Cambrian. The Tremadocian topmost unit in the Mawddach Group shows an influx of more diverse zircon interpreted to represent an influx from Ganderia (Waldron et al., 2011). This change suggests that the Meguma terrane and the Welsh basin were separated, close to the Cambrian–Ordovician boundary, by the sinistral motion along the Menai Strait Fault System that subsequently juxtaposed the Ganderian units of NW Britain with the Welsh basin (Waldron et al., 2011; Pothier et al., 2015a).

Ordovician volcanic successions unconformably overlie the Harlech Dome. A Tremadocian unit (Rhobell Volcanic Formation, Fig. 6) represents a short-lived volcanic arc (Kokelaar, 1988), overlain in turn by a much thicker Floian to early Katian succession including several major volcanic intercalations interpreted to represent backarc environments. The best-known volcanic edifice, in Snowdonia, oversteps the boundary with the Arfon terrane to the NW, showing that the Arfon and Cymru terranes were juxtaposed by the Floian.

From Katian onward, the Welsh basin was filled by mainly clastic sediments, without significant volcanic rocks. All the successions thin toward the south and east where basin-bounding faults were strongly inverted during Acadian (mid-Devonian) deformation (Schofield et al., 2009b). Much thinner successions in the Welsh borders represent the margin of the Wrekin Terrane, regarded as typical of East Avalonia.

Caledonide structures in the Cymru terrane trend mainly NE–SW, but swing westward in SW Wales as a result of interaction with the late Paleozoic Variscan fold and thrust belt. Similar overprinting is seen in the Leinster–Lakesman terrane of SW Ireland and probably in southern parts of the Wrekin Terrane. These Variscan effects must be taken into account in the interpretation of paleomagnetic data.

The Welsh basin and the terranes to the east are assumed by most UK geologists to have been in contact with the “Ganderian” Leinster–Lakesman and Monian terranes since Monian deformation in the Ordovician. However, the Menai Strait fault system (Fig. 10) is not stitched unequivocally by either plutons or overlying sedimentary units until the Carboniferous. To the NE in England it is entirely concealed beneath Mesozoic strata. The south-vergent Carmel Head thrust on Anglesey, and the associated foreland basin redbeds (Schofield et al., 2020), are undated. Hence it is conceivable that the Carmel Head Thrust and/or the Menai Strait fault system were active as a major terrane boundary during Acadian tectonism, in which case the final arrival of the Cymru, Wrekin, and Charnwood terranes would have taken place in the Devonian.

A paleomagnetic result (Table 2) is available from volcanic rocks in the Treffgarne Formation, in SW Wales (Trench et al., 1992), which consists of andesitic flows overlain by marine volcaniclastic, possibly pyroclastic units, and has been correlated with similar Tremadocian volcanic arc rocks of the Rhobell volcanic complex below the Floian unconformity in the Harlech Dome area (Traynor, 1988). Paleomagnetic sample sites were taken along a moderately north-dipping section in quarries in Treffgarne Gorge, representing the andesite flows, a conglomerate with andesite clasts, and overlying purple and green mudstone. ChRM directions in ten sites in andesite and mudstone are retained in both magnetite and hematite, having the same very steep inclination upon tilt correction. Samples also have an intermediate temperature overprint magnetization whose direction resembles Carboniferous (Variscan) overprints seen elsewhere in the UK and Ireland. The intraformational conglomerate clasts have magnetite ChRM directions which scatter from clast to clast, but have a common steep direction in hematite ChRM; this result is interpreted as a positive conglomerate test demonstrating that the magnetite records a primary Early Ordovician remanence, and that the hematite ChRM is also essentially primary, likely acquired during oxidation immediately following the emplacement of the andesite flows and conglomerate (Trench et al., 1992). The steep ChRM places the Cymru terrane at 61° ± 9° S at or before ~479 Ma, but with a declination indicating that the south pole lay to the present NW of the terrane, almost opposite to the ESE to S declinations found in Darriwilian paleomagnetic results from the Stapeley Formation and Builth volcanics (Wrekin Terrane), discussed in section 5.6.

Previous tectonic interpretations (McCabe et al., 1992; Trench et al., 1992) of the Treffgarne paleomagnetic result have emphasized similarity of the high southerly paleolatitude to those of the East Avalonia Darriwilian results, and ascribed the highly anomalous NW declination to a local vertical axis rotation of ~180°, only slightly reduced by taking into account a possible 20° CW rotation associated with Variscan deformation of SW Wales. In this synthesis, we consider that Cymru (Megumia) was contiguous with Wrekin (East Avalonia) in Cambrian–Ordovician time. Given their apparent location associated with the Gondwanan margin in the south polar region, the large shift in south pole paleoazimuth between the Tremadocian Treffgarne and Darriwilian Stapeley results may in part be an apparent rotation due to passage of the margin and associated terranes across the south polar region during the late Cambrian and Early Ordovician (Torsvik et al., 2012). In tectonic terms, this interpretation implies that Gondwana (and the Tremadocian south pole) lay to the NW of Cymru and East Avalonia, and that some combination of terrane rotation and Gondwana margin motion across the pole over ~15 Myr would be required to honour the Darriwilian paleomagnetic results, which locate the south pole to the ESE of Wrekin terrane by ~465 Ma. The paleolocation of these terranes and also Leinster–Lakesman (Ganderia) in or near the south polar region during the Early Ordovician is a useful and important constraint which we will return to in discussion below of the paleogeographic reconstructions and their tectonic implications.

## 6. Discussion

### 6.1. Terrane assemblages

#### 6.1.1. Introduction

From the summary presented in the previous section, it is apparent that the traditional grouping of terranes into domains such as Avalonia, Ganderia and Megumia (e.g. Hibbard et al., 2007; Waldron et al., 2011; van Staal et al., 2020, 2021) successfully recognizes distinct tectonic environments in which the terranes developed on the margin of Gondwana, particularly during the Cambrian Period, but is not an ideal framework in which to discuss the transit of terranes from Gondwana to Laurentia across the Iapetus Ocean during the Ordovician to Devonian interval (Waldron et al., 2019b). As illustrated in Fig. 12 and Fig. 23, components of the orogen clearly left Gondwana and arrived at Laurentia in assemblages larger than the individual terranes, but smaller than the Gondwanan domains Ganderia, Avalonia, and Megumia. We therefore avoid using these domain names as labels for terrane assemblages in transit across the Iapetus Ocean. Some of the assemblage boundaries evidently cross-cut the previous domain boundaries as the groups left Gondwana. We here refer to these entities simply as “terrane assemblages” rather than “superterranes” or “composite terranes” as both these terms have been used in previous syntheses for postulated larger groupings based on a less granular view of the regional tectonics, and without the benefit of the present detrital-zircon database. To avoid proliferation of terms we use, where possible, combinations of existing terrane names to identify these assemblages (e.g. Bronson–Popelogan assemblage).

Our descriptions also make clear that the domain “Ganderia” is composite. Three distinct types of Cambrian succession are present.

- Most typical of Ganderia are those containing clear GCS1: the Moretown, Bronson Hill, Miramichi, Gander, Leinster–Lakesman, and Porth y Felin terranes. The St. Croix terrane and the Pleasant Bay block in the Aspy Belt may also belong to this type.
- A second type includes Cambrian successions dominated by mafic to felsic igneous rocks without clear GCS1, representing environments interpreted as ranging from arc and backarc to oblique rift. These include rocks in the Elmtree inlier of New Brunswick, the Ellsworth and Annidale terranes, and the Victoria terrane in Newfoundland. The Faribault Brook block of the Aspy belt and the Amlwch terrane of the Monian belt are other candidates for inclusion in this type. These terranes were mostly amalgamated by thrusting or strike slip with components of the first type during Penobscottian deformation in the Early Ordovician. Some (but not all) of the resulting assembled terranes were affected by Silurian magmatism of the CIB.
- A third type is represented by the Brookville and Bras d’Or terranes in Maritime Canada. Successions of this type include shaly trilobite-bearing successions in the Miaolingian to Early Ordovician overlying either early Miaolingian volcanic rocks (Bras d’Or) or earlier Cambrian clastic rocks and arc igneous assemblages from around the Ediacaran–Cambrian boundary. The Grey River block in the Hermitage belt may also belong to this type, although it lacks the fossiliferous later Cambrian shaly succession. These terranes were not affected by the CIB, nor by high-grade Acadian metamorphism in the Devonian.

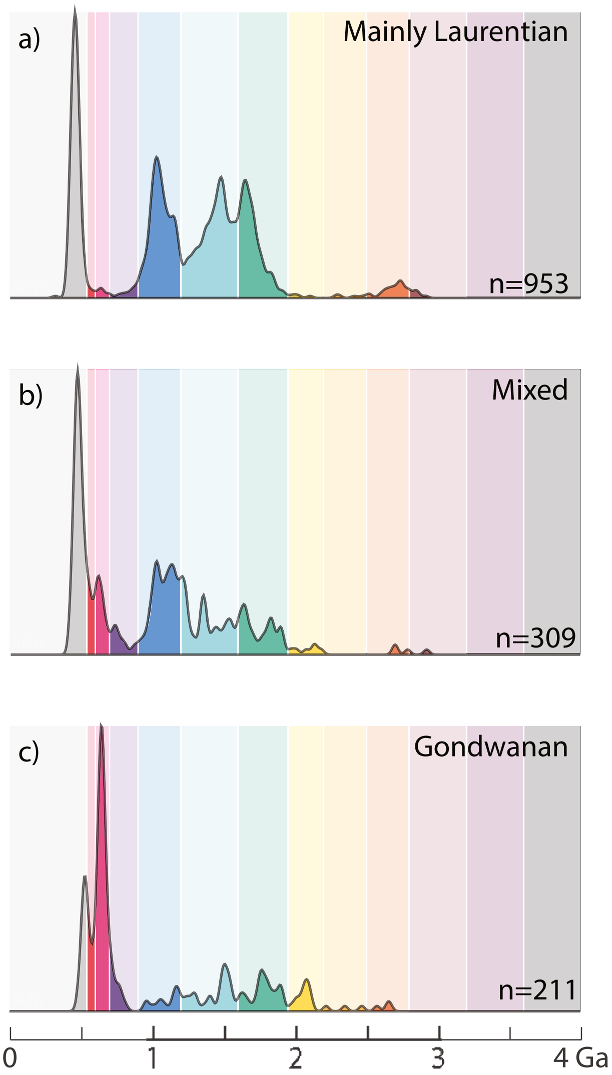


**Fig. 18.** Detrital zircon data from the Merrimack, Bucksport and Fredericton troughs, sorted and merged by overall provenance. (Wintsch et al., 2007; Ludman et al., 2017, 2018; Dokken et al., 2018; Hepburn et al., 2021)

Fig. 23 summarizes the timing of interactions between the various terranes described in sections 4 and 5, distinguishing Penobscottian/Monian events recording interactions between components of Ganderia, from Taconian, Salinian, and Acadian accretionary events at the Laurentian margin. In the following sections we consider how these terranes were grouped in assemblages during their transit across the Iapetus Ocean.

#### 6.1.2. Dashwoods–Tyrone assemblage

Multiple terranes preserved near the NW thrust front of the Appalachian–Caledonide Orogen show clear stratigraphic and provenance links with Laurentia but were deformed well before the adjacent autochthonous platform successions on the Laurentian margin. They include the Dashwoods, Chain Lakes and Chester Dome blocks in the Appalachians, the Tyrone central inlier in Ireland and possibly the Grampian terrane in Scotland. These units show distinctively Laurentian zircon distributions, without significant Ediacaran input, and with large ~1.0 Ga “Grenville” components. They may have formed a continuous ribbon continent (Cawood et al., 2001), or they may have been a chain

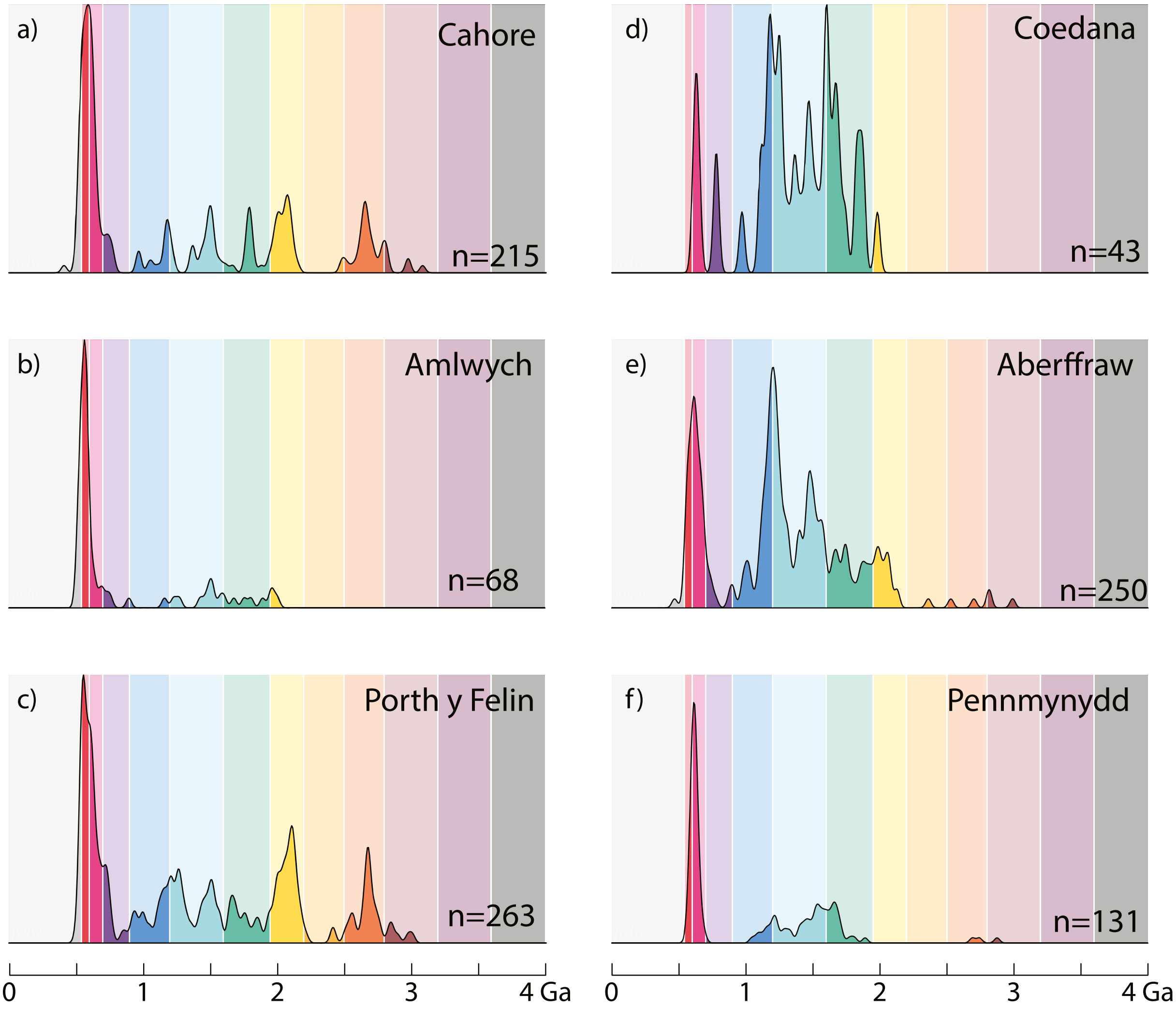


**Fig. 19.** Detrital zircon data from Anglesey and adjoining areas (Collins and Buchan, 2004; Waldron et al., 2014a; Asanuma et al., 2015, 2017). (a) Cahore Group, SE Ireland. (b-f) Terranes in the Monian belt.

of disconnected fragments and hyperextended continental margin material (Chew and van Staal, 2014). Because they were deformed well before the passage of the earliest Taconian flexural bulge across the Laurentian shelf at ~467 Ma (Knight et al., 1991; White and Waldron, 2022), they must have lain at a distance that was large compared with the flexural wavelength of the Laurentian margin lithosphere. We refer to this grouping of peri-Laurentian terranes as the Dashwoods–Tyrone assemblage.

The preservation of early-deformed portions of Laurentia extends into Scandinavia, where rocks preserved in the Upper and Uppermost Allochthons of the Norwegian Caledonides contain Laurentia-sourced sedimentary rocks that were nonetheless deformed during the Ordovician (e.g. Stephens, 2020 and references therein). This deformation took place well before the earliest deformation of northeastern parts of the Greenland margin of Laurentia, where platform sedimentation continued until the onset of the Silurian Scandian Orogeny (Smith and Rasmussen, 2008). The allochthons cannot therefore represent a portion of present conjugate margin of Greenland thrust onto Scandinavia in the Silurian. We therefore argue that these rocks, like other units in the assemblage, may have been rifted, partially or completely from Laurentia in the Neoproterozoic, and were initially deformed in mid-Iapetus during Ordovician terrane interactions (Fig. 25). The Scandian collision emplaced them onto the Baltic margin in the Silurian.

### 6.1.3. *Moretown assemblage*

The Moretown terrane of southern New England, which forms its own assemblage, is characterized by typical metasedimentary rocks of GCS1 — quartz-rich passive-margin turbidites containing a broad range of Meso- and Paleoproterozoic detrital zircon, interpreted to reflect sources in Amazonia (Fig. 16). The transition from passive-margin to active-margin tectonics may be recorded by intrusions at 505 Ma and/or by the juxtaposition of clastic successions with contrasting provenance (Cobble Mountain Formation; Fig. 16). The Moretown terrane was emplaced before 475 Ma onto a southernmost block of the Dashwoods–Tyrone assemblage, to which it was sealed by the development of the Shelburne Falls arc (Macdonald et al., 2014). As the adjacent margin of Laurentia remained passive, and the Taconic seaway remained open until the Late Ordovician (White and Waldron, 2022), we interpret that the subduction that produced the Shelburne Falls arc was SE-dipping, following Karabinos et al. (1998).

### 6.1.4. *Bronson–Popelogan assemblage*

The Bronson Hill arc, northern Maine inliers, and the Popelogan inlier together make up the “Medial New England” zone of Robinson et al. (1998) and earlier workers. We term this the Bronson–Popelogan assemblage. Most successions in this assemblage display thick developments of GCS1 which are overlain at a Penobscottian unconformity by Ordovician arc assemblages that pass laterally and vertically into black shale and locally mélange. These rocks are interpreted as

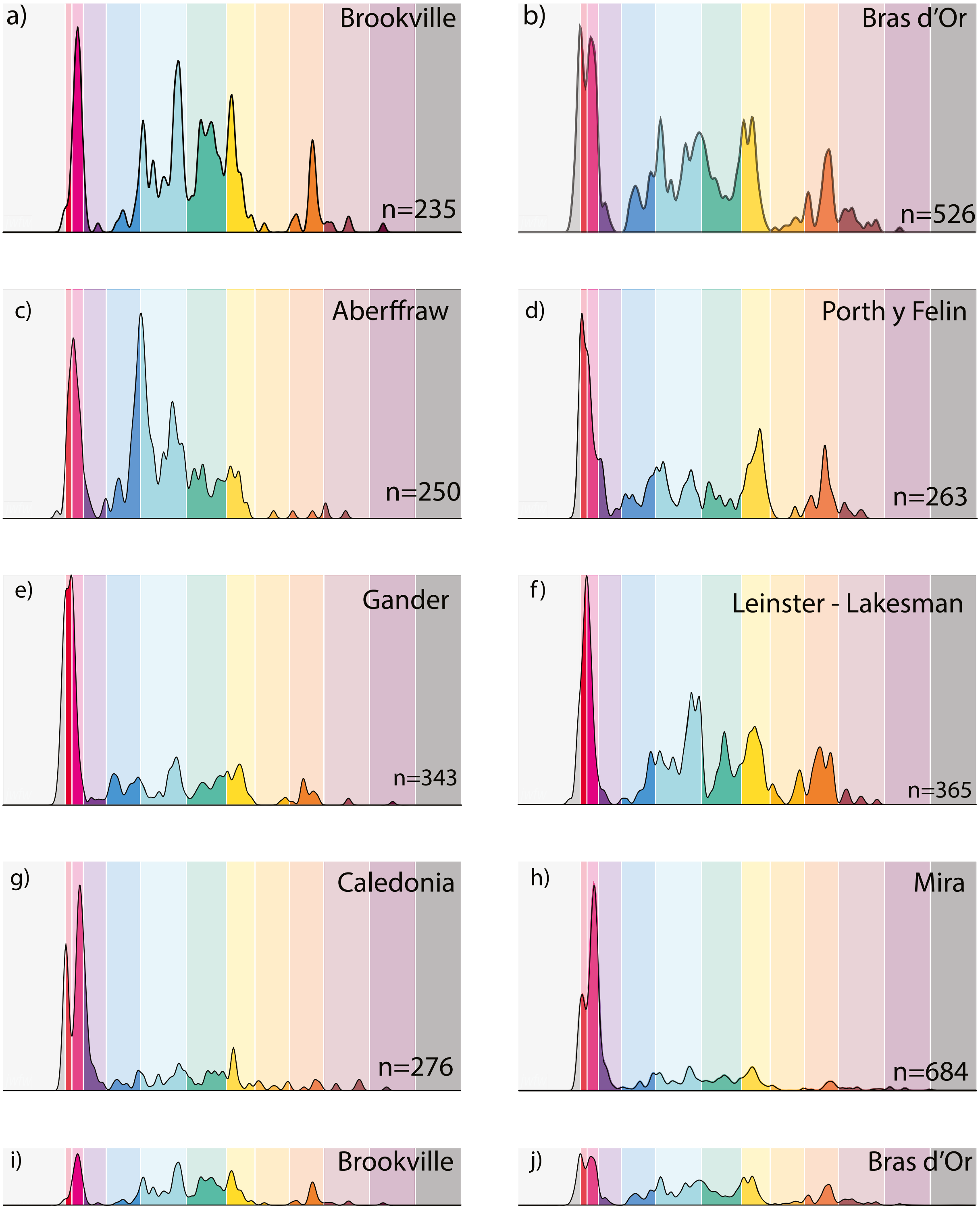


**Fig. 20.** Detrital zircon data from (a) the Brookville and (b) Bras d'Or terranes (Fyffe et al., 2009; Barr et al., 2014b; White et al., 2016a; van Rooyen et al., 2019), showing comparison (c-h) with other terranes assigned to Avalonia and Ganderia, from sources listed in Figs. 17, 20 and 22. (i and j) Amplitude-reduced versions of (a) and (b) to facilitate comparison of pre-Ediacaran components with other terranes.

deposited on a passive margin of Amazonia (e.g. van Staal, 1987), and attributed to the "leading" edge of Ganderia, NW of the Tetagouche–Exploits backarc basin, by van Staal et al., 2016, 2021. Paleomagnetic results from the northern Maine inliers (Wellensiek et al., 1990; Potts et al., 1993, 1995) show mid-Ordovician (470–463 Ma) latitude close to Laurentia, and declinations suggesting moderate counterclockwise rotation as the terranes were accreted.

To the south, Neoproterozoic metavolcanic basement rocks occur in the Pelham Dome where GCS1 is absent, but Robinson et al. (1998) made strong arguments that the basement of the dome was inserted by thrusting in the late Paleozoic. The basement rocks show no sign of the Ordovician partial melting or intrusion that would be expected during development of the overlying arc. Hence it is more likely that they represent basement of a block similar to the Massabesic Gneiss farther

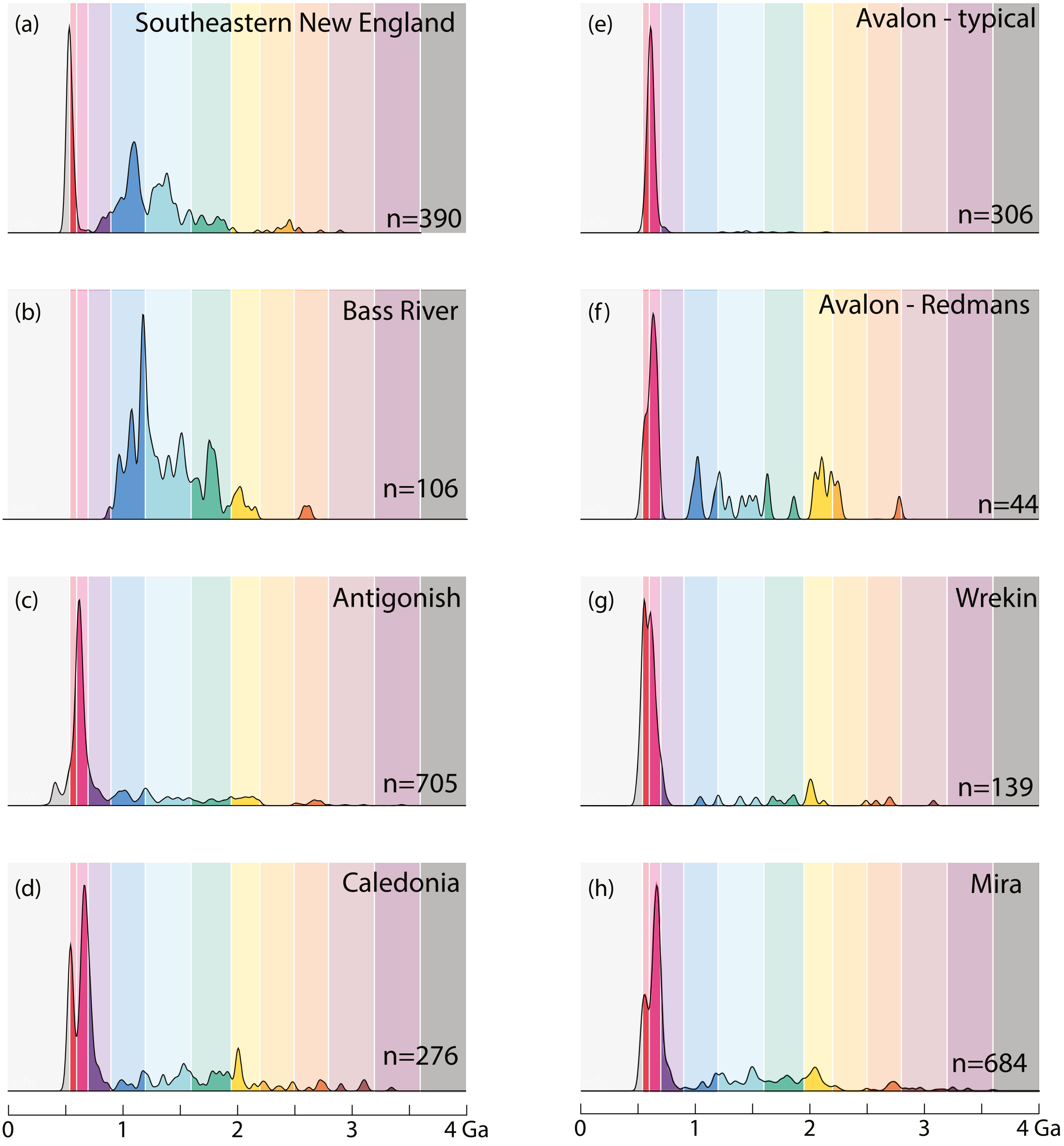


**Fig. 21.** Detrital zircon data from "Avalonia" (Murphy et al., 2004b, 2004c; Walsh et al., 2007; Pollock et al., 2009; Satkowski et al., 2010; Barr et al., 2012, 2019, 2020a; Dorais et al., 2012b; Thompson et al., 2012, 2014; Willner et al., 2013; Henderson et al., 2016; Waldron et al., 2019a). (a) Southeastern New England. (b) Bass River Block of the Cobequid belt. (c) Antigonish highlands. (d) Caledonia terrane of southern New Brunswick. (e) Avalon terrane of Newfoundland, excluding atypical sample from Early Ordovician Redmans Formation. (f) Avalon terrane of Newfoundland, atypical sample from Early Ordovician Redmans Formation. (g) Wrekin terrane of England. (h) Mira terrane of Cape Breton Island.

east, inserted during late Paleozoic tectonic wedging (Wintsch et al., 2014).

### 6.1.5. *Miramichi–Victoria assemblage*

The Miramichi–Victoria assemblage comprises several diverse terranes all attributed to Ganderia, extending from Newfoundland to southern New England. Paleomagnetic results from the Miramichi terrane (section 5.3.2) suggest that it was located far south of the Laurentian margin as late as ~465 Ma (Liss, 1993; van Staal et al., 2012), and likely underwent moderate counterclockwise rotation as it approached composite Laurentia, possibly during deformation involving sinistral strike slip (Fig. 25). Conformably overlying Laurentia-derived flysch units (Fig. 15 a) show that the terrane neared the composite Laurentian margin in the Late Ordovician (Wilson et al., 2015). Blueschist metamorphism in the California Lake slice shows that the north edge of the terrane was partially subducted at the active margin before being rapidly exhumed in the early Silurian.

In Newfoundland to the NE, the Victoria terrane arrived at approximately the same time. Both terranes contain Middle Ordovician arc rocks that are overlain by black shale followed upwards by Katian turbidites containing Laurentian zircon (Fig. 15 b). However, other aspects of the Victoria terrane are very different. The overlying turbidite succession (Badger Group) continues ~10 Myr later than the succession above the Miramichi terrane. Collision of the Exploits terrane was

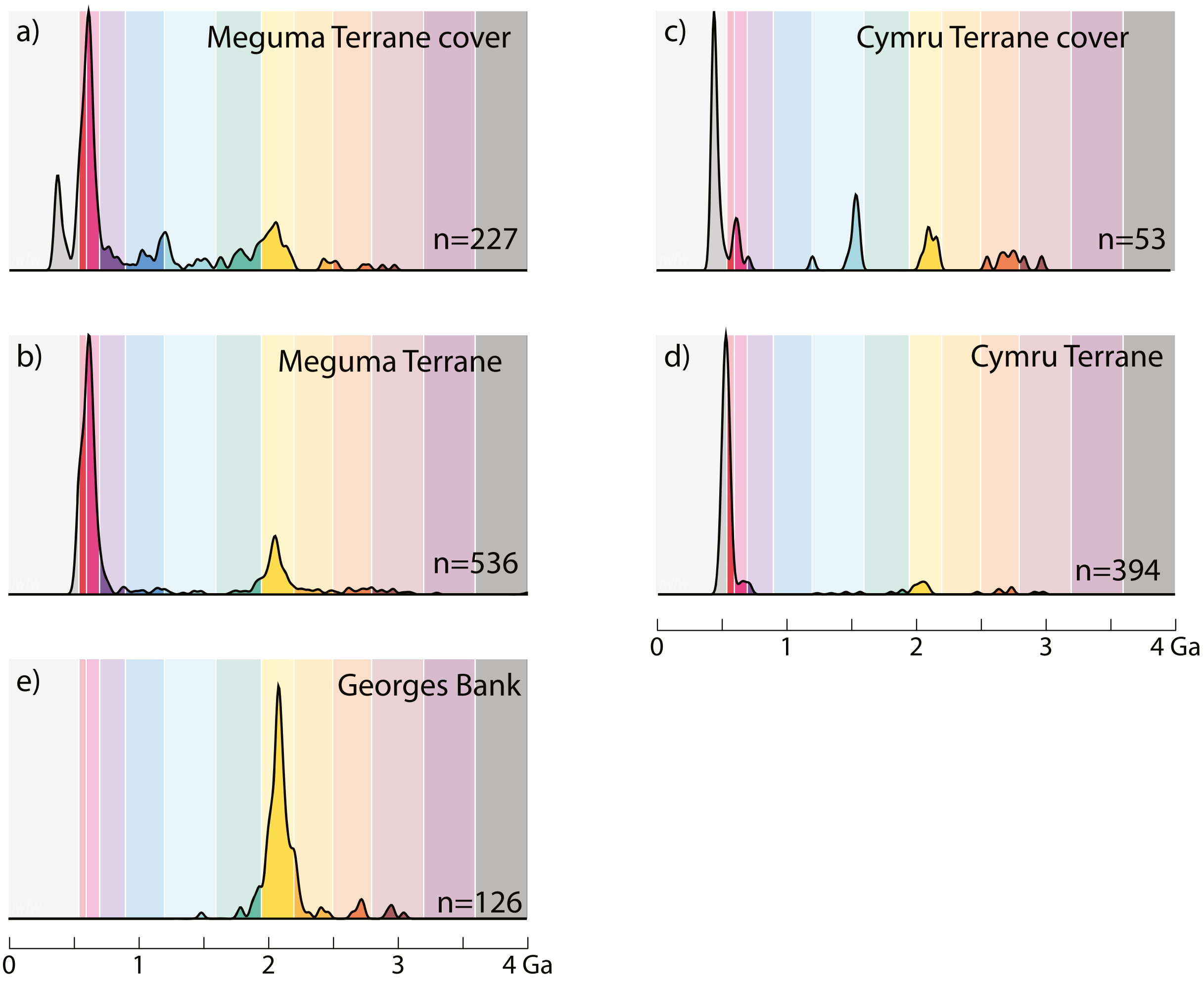


**Fig. 22.** Detrital zircon data from Megumia and possible correlatives (Murphy et al., 2004a; Waldron et al., 2009, 2011; Pothier et al., 2015a, 2015b; Henderson, 2016; Kuiper et al., 2017; White et al., 2018b). (a) Meguma Supergroup of Nova Scotia. (b) Meguma terrane Silurian to Carboniferous (c) Cymru terrane of Wales, Harlech dome succession. (d) Ordovician cover of Harlech dome. (e) Offshore samples from Georges Bank.

protracted and relatively "soft" (van Staal and Zagorevski, 2020) compared with that of the Miramichi terrane.

The Victoria terrane also contrasts with the Miramichi terrane in its pre-accretion stratigraphy (Fig. 4). Whereas the Miramichi terrane displays a thick Cambrian clastic succession (GCS1), the Exploits terrane contains Cambrian arc volcanic rocks (Lake Ambrose belt: Dunning et al., 1991) founded upon Ediacaran (~565 Ma) volcanic and intrusive rocks also of arc affinity (Rogers et al., 2006). Correlative units to the SW of the Miramichi terrane (Liberty–Orrington belt; Fig. 3, Fig. 17) also lack clear evidence of GCS1. The Massabesic Gneiss appears to represent a Cryogenian to Ediacaran arc fragment unlike other units in the belt.

### 6.1.6. *Gander–Lakesman assemblage*

A major boundary in the closure of the Iapetus Ocean is marked by the Silurian Dog Bay Line (Fig. 9) in Newfoundland (Williams et al., 1993), which probably passes through Cape Breton Island within the Aspy belt (Fig. 8). It then passes beneath the Gulf of St. Lawrence and into New Brunswick (Fig. 8) through the Fredericton trough (Reusch and van Staal, 2012; Dokken et al., 2018), continuing southward through the Merrimack trough in New England (Fig. 7). Llandovery rocks to the north typically show abundant Laurentian detrital zircon whereas those to the south are Gondwana-derived (Fig. 18). The corresponding boundary in Ireland and Britain (Fig. 10) is the Navan–Solway line, commonly accepted as the "Iapetus suture" in Irish and British geology (Bluck et al., 1992; Woodcock and Strachan, 2000).

South of the Dog Bay Line in Newfoundland, ophiolites were emplaced above the Gander Group (GCS1) in a Penobscottian "soft" collision between ~494 and ~477 Ma (Fig. 5). Because of their earlier inclusion in the Exploits subzone of Williams et al. (1988), these ophiolites are typically assumed to have been emplaced from an oceanic domain to the NW, the Penobscot backarc of van Staal (1987). However, recognition of multiple oceanic belts separating smaller terranes within the Iapetus Ocean removes the basis for this assumption. We note that the ultramafic-rich rocks of the Pipestone Pond and correlative ophiolites are significantly different from the basement of the Victoria terrane to the NW, which consists of arc rocks founded upon Neoproterozoic continental fragments. Comparison with Britain and Ireland (where Monian deformation is concentrated along the South edge of the belt of Ganderian rocks) and New Brunswick and Maine (Reusch et al., 2018; Pollock et al., 2022), where presumed Penobscottian structures that emplaced the Ellsworth terrane are NW-directed, raises the possibility that the GRUB ophiolites were also emplaced across the Gander terrane from the SE towards the NW. We have therefore tentatively shown the Pipestone Pond Complex SE of the Gander terrane in Fig. 5.

The Gander terrane carries a post-Floian clastic succession that passes up into Silurian shelf sediments (Davidsville and Indian Islands groups: Fig. 5) although relationships close to the Dog Bay line are complex and in need of further investigation (e.g. van Staal et al., 2014 and references therein). The SE edge of the terrane carries an overprint of high-grade metamorphism in a broad Acadian sinistral shear zone (Holdsworth, 1994) that was active from ~422 until ~405 Ma and was succeeded by dextral shear close to the boundary with the Avalon

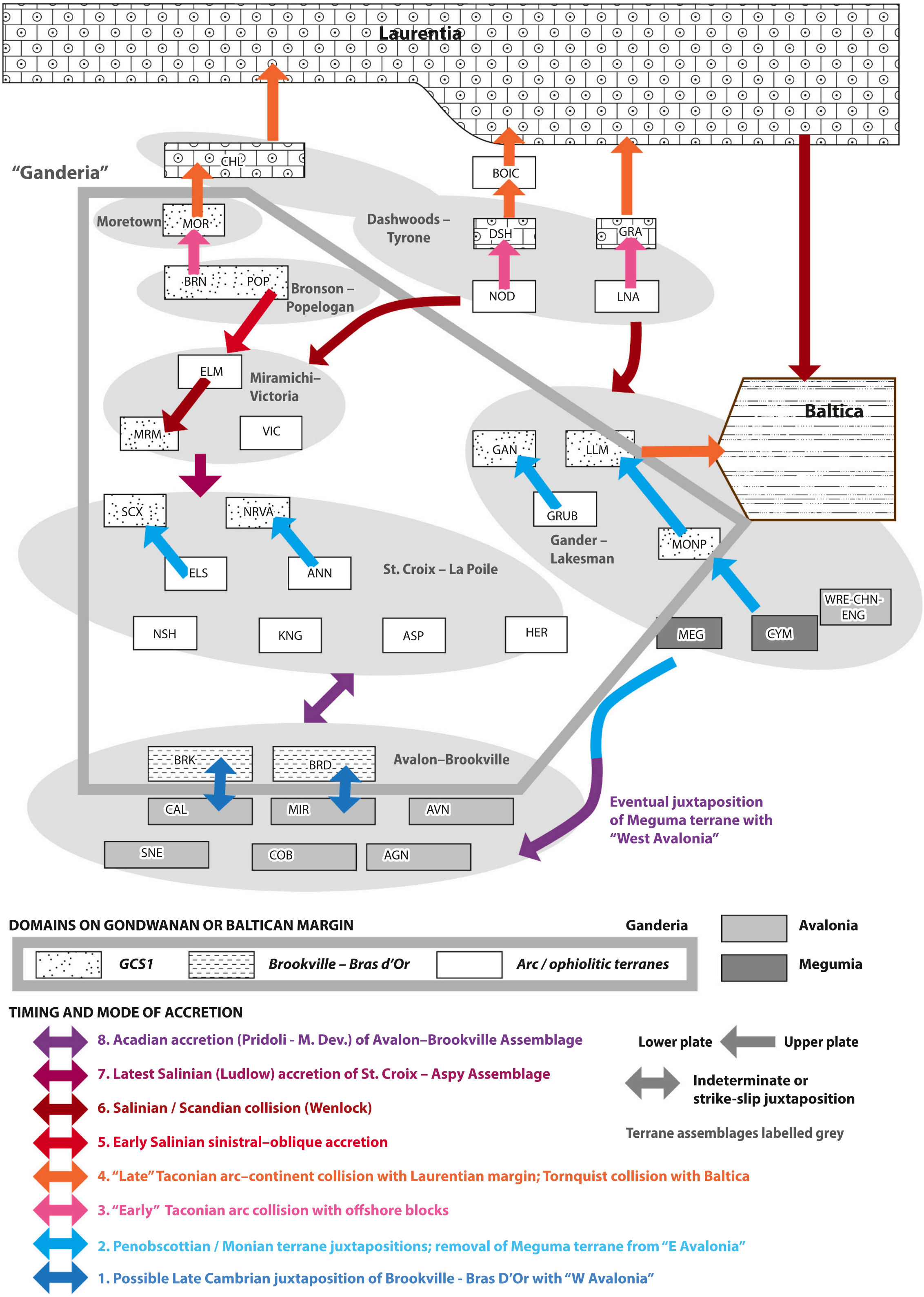


**Fig. 23.** History of terrane interactions shown symbolically. BOIC = Bay of Islands ophiolite complex. GCS1 = First Gander cover succession of van Staal et al., 2021. GRUB = Gander River ultrabasic belt. Other abbreviations as in Table 3.

terrane between ~385 and ~ 377 Ma (Kellett et al., 2016) when the Dover Fault was sealed by the Ackley batholith (Fig. 9). Multiple Devonian granitoid plutons intruded the terrane between 395 and 378 Ma, showing a progressive decrease in deformation and a transition from arc to non-arc origins (Kellett et al., 2016).

The equivalent Leinster–Lakesman terrane in Britain and Ireland terrane records the first Laurentian zircon in the Wenlock at ~430 Ma (Waldron et al., 2014a, 2019b). The underlying succession (Fig. 6)

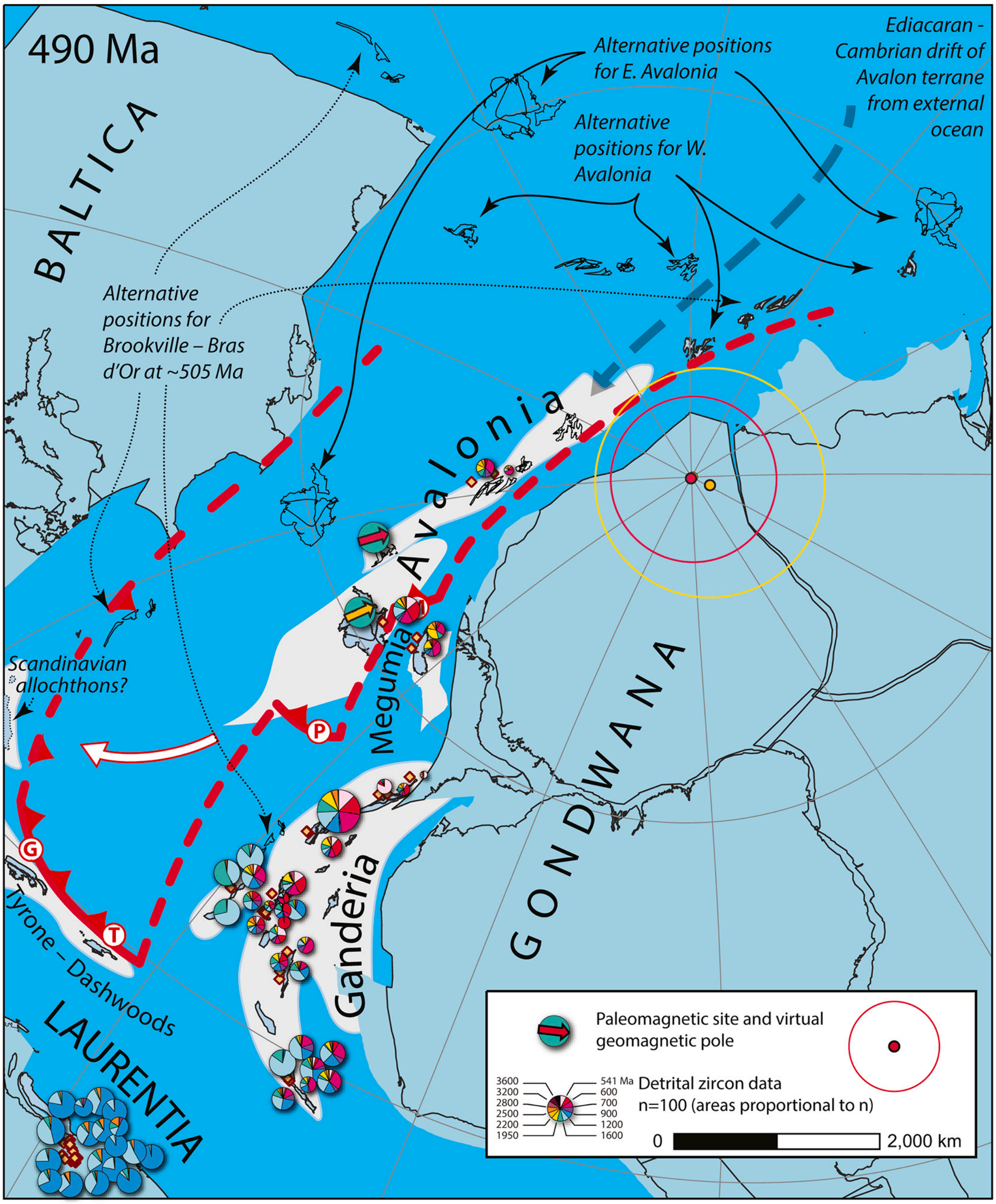


**Fig. 24.** Furongian paleogeographic reconstruction (490 Ma), showing detrital zircon data sets and paleomagnetic poles corresponding to depositional ages from 475 to 505 Ma. Latitudes for major continents after Wu et al. (2021). Alternative positions for peri-Gondwanan terranes are shown. Red circled labels represent collisional events: T = Taconian; G = Grampian; P = Penobscottian; M = Monian. Dashed grey arrow shows previous possible trajectory of Avalon terrane from external ocean. Solid white arrow shows possible future trajectory of "East Avalonia" into Iapetus Ocean with rotation. Coloured circles show rotated apparent paleomagnetic pole positions for Cymru (Treffgarne pole: yellow) at ~479 Ma and Southeastern New England (Nahant pole; red) at 489 Ma. Colours in pie charts as in Fig. 7.

includes an arc assemblage in the Late Ordovician, overlying Early Ordovician turbidites with GCS1 characteristics (Fig. 16 g) (Waldron et al., 2014a, 2019a). Paleomagnetic data from Middle Ordovician and Llandovery rocks (section 5.4.7) track the northward drift of the terrane as it approached Laurentia with moderate CCW rotation. An unconformity and abundant soft-sediment structures suggest instability around 465 Ma. Farther SE, however, tectonic slices in Anglesey show major Early Ordovician deformation structures, overstepped by a Floian cover succession. In Ireland, equivalent units (Tietzsch-Tyler and Phillips, 1989) are juxtaposed with the Leinster–Lakesman terrane at a N-dipping post-Ordovician boundary.

Relations between Ganderian rocks of the British Isles (Fig. 6) and the terranes to the south, assigned to "East Avalonia" (e.g. Bluck et al., 1992) (Cymru, Wrekin, and Charnwood terranes) are somewhat poorly constrained, although British geologists have typically assumed that the Ganderian and Avalonian units have been in contact since at least the Floian (Woodcock and Strachan, 2000). This hypothesis is supported by the presence of probable Ganderian detrital zircon in Ordovician sandstones of the Cymru terrane (Pothier et al., 2015a). If this is correct, then England, Wales, and southern Ireland formed part of the Gander–Lakesman assemblage, which therefore includes components of three peri-Gondwanan domains: Ganderia, Megumia, and Avalonia. However, it is also possible that the largely unexposed and poorly understood contact between the Monian and Leinster – Lakesman terranes,

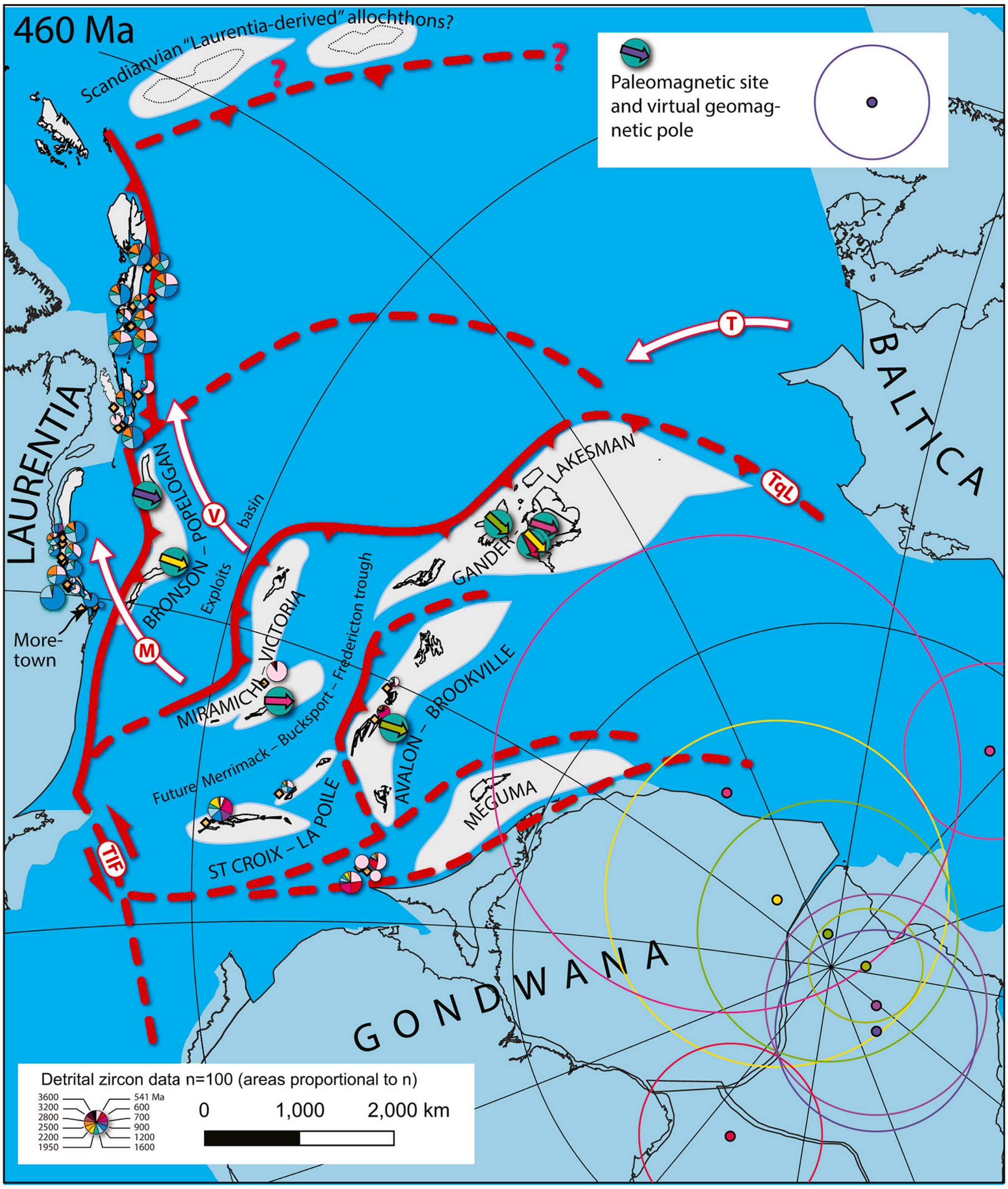


**Fig. 25.** Middle Ordovician (460 Ma) generalized paleogeographic reconstruction showing schematic possible plate boundary locations, terrane assemblages, paleomagnetic poles, and detrital zircon data sets with depositional ages between 465 and 455 Ma. TIF: Trans-Iapetus fault. TqL Tornquist line. White arrows show convergence trajectories towards Late Ordovician collisions. V: Trajectory of Victoria terrane towards end-Ordovician soft docking with Laurentia in Newfoundland. M: Trajectory of Miramichi terrane towards subduction-collision with Laurentia in New Brunswick. T: Trajectory of Baltica towards Tornquist collision with Gander – Lakesman – East Avalonia. Coloured circles show rotated apparent paleomagnetic pole positions for: Dunn Point; Stapeley; Builth; Tetagouche; Tramore; Staceyville; Bluffer Pond. Colours in pie charts as in Fig. 7.

paralleling the Menai Strait fault zone (Fig. 10) conceals significant relative motion at any time prior to the Carboniferous. Llandovery volcanic rocks in Anglesey and South Wales might also suggest the existence of a Silurian plate boundary. A "Trans-Suture suite" of Early Devonian calc-alkaline intrusions and associated andesitic volcanic rocks (Brown et al., 2008; Stone et al., 2012; Miles et al., 2016) in the Southern Uplands and Lakesman terranes was intruded during Acadian transtension and transpression between 404 and 394 Ma (Woodcock et al., 2019). These relationships are compatible with Acadian oblique subduction to the south of the Leinster–Lakesman terrane. If this occurred, the terranes south of Leinster–Lakesman may not have accreted to Laurussia until the Devonian, and southern Britain would instead form part of the Avalon–Brookville assemblage (section 6.1.8). Future detrital zircon work may resolve this uncertainty.

Paleomagnetic results from Middle Ordovician rocks in the Welsh borders (section 5.6) yielded paleolatitudes generally consistent with those from the Lakesman terrane. However, they suggest that up to 45° of CCW rotation took place during the later Ordovician and Silurian as the terrane assemblage approached Laurentia. The result from the early Ordovician (latest Tremadocian) Treffgarne volcanic rocks in South Wales provides support for a southerly position that is consistent with a location close to the Gondwanan margin, but which requires an "upside down" position of England and Wales relative to their present position, and about 90° of additional rapid clockwise rotation between Early and

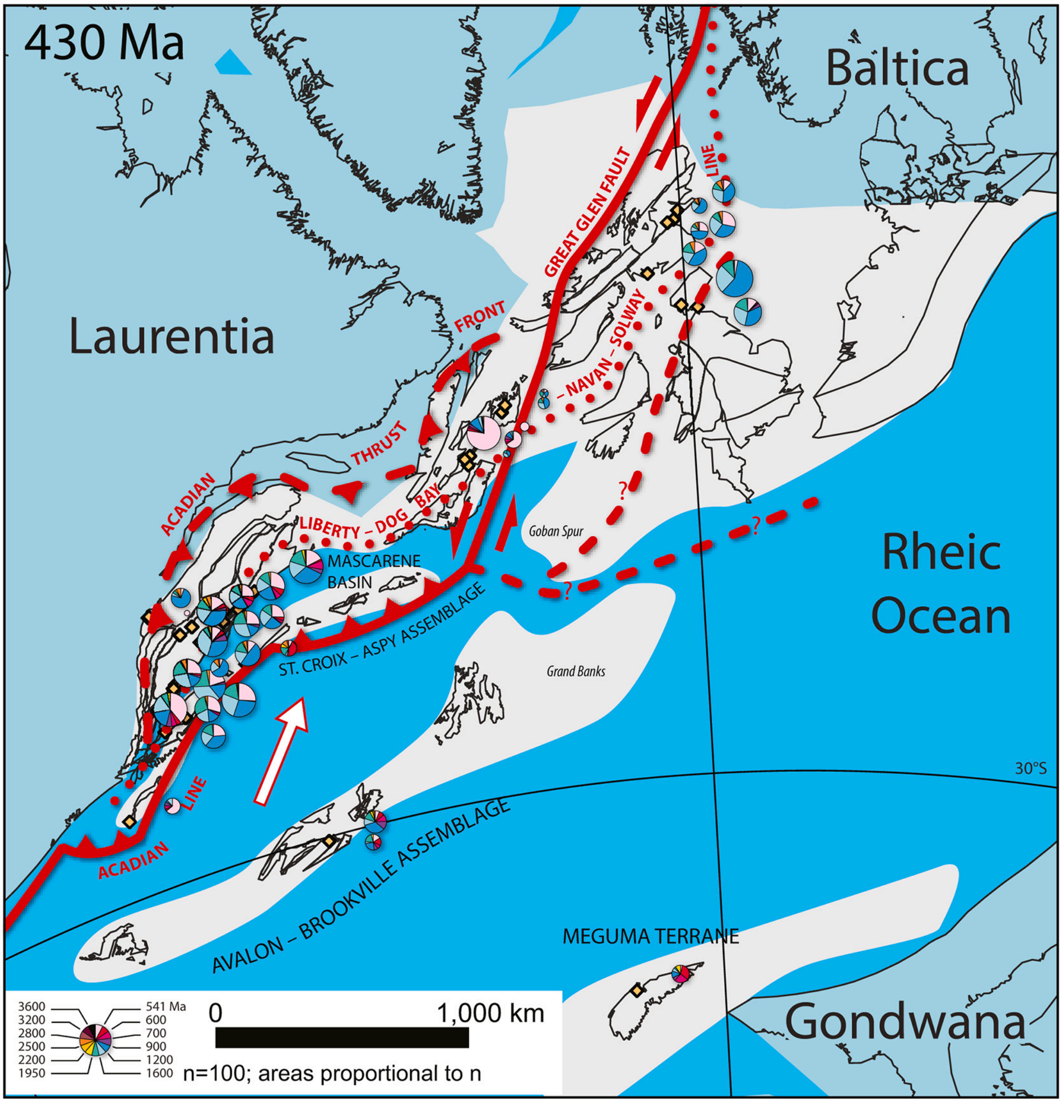


**Fig. 26.** Schematic Silurian (~430 Ma) paleogeographic reconstruction showing interpreted tectonic activity leading to Acadian Orogeny, and detrital zircon data sets with depositional ages between 435 and 425 Ma. Dotted red line: Liberty – Dog Bay – Navan – Solway line representing final Salinian subduction boundary. Solid red line: Oblique collisional boundary at which Acadian Orogeny was initiated (Acadian line). Dashed red line: final NE position of Acadian thrust front in mid-Devonian. Colours in pie charts as in Fig. 7.

Middle Ordovician. This and several alternative positions, consistent with the paleomagnetic data, are shown in Fig. 24, and further discussed in section 6.2.3.

Following accretion of southern Britain to composite Laurentia (Fig. 26), the southern margin of “East Avalonia” remained open to the Rheic Ocean which lay to its south. Its closure in the Devonian to Permian interval resulted in the Variscan (Hercynian) Orogeny in Europe and ophiolite emplacement in SW England (e.g. Strachan et al., 2014 and references therein). Variscan deformation affected the southwestern extremities of the Leinster–Lakesman, Cymru, and Wrekin terranes, causing oroclinal bending of NW-SE Caledonide trends, potentially reorienting paleomagnetic orientations in these rocks.

### 6.1.7. *St. Croix – La Poile assemblage*

South of the Dog Bay Line, a series of terranes in New England and Atlantic Canada represent portions of Ganderia that are characterized by the Silurian CIB with arc to backarc chemical characteristics. The volcanic successions in many cases extend into the Přídolí or earliest Devonian. Such terranes include the Nashoba terrane of New England, St. Croix terrane in coastal Maine and southern New Brunswick, the northern slices of the New River belt and the Kingston terrane, also in southern New Brunswick, the Aspy terrane of Cape Breton Island, and the La Poile Bay block of the Hermitage belt of southern Newfoundland. The St. Croix terrane is stitched to the Laurentian margin at ~422 Ma by the Pocomoonshine pluton (West et al., 1992; Ludman et al., 2018).

Pre-Silurian successions in this assemblage are diverse. The Nashoba terrane is founded on Ediacaran to Cambrian arc volcanic rocks, whereas the St. Croix terrane contains quartzose continental margin sedimentary rocks (GCS1), overlying Precambrian quartzite and marble. The adjacent Ellsworth terrane to the SE displays a volcanic-dominated Cambrian record interpreted as formed in an oblique rift similar to the modern Gulf of California (Schulz et al., 2008) or the Cayman trough in the Caribbean. It contains NW-vergent thrust-sense shear zones that imply that it was thrust over the St. Croix terrane from the SE (Reusch, 2003; Pollock et al., 2022). Fabrics in these shear zones are overprinted by static metamorphic porphyroblasts in the aureoles of Silurian intrusions, indicating that the Ellsworth and St. Croix terranes were already juxtaposed at this time. A contact between the related Annidale terrane in New Brunswick and the adjacent Almond Road succession (part of the New River belt) is stitched by the ~479 Ma Stewarton Gabbro (Johnson et al., 2012).

The diverse geology of these terranes can be envisaged as the result of Penobscottian juxtaposition of a volcanic-dominated belt (Ellsworth and Annidale terranes) involving complex arc, backarc and pull-apart environments, with a block (St. Croix terrane) derived from the continental margin of Gondwana. Well exposed relationships in the St. Croix and Ellsworth terranes suggest that the volcanic-dominated successions were thrust NW, in present-day coordinates, relative to the continental-margin block (Pollock et al., 2022). Although no paleomagnetic data are available, the data reviewed here and by others (van Staal et al., 2021, and references therein) indicate that Penobscottian deformation occurred near the Gondwanan margin, before the transit of the assemblage across the Iapetus Ocean. The Silurian CIB records arc–backarc activity during and/or subsequent to the arrival of the assemblage at the Laurentian margin.

Most of the volcanic successions show an overprint of Acadian (~423-395 Ma) metamorphism, typically of Barrovian, high P/T aspect. In some cases this metamorphism is combined to a narrow zone along the SW edge of the terrane (e.g. Kingston terrane: White et al., 2006). In other areas (e.g. Aspy and Hermitage belts, Nashoba Terrane) it is more widespread (Plint and Jamieson, 1989; Kay et al., 2017). Any tectonic model therefore needs to explain how the St. Croix – La Poile assemblage rapidly transitioned from a supra-subduction position in the Silurian to a lower-plate, high P/T metamorphic environment in the Early Devonian.

#### 6.1.8. *Acadian Line and Avalon–Brookville assemblage*

The SE boundary of the St. Croix – La Poile assemblage is marked by a juxtaposition of rocks metamorphosed at high grade in the Early Devonian Acadian Orogeny, lying to the NW, against rocks that preserve fossiliferous sedimentary successions extending back into the Cambrian, lying to the SE. This fundamental boundary is here termed the *Acadian line* (Fig. 1). Traced SW, this line separates the Nashoba terrane from Southeastern New England (Fig. 7). To the NE, the boundary can be correlated through the Eastern Highlands shear zone of Cape Breton Island (Fig. 8), and thence through the Hermitage belt into the Dover Fault in Newfoundland (Fig. 9). The area to the SE of the Acadian line thus includes terranes that have previously been included in both Ganderia and Avalonia. We infer that they originated in contrasting environments on the margin of Gondwana, but there is no evidence that any of these terranes arrived at the composite Laurentian margin prior to the Early Devonian.

The continuation of the Acadian line into Europe is unclear, as Britain and Ireland lack much of the Acadian metamorphism that is characteristic of the Acadian Orogeny in New England. The relationships between Acadian events in the Appalachians and Caledonides are considered further in section 6.2.1

Adjacent to the Acadian line on its SE side are two terranes that show Ganderian affinities in their Ediacaran to Miaolingian stratigraphic development: the Brookville terrane of southern New Brunswick, and the Bras d'Or terrane of Cape Breton Island (Fig. 8). In addition, the Grey River block in the Hermitage belt of Newfoundland (Fig. 9) probably represents an extension of the Bras d'Or terrane. Both the Brookville and Bras d'Or terranes contain distinctive Precambrian components including Cryogenian to early Ediacaran marble and quartzite. Late Ediacaran successions include arc successions and major intrusive suites that extend into the Terreneuvian. Both terranes were affected by late Ediacaran regional metamorphism. Where they are present, the Brookville and Bras d'Or terranes separate West Avalonia (Mira, Caledonia terranes) from the St. Croix – La Poile assemblage to the NW. Farther north and south in the orogen, the Brookville and Bras d'Or terranes are absent; in those areas West Avalonian terranes are juxtaposed directly against the Acadian line.

During the later Cambrian, the evolution of the Brookville and Bras d'Or terranes may converge with Caledonia and Mira to the SE, a change interpreted by van Staal et al. (2021) to record collision during the Avalonian orogeny. Cambrian convergence between these otherwise contrasting Ganderian and Avalonian terranes can explain Cambrian to Early Ordovician stratigraphic and provenance similarities (Fig. 4, Fig. 20) that in some cases, resulted in the use of the same formation and group names across terrane boundaries. This convergence would have taken effect earlier in New Brunswick, where the units of the Saint John Group have been correlated between the Brookville and Caledonian terranes from Cambrian Series 2 onward. In Cape Breton Island the Bras d'Or and Mira terranes display contrasting stratigraphy until the Furongian, but thereafter a muddy shelf succession continues into at least the early Floian. There is no evidence to suggest that these terranes were affected by Penobscottian deformation.

The terranes included in "West Avalonia" — Avalon (Newfoundland), Mira, Antigonish and the Cobequid belt (Nova Scotia), Caledonia (New Brunswick), and Southeastern New England — can be grouped into two belts based on their restored positions (with respect to Laurentia) prior to Devonian–Carboniferous strike slip (Waldron et al., 2015). A "NW belt" comprises most of the on-land parts of the Avalon terrane, together with the Mira and Caledonia terranes. This belt largely lacks 610–590 Ma plutons, thick late Ediacaran marine sedimentary successions, and Silurian sedimentary basins. Populations of Meso- and Paleoproterozoic zircon (Fig. 21) in Cambrian rocks in the NW belt of West Avalonia show strong correlation with the adjacent "Ganderian" terranes, supporting the hypothesis that these terranes were juxtaposed from Cambrian onward. No detrital zircon data are yet published from Cambrian strata in the western part of the Avalon terrane in Newfoundland for comparison. However, data from the eastern part of the Newfoundland Avalon are resolutely sourced in the immediately underlying Ediacaran arcs until the youngest sample, which shows an influx (Pollock et al., 2009) of probable Ganderian zircon possibly following the Penobscottian event.

A "SE belt" (Antigonish terrane, Cobequid belt, Southeastern New England and probably eastern and offshore Newfoundland) includes terranes with 610–590 plutons, thick marine Ediacaran successions, and in some cases, Silurian marine sedimentary basins. A distinctive population of Mesoproterozoic zircon (Fig. 21) with large peaks in the Mesoproterozoic, particularly at ~1.25 Ga, is present in basement quartzitic metasedimentary rocks of both Southeastern New England and in the Cobequid belt, suggesting common provenance. This population can be recognized in younger units of both terranes, where it is variably diluted by Ediacaran zircon.

Several reliable paleomagnetic poles are available from the Avalon–Brookville assemblage (Table 2). Younger Ordovician poles track its progress from Gondwana to Laurentia. For example, the result from the ~460 Ma Dunn Point volcanic rocks (Hamilton and Murphy, 2004) in the Antigonish terrane (section 5.5.3) places the terrane approximately mid-way between the two larger continents. Unlike Ordovician poles from south Britain and Ireland it does not require significant vertical-axis rotation to explain its declination. A similar result applies to the slightly younger Cape St. Mary's sills in the eastern Avalon terrane of Newfoundland (section 5.5.5). A pole from close to the Tremadocian–-Floian boundary (the time of the Penobscottian Orogeny) from Southeastern New England (section 5.5.1), places the terrane assemblage on the Gondwanan margin as expected. However, various declination solutions are possible: "right way up" near the boundary between W Africa and Amazonia, or to the east near the Baltican or Arabian platforms in an "upside down" orientation (cf. Cawood and Pisarevsky, 2006) (Fig. 24). Two analogous solutions are possible for a pair of poles from the Cambrian Bourinot belt (~506 Ma) in the Bras d'Or terrane.

#### 6.1.9. *Meguma terrane / assemblage*

The Meguma terrane, uniquely amongst terranes SE of the Acadian line, shows evidence for penetrative Acadian fabrics, generated at ~395-

388 Ma (Hicks et al., 1999), in a succession that extends well into the Early Devonian (ca. 410 Ma) without any indication of contact with composite Laurentia. Detrital zircon populations from the Meguma terrane (Fig. 22) show abundant "Eburnean" zircon, in addition to twin peaks in the Ediacaran, typical of almost all peri-Gondwanan terranes. However, Mesoproterozoic and younger Paleoproterozoic ages are much reduced in comparison with Ganderia. Close stratigraphic and provenance similarities in the Cambrian with rocks of the Cymru and Wrekin terranes (Waldron et al., 2011, 2019a) suggest that all three terranes lay in close proximity on the West African, or possibly Baltican (Landing et al., 2022) margin in the Cambrian. The development of the Menai Strait fault system divided the domain Megumia, while it was still near the continental margin, into the Meguma and Cymru terranes. The Cymru terrane together with the adjacent "East Avalonia" (Wrekin, Charnwood terranes) were removed into a position adjacent to Ganderia (the Monian and Leinster–Lakesman terranes) while the Meguma terrane may have remained close to the West African margin into at least the Early Ordovician (Pothier et al., 2015a).

From there, the odyssey of the Meguma terrane is controversial. Some authors (e.g. Schenk, 1971) have speculated that it remained attached to West Africa throughout the Paleozoic while others have supposed that it remained attached to West Avalonia throughout (e.g. Keppie et al., 2018), based on the inferred similarity of its basement with that of Avalonia. In the absence of viable paleomagnetic results from the Meguma terrane in the Ordovician and Silurian we cannot further constrain its pathway. Fig. 11 shows a possible approximate Acadian location for the Meguma terrane, based on plausible restorations of Devonian–Carboniferous faults, outboard of the Avalon terrane at the edge of the present Grand Banks of Newfoundland. This would place it on-strike with the belt of Acadian deformation that extends through the St. Croix – La Poile assemblage, but also reasonably close to southern Britain, from which it was removed in the Cambrian.

### 6.2. *Towards a kinematic model*

Most previous kinematic models (e.g. Domeier, 2016) for the Appalachian–Caledonide Orogen have sought to explain the motion of Gondwana-derived terranes using one or two plates within the Iapetus ocean. Section 6.1 has identified seven separate pari–Gondwanan terrane assemblages, distinguished by their different histories within the Iapetus Ocean. Although not every assemblage necessarily represents a separate plate, the diversity of these components strongly suggests a multi-plate configuration, perhaps similar to the present-day west Pacific (van Staal et al., 1998) as shown in Fig. 13.

To unravel the history of the orogen, it is prudent to work backwards from more recent configurations to older. Fig. 11 shows a possible configuration of the northern Appalachian and Caledonide Orogen at ~370 Ma, following the Acadian Orogeny. It corresponds in overall topology to the earliest map of Waldron et al. (2015), restoring motion on Carboniferous (mainly dextral) faults, but has been reconstructed on a spherical surface, and takes into account Mesozoic stretching of continental margins (Ady and Whittaker, 2019). Structures in the British Isles (not discussed by Waldron et al., 2015) are based on published examples of late dextral strike-slip motion, particularly in the Midland Valley of Scotland (e.g. Rippon et al., 1996; Caldwell and Young, 2013; Underhill et al., 2008). The following sections (6.2.1 to 6.2.6) work backwards through major events recorded in Appalachian–Caledonide terranes to suggest possible stages in the kinematic evolution of the orogen. Uncertainty naturally increases with age, and we attempt to highlight these uncertainties as areas of focus for future work. We present three possible "snapshots" in Iapetus history (Fig. 24 to Fig. 26), but a complete kinematic model with Euler poles is beyond the scope of this paper. Once completed, such a model may add additional kinematic constraints.

#### 6.2.1. *Acadian Orogeny*

The Acadian Orogeny (Robinson et al., 1998; Bradley et al., 2000) encompasses major tectonism from latest Silurian (~423 Ma) to the end of the Middle Devonian (~383 Ma). In New England the start of Acadian tectonism is conveniently marked by the Pocomoonshine Pluton (West et al., 1992; Ludman et al., 2018), which seals the earlier (Salinian) boundary between the Merrimack–Bucksport–Fredericton trough and the St. Croix terrane (Fig. 7). In southern New England the Acadian Orogeny generated high-grade metamorphism and recumbent folds that transported both the accreted terranes and their Silurian to Devonian cover northwestward. Metamorphic grade decreases spectacularly at the Acadian line, marked locally by the Lake Char fault (Fig. 7), such that the Southeastern New England terrane largely lacks an Acadian metamorphic overprint. NW of the Acadian line, metamorphic grade decreases gradually along strike to the NE such that the equivalent units in New Brunswick (Fig. 8) are mostly at low greenschist facies. In this transitional region, Acadian deformation is associated with the development of Přídolí or younger structures indicating sinistral transpression (Hibbard and Hall, 1993; Hibbard, 1994; de Roo and van Staal, 1994). Local areas of higher-grade Acadian Barrovian metamorphism exist, most notably along the Kennebecasis fault (Fig. 8) at the SE boundary of the Kingston terrane (White et al., 2006), where Silurian high-pressure metavolcanic rocks are juxtaposed against the Brookville terrane which lacks evidence for either Silurian magmatism or Acadian metamorphism.

Grade increases again in Cape Breton Island where equivalent rocks of the Aspy belt are pervasively metamorphosed at greenschist and amphibolite facies under Barrovian conditions. The Acadian line is represented by the Eastern Highlands shear zone (Fig. 8) that separates the Aspy terrane from the Bras d'Or terrane to the SE, where Silurian magmatic rocks are absent and the presence of unmetamorphosed fossiliferous Cambrian strata in the Bourinot belt demonstrates the lack of Acadian metamorphism.

In Newfoundland, high-grade metamorphic rocks occur in the Gander terrane (Fig. 9), which shows pervasive development of Acadian sinistral strike-slip fabrics. Those fabrics are overprinted by later dextral fabrics in a narrow zone along the boundary with sub-greenschist facies rocks of the Avalon terrane, marked by the Dover Fault (Holdsworth, 1994; Kellett et al., 2014, 2016). Salinian-accreted terranes in central Newfoundland are deformed by NW-vergent Acadian thrusts and folds (Valverde-Vaquero et al., 2006a; van Staal et al., 2014), and Acadian deformation reactivated Taconian normal faults at the thrust front in western Newfoundland (Waldron et al., 1993; White and Waldron, 2019). The La Poile Bay block in the Hermitage belt to the south (Fig. 9) also shows Acadian metamorphism and deformation associated with complex strike-slip movements (O'Brien et al., 1991, 1996) but the Grey River block apparently escaped both Silurian magmatism and Acadian metamorphism. Thus, the Acadian line in Newfoundland can be traced along the unnamed fault at the north edge of the Grey River block into the Dover fault that forms the eastern boundary of the Gander terrane.

In Britain and Ireland, Acadian deformation is associated with only very low-grade metamorphism, together with the development of pervasive cleavage in orientations consistent with sinistral shear along the orogen (Woodcock et al., 2006, 2007). Intrusions as young as 397 Ma in the Southern Uplands terrane (Fig. 10) show syn-magmatic fabrics produced by sinistral shear (Stone et al., 2012; Miles et al., 2016; Woodcock et al., 2019). Dewey and Strachan (2003) pointed out that juxtaposition of the Grampian terrane (which displays an Ordovician deformation record but no significant Silurian tectonism) against the Northern Highlands terrane (with major Silurian thrusting and folding) along the Great Glen Fault (Fig. 10, Fig. 26) implies sinistral motion of at least 900 km. This conclusion has major implications for Newfoundland tectonics as the width of the restored continental shelves between Ireland and Newfoundland is only 700 km; major overlaps, for example between Grand Banks and Goban Spur (Fig. 26) result from any reconstruction that does not involve major Acadian sinistral shear in

Newfoundland.

In Fig. 26 this sinistral strike-slip motion is shown passing through the Gander terrane of Newfoundland and into the Hermitage belt. Because of changes in the strike of the margin of composite Laurentia, this motion would have been involved a component of convergence that increased towards the SE, accounting for the major shortening seen in the Acadian Orogen in New England.

A fundamental paradox of these relationships is that the belt of Silurian arc–backarc magmatism that existed in the St. Croix – La Poile assemblage along the margin of composite Laurentia prior to the Acadian Orogeny is interpreted as recording NW-dipping subduction, whereas the vergence of major structures and the distribution of Barrovian metamorphic rocks suggests NW-vergent transport.

Two solutions to this paradox are viable, and both may have operated simultaneously in the Acadian Orogeny (Fig. 26). First, highly transpressive plate boundaries (for example the Alpine Fault in New Zealand) may show along-strike changes in the vergence of contractional structures as restraining bends interact with one another over time. Second, the Mascarene basin that developed on the St. Croix terrane in the Silurian indicates that a backarc basin opened NW of the Kingston arc. Initial collision of the Avalon-Brookville assemblage with the Kingston arc at a NW-dipping subduction zone may have been followed by subduction polarity reversal which consumed part of the Mascarene backarc and led to major NW-vergent thrusting in the Acadian Orogen.

Several aspects of the reconstruction in Fig. 26 are controversial, and present avenues for future research. First, an “Acadian seaway” passed between the St. Croix – La Poile assemblage and the Brookville and Bras d’Or terranes of Atlantic Canada, based on the strong contrast in Silurian–Devonian magmatic and metamorphic history across this boundary, and the apparent Cambrian–Ordovician links between the components of the Avalon–Brookville assemblage (section 6.1.8). Previous reconstructions (van Staal and Barr, 2012; van Staal et al., 2021), have shown this seaway passing southeast of Brookville–Bras d’Or, attributing the lack of Silurian-Devonian tectonism in those terranes to flat-slab subduction.

Second, we have included southern Britain in the Gander–Lakesman assemblage and suggest that the Acadian Orogeny in Britain and Ireland was entirely the result of distributed intra-plate strike-slip, following the interpretation of most British geologists (e.g. Woodcock et al., 2006, 2007). Any major Acadian convergence would have been located to the south of England where its effects are overprinted by later, Variscan deformation. However, the possibility cannot be excluded that an oceanic tract existed between the Leinster–Lakesman terrane and southern Britain, passing either north or south of the Monian terranes (Section 6.1.6). Closure of such a tract might help to explain Early Devonian calc-alkaline magmatism in the Lake District and Southern Uplands (e.g. Brown et al., 2008; Stone et al., 2010, 2012; Miles et al., 2016; Woodcock et al., 2019), and apparent Acadian thrusting and foreland basin development in Anglesey (Schofield et al., 2020). In this case, Wales and southern England would be included in the Avalon–Brookville assemblage, not the Gander–Lakesman assemblage. We plan detrital zircon work in the latest Silurian and Devonian rocks of southern Britain to investigate this possibility.

A third area of uncertainty and controversy is the poorly constrained role and location of the Meguma terrane of Nova Scotia, which was first deformed in the Early Devonian. A possible solution is presented by the paleocontinental reconstruction of Wu et al. (2021), slightly modified here, in which the first approach of Gondwana to Laurentia is interpreted to have occurred in the Early Devonian, which was followed by widening of the Rheic Ocean during the later Devonian, prior to Alleghanian convergence in the Carboniferous to Permian. This Devonian close approach could have resulted in the deformation of the Meguma terrane and its transfer from Gondwana to Laurussia at the same time as the Acadian Orogeny. Further work would be needed to determine whether such a mechanism could explain the Devonian metamorphism and plutonism in the Meguma terrane.

### 6.2.2. *Salinian accretion*

Prior to intrusion of the Pocomoonshine gabbro–diorite at ~422 Ma, the preserved geological record in Atlantic Canada and New England indicates progressive Salinian accretion of peri-Gondwanan crustal fragments back to the late Ordovician. The St. Croix – La Poile assemblage was the latest to be accreted, along the line of the MBF trough (Dog Bay – Liberty line), during the Wenlock or Ludlow. Development of arc volcanic rocks in the St. Croix and Kingston terranes from Llandovery onwards suggests that this assemblage contained an arc prior to its accretion to composite Laurentia in the Wenlock or Ludlow. The polarity of subduction at this arc is uncertain, but in the absence of evidence for a subduction polarity reversal during the Silurian, it is here assumed to have been NW-dipping.

North of the MBF trough the arrival of the Miramichi-Victoria terrane assemblage at the Laurentian margin in the Late Ordovician marks the earliest phase of Salinian tectonism (as defined in section 2.7). Salinian blueschist metamorphism in the Miramichi terrane was the product of NW-dipping subduction beneath the margin of composite Laurentia close to the Ordovician–Silurian boundary (van Staal et al., 2008). Preservation of the blueschists required rapid exhumation following subduction. A possible scenario is shown with arrow M in Fig. 25 and involves a sinistral strike-slip component of convergence. This scenario helps to explain both the counterclockwise rotation recorded by paleomagnetic data, and the survival of the blueschists, which are uniquely present in the Québec re-entrant (Thomas, 1977) of the Laurentian margin.

The Victoria terrane records a much “softer” collision (van Staal and Zagorevski, 2020) with the Laurentian margin, and continued to receive sediment into its foredeep well into the Llandovery (Waldron et al., 2012 and references therein). Sinistral transport of the Victoria terrane may have carried it outboard of the Newfoundland promontory (arrow V in Fig. 25), so that it was not affected by the rapid burial–exhumation cycle that occurred in the Miramichi terrane.

Contemporary accretion-related units in Britain and Ireland are trench-fill turbidites of the Southern Uplands terrane (Leggett et al., 1979) that are largely Laurentia-derived (Stone and Merriman, 2004; Waldron et al., 2008). This interpretation suggests that the Iapetus Ocean at the longitude of Britain and Ireland had a simpler configuration, without many of the peri-Gondwanan arcs and backarc basins that filled the northern Appalachian segment (Waldron et al., 2014a; McConnell et al., 2015)

### 6.2.3. *Ordovician travel of terrane assemblages*

The most abundant paleomagnetic data in our compilation (Table 2) are from Middle Ordovician (~460 Ma; Fig. 25) rocks. These data show that whereas the Bronson Hill – Popelogan assemblage was already close to Laurentia, other assemblages (Miramichi, Avalon–Brookville, and Gander–Lakesman) were all located between 30° and 50° south of the equator. No data are available for the Moretown terrane (presumably already docked with Laurentia), the St. Croix – La Poile assemblage, or the Meguma terrane.

Between 490 Ma (Fig. 24) and 460 Ma, paleomagnetic data suggest that southern Britain, interpreted here as part of the Gander–Lakesman assemblage, underwent at least 90° of apparent clockwise rotation relative to Laurentia. This rotation is constrained to have occurred between about 479 Ma (the age of the Treffgarne volcanics) and ~464 Ma (the age of several paleomagnetic results in the Welsh Borders of the Wrekin terrane. This rate of rotation is rapid (~6°/Myr), and depending on the size of the plate involved, translation rates may also have been large. However, comparable tectonic rotation rates of 5 – 18°/Myr occur in several locations in the modern Earth, typically where relatively small, buoyant crustal blocks enter subduction zones undergoing rapid slab roll-back (Taylor et al., 2000; Wallace et al., 2005, 2009).

Other explanations for the large apparent rotations are possible.

Fig. 24 shows several alternative positions for the southern Britain at 490 Ma. From a starting position east of Baltica, rapid motion along a great circle would have carried the assemblage past the South Pole, achieving a similar apparent declination change with less tectonic vertical-axis rotation, but faster translation rates through the polar region.

Despite these uncertainties, the majority of data considered here favour a location for southern Britain in an "upside down" location approximately between Baltica and Gondwana at ~490 Ma. This explanation can explain both the paleomagnetic and the provenance data, providing a West African or Baltican source for the Eburnean and Ediacaran components of Avalonian detrital zircon distributions (Fig. 21).

### 6.2.4. *Taconian arc-continent collision*

In Newfoundland and areas to the NE, the Taconian Orogeny was driven by collision between complex, hyperextended peri-Laurentian fragments and an impinging oceanic arc system, parts of which are preserved in the Unst, Lough Nafooey, Twillingate, Lush's Bight, and Little Port ophiolitic assemblages. Murphy et al. (2014) and Waldron et al. (2014a) suggested that these ophiolitic rocks originated not within the Iapetus but in the surrounding "Panthalassa" ocean. Collision of these arcs with the Dashwoods–Tyrone assemblage began around 490 Ma (Waldron and van Staal, 2001; Chew et al., 2010).

No direct evidence exists for the location of these collisions in the Iapetus Ocean. Most reconstructions (since Cawood et al., 2001; Waldron and van Staal, 2001) have assumed both that the Taconic seaway inboard of the Dashwoods–Tyrone assemblage opened later than the main tract of the Iapetus Ocean, and that it was narrower, and that much of the seaway may have been floored by hyperextended continental crust (van Staal et al., 2013; Robert et al., 2021). Therefore, the first Taconian collisions occurred close to the Laurentian margin. However, there is no definitive evidence for either of these suppositions. In modern passive margins that involve off-margin microcontinental blocks, such as Rockall in the North Atlantic and Madagascar in the Indian Ocean, the widest ocean basin formed from the youngest parts of the initial rift system. Thus, the Dashwoods–Tyrone assemblage could have reached a position far from the margin. At typical subduction rates (e.g. 100 mm/yr) it is possible that up to 2000 km of Taconic seaway could have been consumed during the 20 Myr between initial collision with the Dashwoods–Tyrone assemblage and final emplacement onto the Laurentian margin. In the light of these considerations it is even conceivable that parts of the Dashwoods–Tyrone assemblage were closer to the Amazonian side of the Iapetus Ocean prior to Taconian collision.

The back-and-forth migration of the Dashwoods–Tyrone assemblage away from, and then towards the Laurentian margin was coeval with the successive accretion of the Laurentia-derived Arequipa–Antofalla and Cuyania terranes to Amazonia (e.g. Escayola et al., 2011; Thomas and Astini, 2003) much farther south. Contrasting kinematics recorded in the southern Appalachians may have been accommodated by a trans-Iapetus transform fault (Fig. 25: TIF) that likely originated during breakup of Rodinia (Wu et al., 2022). The along-margin component of motion of the Dashwoods–Tyrone assemblage is similarly unconstrained. White and Waldron (2022) suggested southwestward along-margin transport of detrital zircon by either tectonic or sedimentary processes.

The subsequent history of the northern Laurentian margin is best recorded in Newfoundland, where the collided arc underwent extension and renewed subduction initiation, producing the boninitic, and relatively young (~485 Ma) Bay of Islands Ophiolite, probably by intra-arc or fore-arc spreading (Dewey and Casey, 2013), as the remaining Taconic seaway was subducted. The amalgamated edifice of arc rocks and Laurentian off-margin material collided with the main Laurentian margin in the Middle Ordovician, leading to emplacement of the Humber Arm Allochthon at ~460 Ma (White and Waldron, 2022). Corresponding events in Britain and Ireland led to the mid-Ordovician Grampian Orogeny which may also have been accompanied by the emplacement of an analogous ophiolite sheet across the Grampian terrane (Dewey and Shackleton, 1984; Dewey and Ryan, 2016), although the original extent and kinematics of such a sheet are unclear (e.g. Tanner and Sutherland, 2007; Cawood et al., 2012; Tanner, 2014).

South of Newfoundland, in Atlantic Canada and New England, Taconian collision involved peri-Gondwanan fragments. The earliest of these fragments to arrive was the Moretown terrane, emplaced above the southernmost portion of the Dashwoods–Tyrone assemblage by 475 Ma, but not thrust over the Laurentian carbonate margin until ~448 Ma. The role of the geometry of the margin in these along-margin timing differences is explored in a separate paper (White and Waldron, 2022).

The Bronson–Popelogan assemblage arrived later in the Ordovician, but there is some uncertainty as to the polarity of subduction that juxtaposed it with the Laurentian margin. Karabinos et al. (2017) proposed subduction polarity reversal around 465 Ma, contemporary with that in Newfoundland, in which case the Bronson–Popelogan assemblage could have been accreted at a W-dipping subduction interface associated with continuing development of the Shelburne Falls arc farther inboard on the Laurentian margin. On the other hand, the continuity of continental-slope-and-rise sedimentary strata in the Taconic allochthon (Fig. 3) argues against this (White and Waldron, 2022), as does the lack of an arc inboard of the Popelogan inlier to the north. Hence, we favour an interpretation in which both the Moretown and the younger Bronson Hill arcs were brought into contact with the Laurentian margin by E-dipping "Taconian" subduction zones, operating either simultaneously or serially, associated with Late Ordovician arc plutonism in the Bronson Hill terrane (Hildebrand and Whalen, 2021). The collision of these terranes was responsible for the rapidly subsiding and migrating Late Ordovician Taconian foreland basin on the Laurentian margin, which continued to receive sediment until late in the Katian (~448 Ma) (White and Waldron, 2022).

### 6.2.5. *Monian–Penobscottian deformation*

Many peri-Gondwanan terranes preserve a record of Early Ordovician deformation attributed to the Monian or Penobscottian Orogeny. Like the Taconian/Grampian Orogeny, this event was protracted and somewhat diachronous through the Furongian to Floian; the two episodes largely overlapped in time.

The Monian–Penobscottian event resulted in the juxtaposition of predominantly ensimatic, or oceanic terranes (preserved in the Elmsdale inlier, the Victoria terrane, and the Ellsworth terrane, for example) with continental fragments carrying GCS1, including the Moretown, Bronson Hill, Miramichi, St. Croix, Gander and Leinster–Lakesman terranes. Both components are preserved in several different terrane assemblages, suggesting that any single Monian–Penobscottian suture was cross-cut and dissected during the rifting and dispersal of terrane assemblages into the Iapetus Ocean.

The kinematics of this event are best preserved in the Ellsworth terrane, which was thrust NW onto the St. Croix terrane (Pollock et al., 2022). However, in Anglesey and adjacent North Wales, many authors have argued that multiple Monian terranes, recording contrasting burial histories but lacking the foreland basins and consistent stacking order of thrust belts, can have been juxtaposed only by strike-slip or transpressional motion (Schofield et al., 2020 and references therein). Where available, kinematic indicators suggest that motion was sinistral.

Fig. 24 shows Monian–Penobscottian deformation driven by a complex continental-margin transform fault system, probably similar to the margins of the present-day Caribbean and Scotia arcs, as proposed by Waldron et al. (2014b), Pothier et al. (2015a), Schofield et al. (2020), and Landing et al., (2022). This model helps to explain many otherwise puzzling features of Appalachian–Caledonide tectonics, including:

- Transfer of peri-Gondwanan terranes with West African or Baltican affinities westward into the Iapetan realm from an inferred origin along the northern margin of Gondwana facing Baltica in most

Rodinia reconstructions (e.g. Linnemann et al., 2008, 2014; Nance et al., 2010), and along a Baltican margin in others (e.g. van Staal et al., 2020; Landing et al., 2022);
- Subduction initiation that appears to have occurred almost simultaneously along opposing Iapetan passive margins, a process unknown in oceans formed by the breakup of Pangea. Incursion of a Caribbean/Scotia-style plate provides an actualistic means to "infect" an opening ocean with subduction (Waldron et al., 2014b);
- Neoproterozoic blueschists such as those in the Penmynydd terrane of Anglesey (Schofield et al., 2020), that are most plausibly derived from a subduction belt marginal to Rodinia as it broke up;
- Isotopic characteristics of ophiolites that suggest extraction from a previously depleted mantle that would have existed in the external ocean surrounding outside the Iapetan realm (Murphy et al., 2014).

### 6.2.6. *Original positions of peri-Gondwanan terranes*

In Fig. 24 we show possible origins for terrane assemblages on the Gondwanan margin in the Ediacaran-Cambrian. Eastern, on-land parts of the Avalon terrane of Newfoundland occupy a unique position in this mosaic, as they were largely free of input from Mesoproterozoic and older crust until the Early Ordovician. This area was likely not part of the supercontinent Rodinia, but formed in the surrounding ocean as an arc (Nance and Murphy, 1994; Murphy et al., 2008) and entered the young ocean between Baltica and Gondwana in a manner similar to the entry of the Caribbean oceanic plateau into the Atlantic ocean in the Mesozoic (e.g. Pindell and Kennan, 2009). Part of Avalonia may thus indeed have existed as an island continent since the Ediacaran as envisaged by Landing (1996). However, by the Terreneuvian, the terranes of West Avalonia show similar stratigraphies, and we infer that they occupied positions along the margin of either Baltica (Landing et al., 2022) or Gondwana. Contrasts in provenance between the components of West Avalonia suggest that the belt of Cambrian platformal sedimentation that characterizes Avalonia may have extended far along the margin, covering multiple belts in older Gondwana and/or Baltica. They may have been amalgamated later in the Cambrian with the Brookville and Bras d'Or terranes, which show earlier histories closer to those of other Ganderian terranes.

Paleomagnetic data allow two possible solutions for the location of the terranes in the Avalon–Brookville assemblage on the Gondwanan margin, either "right way up" adjacent to west Africa or "upside down" between the Arabian and Baltic platforms. The latter origin near the shaly Arabian and Baltic platforms provides a somewhat better fit sedimentologically in the Cambrian than the carbonate-dominated, warmer water environment of the Moroccan margin which may provide a less than ideal match for Cambrian West Avalonia (Landing, 1996, 2004, 2005; Landing and Westrop, 2004; Landing et al., 2022). However, Álvaro (2021) has argued for compatibility between Avalonia and the Moroccan margin.

From its far eastern origin close to Arabia and Baltica, components of Avalonia required sinistral translation along the Gondwanan margin (Landing and Westrop, 2004; Landing et al., 2022; Nance and Murphy, 1996; Nance et al., 2008; Pothier et al., 2015a; Schofield et al., 2020; Waldron et al., 2014b), bringing them in contact with the Amazonian portion of Gondwana, and allowing them to enter the central Iapetus Ocean. In the process, the opening of small, obliquely opening ocean basins at releasing bends analogous to the present-day Cayman trough would have produced rift-influenced oceanic crust of the Ellsworth and related terranes (Schulz et al., 2008). By the end of the Cambrian period, components of Avalonia (e.g. Mira, Caledonia) may have juxtaposed with components of Ganderia (Bras d'Or, Brookville). Others were probably juxtaposed in the Early Ordovician Monian / Penobscottian events (Pothier et al., 2015a; Waldron et al., 2019a; Schofield et al., 2020)

Quartzose, continentally derived turbidites of GCS1 were most likely deposited on a promontory extending into the Iapetus Ocean from the margin of Amazonia (van Staal et al., 2012, 2021). In such a position they would inevitably have encountered the westward-propagating arc of an impinging Caribbean-like plate. SE-dipping subduction at the leading boundary of this plate would have emplaced rocks of the Penobscot arc onto GCS1 as in the Gander terrane of Newfoundland. More northerly portions of the impinging arc system likely 'missed' the Gondwanan promontory, colliding instead with the Dashwoods–Tyrone assemblage and initiating the Taconian Orogeny. In an intermediate region the northern extremity of GCS1 was emplaced onto the southernmost extremity of the Dashwoods–Tyrone assemblage as the Moretown terrane.

Dispersing the remaining fragments of the Monian–Penobscot Orogen into the Iapetus Ocean required a transition to transtension along the margin of Gondwana, perhaps prompted by slab-pull from the margin of Laurentia (e.g. van Staal et al., 2012) following post-Taconian subduction polarity reversal.

Alternative scenarios can be envisaged for the kinematics of peri-Gondwanan terranes. Wu et al. (2022) noted that relationships in the southern Appalachians require a major transform fault across the Iapetus Ocean following migration of the Cuyania microcontinent towards the northern Argentine region of South America where it is now found (Thomas and Astini, 2003, and references therein). Long transform faults are known to be likely sites for subduction initiation (e.g. Stern and Bloomer, 1992), so some of the arcs and terranes preserved in the Appalachians may have migrated into the Iapetus Ocean from the SW, rather than the SE as envisaged by Waldron et al. (2014b). Future examination of this possibility will depend on integrating paleomagnetic and provenance data for the southern Appalachians, beyond the scope of this already lengthy review.

## 7. Conclusions

By examining the stratigraphy, provenance, and paleomagnetism of the major tectonostratigraphic units of the northern Appalachian and western Caledonide Orogens, coupled with a compilation of previous work on the geochronology of igneous units, we have been able to systematically identify and compare the large number of "terranes" that have been identified in the orogen.

The traditionally identified domains Ganderia, Avalonia, and Megumia are based on stratigraphic and isotopic characteristics of Precambrian and Cambrian rocks. They provide a basis for the identification of distinct tectonostratigraphic environments that existed on the Gondwanan or Baltican margin prior to a series of events in the Cambrian and early Ordovician (Monian–Penobscottian) that resulted in the dispersal of terranes into the Iapetus Ocean as reorganized terrane assemblages, some of which cross-cut two or more of the earlier domains.

Following their dispersal, we identify several terrane assemblages that crossed the Iapetus Ocean, reaching the Laurentian margin between the Early Ordovician and at least the Early Devonian. Some of these terrane assemblages underwent substantial rotations as they separated from Gondwana and crossed the Iapetus Ocean. These aspects of terrane kinematics favour a "Caribbean-style" model for the tectonics of the Iapetus (Waldron et al., 2014b; Pothier et al., 2015a; Schofield et al., 2020). As a result of this activity, the Iapetus Ocean contained a denser population of arcs and microcontinental blocks in the Appalachian sector than in the British sector. These arcs and microcontinental blocks were accreted to Laurentia and subsequently dissected in a series of events that shaped the modern Appalachian and Caledonide orogens.

- The Taconian/Grampian Orogeny was probably initiated by diachronous collision of an island arc system with the complex passive margin of Laurentia (e.g. van Staal et al., 1998; Zagorevski et al., 2008; White and Waldron, 2022), including off-margin blocks of the Dashwoods–Tyrone assemblage in the latest Cambrian to Late Ordovician. In the NE (Britain and Ireland, Newfoundland) this collision involved an oceanic island arc system (Lough Nafooey arc) whereas in the SW (New England) it brought in arcs founded on the microcontinental blocks of the Moretown and Bronson assemblages.

- Taconian arc–continent collision was followed, also somewhat diachronously (van Staal et al., 1998), by subduction-polarity reversal, producing an active continental-margin trench system, and a corresponding volcanic arc on the margin. Terranes were accreted in a protracted series of accretionary events broadly categorized as Salinian. The Miramichi–Victoria assemblage was first to arrive at the composite Laurentian margin. In New Brunswick, oblique accretion was accompanied by blueschist facies metamorphism around 445 Ma in the Québec reentrant (van Staal et al., 2008). Arrival of the Victoria terrane at the Newfoundland promontory was similarly timed but resulted in a "soft" collision (van Staal and Zagorevski, 2020) without exhumation of high-pressure rocks.
- The Gander–Lakesman assemblage arrived in the Wenlock–Ludlow in another "soft" collision (e.g. King, 1994), but simultaneously with Scandian "hard" collision of Baltica with Greenland in the NE Caledonides. In Atlantic Canada, the St. Croix – La Poile assemblage, overlain by a major Silurian arc system, possibly arrived slightly later, close to the Ludlow–Pridoli boundary.
- Acadian strike-slip faults resulted in the sinistral dissection of the orogen in Britain and Ireland (Woodcock et al., 2006, 2019). Transpression and convergence in Atlantic Canada resulted in the collapse of the Silurian arc–backarc system and the accretion of the Avalon–Brookville assemblage. Subduction polarity reversal was followed by Barrovian metamorphism in a belt of Acadian deformation that resulted in NW-directed thrusting and recumbent folding in New England (e.g. Robinson et al., 1998).
- The resulting collage of accreted terranes was then dissected by Devonian–Carboniferous faults, producing Quaboagian transpression, metamorphism, and major crustal thickening in southern New England (e.g. Hillenbrand et al., 2021), coupled with Devono-Carboniferous transtension, crustal thinning, and sediment accumulation in Atlantic Canada, producing the Maritimes Basin (Hibbard and Waldron, 2009; Waldron et al., 2015).
- Alleghanian shortening in the southern Appalachians was accompanied by east-west dextral strike-slip motion and transpression in the northern Appalachians, inverting parts of the Maritimes Basin (e.g. Snyder and Waldron, 2021).
- The latest stages of deformation occurred in the Mesozoic, stretching the continental margins and opening the Atlantic Ocean, so that closely related components of the orogen are now widely separated (Wilson, 1966).

This review has shown how large databases of stratigraphy, paleomagnetism, and provenance studies can be combined to produce a detailed history of an orogen, involving break-up, drift, accretion, and collisional phases. It suggests avenues for further work in resolving remaining problems such as the following: What was the path of the Meguma terrane from an origin close to N. Wales to its present position in southern Nova Scotia? Did England and Wales travel with the Leinster–Lakesman terrane throughout the Ordovician and Silurian, or does the Monian belt conceal an Acadian suture? What was the provenance and paleogeographic location of the St. Croix belt, which is stratigraphically and paleomagnetically under-explored? What was the polarity of thrusting in the Newfoundland Penobscottian event, traditionally interpreted as SE-vergent but here identified as possibly NW-vergent by analogy with similar events in New Brunswick and coastal Maine?

As a final observation, we note that because of the complex history of terrane accretion, the search for a "main tract of Iapetus" or an "Iapetus suture" is probably futile. The original floor of the rifted Iapetus Ocean was probably entirely subducted by the Middle Ordovician. The orogen preserves an anastomosing network of sutures, arcs, and backarc basins that survived subduction, reflecting the variability in time and space of its constituent terranes. Based on modern convergent systems, this type of complexity is typical of orogens, both modern and ancient.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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## Data availability

Data supporting this paper are made available at https://era.library.ualberta.ca/items/d381a9f3-ecf7-4bb7-b486-4b60a9c7b687.

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## References

Ady, B., Whittaker, R., Wilson, Woody, 2019. A palinspastic deformable plate kinematic reconstruction of the southern North Atlantic and Labrador Sea: implications for reconstruction of the Appalachian-Caledonide orogen. In: Houseman, G.A., McCaffrey, K.J.W., Doré, A.G., Buiter, S.J.H. (Eds.), Fifty Years of the Wilson Cycle Concept in Plate Tectonics, Geological Society London Special Publications.

Allen, J.S., 2009. Paleogeographic Reconstruction of the St. Lawrence Promontory, Western Newfoundland (PhD thesis). University of Kentucky.

Álvaro, J.J., 2021. Cambrian syn-rift tectonic pulses at unconformity-bounded carbonates in the Avalon Zone of Newfoundland, Canada. Basin Res. 33, 1520–1545. https://doi.org/10.1111/bre.12525.

Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis, NOAA Technical Memorandum, NESDIS NGDC-24. National Geophysical Data Center, NOAA.

Anson, G.L., Kodama, K.P., 1987. Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment. Geophys. J. R. Astron. Soc. 88, 673–692.

Archibald, D.B., Barr, S.M., Murphy, J.B., White, C.E., MacHattie, T.G., Escarraga, E.A., Hamilton, M.A., McFarlane, C.R.M., Hibbard, J., 2013. Field relationships, petrology, age, and tectonic setting of the Late Cambrian–Ordovician West Barneys River Plutonic Suite, southern Antigonish Highlands, Nova Scotia, Canada. Can. J. Earth Sci. 50, 727–745. https://doi.org/10.1139/cjes-2012-0158.

Armstrong, H.A., Owen, A.W., Scrutton, C.T., Clarkson, E.N.K., Taylor, C.M., 1996. Evolution of the Northern Belt, Southern Uplands: implications for the Southern Uplands controversy. J. Geol. Soc. Lond. 153, 197–205.

Asanuma, H., Okada, Y., Fujisaki, W., Suzuki, K., Sato, T., Sawaki, Y., Sakata, S., Yamamoto, S., Hirata, T., Maruyama, S., Windley, B.F., 2015. Reconstruction of ocean plate stratigraphy in the Gwna Group, NW Wales: Implications for the subduction–accretion process of a latest Proterozoic trench-forearc. Tectonophysics 662, 195–207. https://doi.org/10.1016/j.tecto.2015.04.016.

Asanuma, H., Fujisaki, W., Sato, T., Sakata, S., Sawaki, Y., Aoki, K., Okada, Y., Maruyama, S., Hirata, T., Itaya, T., Windley, B.F., 2017. New isotopic age data constrain the depositional age and accretionary history of the Neoproterozoic-Ordovician Mona Complex (Anglesey-Lleyn, Wales). Tectonophysics 706–707, 164–195. https://doi.org/10.1016/j.tecto.2017.03.017.

Aubouin, J., 1965. Geosynclines. Elsevier, Amsterdam, New York.

Ayuso, R.A., Barr, S.M., Longstaffe, F.J., 1996. Pb and O isotopic constraints on the source of granitic rocks from Cape Breton Island, Nova Scotia, Canada. Am. J. Sci. 296, 789–817. https://doi.org/10.2475/ajs.296.7.789.

Barr, S.M., Hegner, E., 1992. Nd isotopic compositions of felsic igneous rocks in Cape Breton Island, Nova Scotia. Can. J. Earth Sci. 29, 650–657. https://doi.org/10.1139/e92-056.

Barr, S.M., Jamieson, R.A., 1991. Tectonic setting and regional correlation of Ordovician–Silurian rocks of the Aspy terrane, Cape Breton Island, Nova Scotia. Can. J. Earth Sci. 28, 1769–1779. https://doi.org/10.1139/e91-158.

Barr, S.M., MacDonald, A.S., 1989. Geology of the Mabou Highlands. Western Cape Breton Island, Nova Scotia, Nova Scotia Department of Mines and Energy Paper, 89–2.

Barr, S.M., Mortensen, J.K., 2019. Neoproterozoic U–Pb (zircon) and 40Ar/39Ar (muscovite) ages from granitic pegmatite clasts, basal Ross Island Formation, Grand Manan Island, New Brunswick, Canada. Atl. Geol. 265–274. https://doi.org/10.4138/atlgeol.2019.009.

Barr, S.M., Raeside, R.P., 1989. Tectono-stratigraphic terranes in Cape Breton Island, Nova Scotia: implications for the configuration of the northern Appalachian orogen. Geology 17, 822–825.

Barr, S.M., White, C.E., 2017. Bedrock Geology Map of the Lake Ainslie Area, NTS 11K/03, Inverness and Victoria Counties, Nova Scotia. Nova Scotia Department of Natural Resources Open File Map, ME 2017-018.

Barr, S.M., Raeside, R.P., van Breemen, O., 1987. Grenvillian basement in the northern Cape Breton Highlands, Nova Scotia. Can. J. Earth Sci. 24, 992–997.

Barr, S.M., Bevier, M.L., White, C.E., Doig, R., 1994. Magmatic history of the Avalon terrane of southern New Brunswick, Canada, based on U-Pb (zircon) geochronology. J. Geol. 102, 399–409.

Barr, S.M., Raeside, R.P., White, C.E., 1998. Geological correlations between Cape Breton Island and Newfoundland, northern Appalachian orogen. Can. J. Earth Sci. 35, 1252–1270.

Barr, S.M., Fyffe, L.R., King, S., McLaughlin, K.J., McLeod, M.J., Miller, B.V., Thompson, M.D., White, C.E., 2002a. New U-Pb zircon ages, geophysical compilations, and terranes in southern New Brunswick (Information Circular No. 2002–1). In: Abstracts 2002: 27th Annual Review of Activities. New Brunswick Department of Natural Resources & Energy.

Barr, S.M., White, C.E., Miller, B.V., 2002b. The Kingston terrane, southern New Brunswick, Canada: evidence for an Early Silurian volcanic arc. Geol. Soc. Am. Bull. 114, 964–982.

Barr, S.M., White, C.E., Miller, B.V., 2003a. Age and geochemistry of Late Neoproterozoic and Early Cambrian igneous rocks in southern New Brunswick: similarities and contrasts. Atl. Geol. 39, 55–73.

Barr, S.M., Davis, D.W., Kamo, S.L., White, C.E., 2003b. Significance of U-Pb detrital zircon ages in quartzite from peri-Gondwanan terranes, New Brunswick and Nova Scotia, Canada. Precambrian Res. 126, 123–145.

Barr, S.M., Mortensen, J.K., Thompson, M.D., Hermes, O.D., White, C.E., 2011. Early to Middle Devonian granitic and volcanic rocks from the central Gulf of Maine. Lithos 126, 455–465. https://doi.org/10.1016/j.lithos.2011.06.009.

Barr, S.M., Hamilton, M.A., Samson, S.D., Satkowski, A.M., White, C.E., 2012. Provenance variations in northern Appalachian Avalonia based on detrital zircon age patterns in Ediacaran and Cambrian sedimentary rocks, New Brunswick and Nova Scotia, Canada. Can. J. Earth Sci. 49, 533–546. https://doi.org/10.1139/e11-070.

Barr, S.M., Pin, C., McMullin, D., White, C.E., 2013. Whole-rock chemical and Nd isotopic composition of a Late Proterozoic metasedimentary sequence in Ganderia: Kellys Mountain, Bras d'Or terrane, Nova Scotia, Canada. Atl. Geol. 49, 57–69.

Barr, S.M., Dehler, S.A., Zsámboki, L., 2014a. Connecting Cape Breton Island and Newfoundland, Canada: geophysical modeling of pre-Carboniferous "Basement" Rocks in the Cabot Strait Area. Geosci. Can. 41, 186. https://doi.org/10.12789/geocanj.2014.41.041.

Barr, S.M., White, C.E., Davis, D.W., McClelland, W.C., van Staal, C.R., 2014b. Infrastructure and provenance of Ganderia: Evidence from detrital zircon ages in the Brookville terrane, southern New Brunswick, Canada. Precambrian Res. 246, 358–370. https://doi.org/10.1016/j.precamres.2014.03.022.

Barr, S.M., van Rooyen, D., White, C.E., 2018. Granitoid plutons in peri-Gondwanan terranes of Cape Breton Island, Nova Scotia, Canada: new U-Pb (zircon) age constraints. Atl. Geol. 021–080 https://doi.org/10.4138/atlgeol.2018.002.

Barr, S.M., van Rooyen, D., Miller, B.V., White, C.E., Johnson, S.C., 2019. Detrital zircon signatures in Precambrian and Paleozoic sedimentary units in southern New Brunswick – more pieces of the puzzle. Atl. Geol. 55, 275–322. https://doi.org/10.4138/atlgeol.2019.010.

Barr, S.M., White, C.E., Jensen, S., Palacios, T., van Rooyen, D., 2020a. Ediacaran and Cambrian rocks on Scatarie Island and nearby Hay Island, Avalonian Mira terrane, Cape Breton Island, Nova Scotia, Canada. Atl. Geol. 56, 257–279. https://doi.org/10.4138/atlgeol.2020.011.

Barr, S.M., Johnson, S.C., Dunning, G.R., White, C.E., Park, A.F., Wälle, M., Langille, A., 2020b. New Cryogenian, Neoproterozoic, and middle Paleozoic U–Pb zircon ages from the Caledonia terrane, southern New Brunswick, Canada: better constrained but more complex volcanic stratigraphy. Atl. Geol. 56, 163–187. https://doi.org/10.4138/atlgeol.2020.007.

Berry, H.N., Osberg, P.H., 1989. A stratigraphic synthesis of eastern Maine and western New Brunswick. Stud. Maine Geol. Maine Geol. Surv. 2, 1–32.

Berry, H.N., West, D.P., Burke, W.B., 2016. Bedrock Relationships Along the Sennebec Pond Fault: A Structural Puzzle, a Stratigraphic Enigma, and a Tectonic Riddle, in: Berry, H.N., West, D.P. (Eds.), Guidebook for Field Trips along the Maine Coast from Maquoit Bay to Muscongus Bay, New England Intercollegiate Geological Conference, Field Guide. pp. 43–70. Maine Geological Survey Open-File Report NEIGC16C:A3.

Bevier, M.L., Barr, S.M., White, C.E., Macdonald, A.S., 1993. U–Pb geochronologic constraints on the volcanic evolution of the Mira (Avalon) terrane, southeastern Cape Breton Island, Nova Scotia. Can. J. Earth Sci. 30, 1–10. https://doi.org/10.1139/e93-001.

Bird, J.M., Dewey, J.F., 1970. Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen. Geol. Soc. Am. Bull. 81, 1031–1060.

Bird, A.F., Thirlwall, M.F., Strachan, R.A., Manning, C.J., 2013. Lu–Hf and Sm–Nd dating of metamorphic garnet: evidence for multiple accretion events during the Caledonian orogeny in Scotland. J. Geol. Soc. 170, 301–317. https://doi.org/10.1144/jgs2012-083.

Bluck, B.J., Gibbons, W., Ingham, J.K., 1992. Terranes. In: Cope, J.C.W., Ingham, J.K., Rawson, P.F. (Eds.), Atlas of Palaeogeography and Lithofacies, Geological Society of London Memoir, pp. 1–4.

Boucot, A.J., 1962. Appalachian Siluro-Devonian. In: Coe, K. (Ed.), Some Aspects of the Variscan Fold Belt: 9th Inter-University Geological Congress. Manchester University Press, Manchester, UK, pp. 155–163.

Bouyx, E., Blaise, J., Brice, D., Degardin, J.M., Goujet, D., Gourvennec, R., Le Menn, J., Lardeux, H., Morzadec, P., Paris, F., 1997. Biostratigraphie et paleobiogeographie du Siluro-Devonien de la zone de Meguma (Nouvelle-Ecosse, Canada). Can. J. Earth Sci. 34, 1295–1309.

Boyce, W.D., Johnson, S., 2004. Early Cambrian trilobites from the Hanford Brook Formation, Public Landing, southern New Brunswick, Canada. In: Geological Association of Canada, Paleontology Division, Canadian Paleontology Conference Proceedings, vol. 2, p. 14.

Bradley, D.C., 1989. Taconic plate kinematics as revealed by foredeep stratigraphy, Appalachian Orogen. Tectonics 8, 1037–1049.

Bradley, D.C., O'Sullivan, P., 2016. Detrital zircon geochronology of pre-and syn-collisional strata, Acadian orogen, Maine Appalachians. Basin Res. 29, 571–590. https://doi.org/10.1111/bre.12188.

Bradley, D.C., O'Sullivan, P., Cosca, M.A., Motts, H., Horton, J.D., Taylor, C.D., Beaudoin, G., Lee, G.K., Ramezani, J., Bradley, D.B., Jones, J.V., Bowring, S., 2015. Second Projet de Renforcement Institutionnel du Secteur Minier de la République Islamique de Mauritanie (PRISM-II) Synthesis of Geological, Structural, and Geochronologic Data: Phase V, Deliverable 53. United States Geological Survey Open-File Report, 2013–1280.

Bradley, D.C., Tucker, R.D., Lux, D., Harris, A.G., McGregor, D.C., 2000. Migration of the Acadian orogen and foreland basin across the Northern Appalachians. United States Geological Survey Professional Paper, 1615.

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. https://doi.org/10.2475/02.2007.01.

Brenchley, P.J., Rawson, P.F., 2006. England and Wales through geologic time. In: Brenchley, P.J., Rawson, P.F. (Eds.), The Geology of England and Wales. The Geological Society, London, pp. 1–7.

Brenchley, P.J., Rushton, A.W.A., Howells, M., Cave, R., 2006. Cambrian and Ordovician: the early Palaeozoic tectonostratigraphic evolution of the Welsh Basin, Midland and Monian Terranes of Eastern Avalonia. In: Brenchley, P.J., Rawson, P.F. (Eds.), The Geology of England and Wales. The Geological Society, London, pp. 25–74.

Bresser, G., Walter, R., 1999. A new structural model for the SW Irish Variscides The Variscan front of the NW European Rhenohercynian. Tectonophysics 309, 197–209.

Briden, J.C., Morris, W.A., Piper, J.D.A., 1973. Palaeomagnetic Studies in the British Caledonides; VI, Regional and Global Implications. Geophys. J. R. Astron. Soc. 34, 107–134.

British Geological Survey, 2007. Bedrock Geology UK scale 1:625,000.

Brown, P.E., Ryan, P.D., Soper, N.J., Woodcock, N.H., 2008. The Newer Granite problem revisited: a transtensional origin for the Early Devonian Trans-Suture Suite. Geol. Mag. 145 https://doi.org/10.1017/S0016756807004219.

Buschette, M.J., Piercey, S.J., 2016. Hydrothermal alteration and lithogeochemistry of the Boundary volcanogenic massive sulphide deposit, central Newfoundland, Canada. Can. J. Earth Sci. 53, 506–527. https://doi.org/10.1139/cjes-2015-0237.

Butler, R.F., 1992. Paleomagnetism; Magnetic Domains to Geologic Terranes. Blackwell, Boston.

Caldwell, W.G.E., Young, G.M., 2013. The Cumbrae Islands: a structural Rosetta Stone in the western offshore Midland Valley of Scotland. Scott. J. Geol. 49, 117–132. https://doi.org/10.1144/sjg2011-462.

Cartwright, S.F.A., David, P., West, J., Amidon, W.H., 2019. Depositional constraints from detrital zircon geochronology of strata from multiple lithotectonic belts in south-central Maine, USA. Atl. Geol. 55, 093–136. https://doi.org/10.4138/atlgeol.2019.003.

Cavagnaro, D.B., Strauss, J.V., Reusch, D.N., Waldron, J.W.F., Slack, J.F., 2019. New U-Pb detrital and igneous zircon geochronological results from the St. Croix Terrane and Islesboro block, Penobscot Bay, Maine. In: Geological Society of America Abstracts, 32. Portland ME, p. T19.

Cave, R., 2008. Geology of the Welshpool District; A Brief Explanation of the Geological Map Sheet 151 Welshpool Sheet Explanation of the British Geological Survey, Sheet Explanation of the British Geological Survey. NERC, United Kingdom.

Cawood, P.A., Nemchin, A.A., 2001. Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland

Appalachians. Geol. Soc. Am. Bull. 113, 1234–1246. https://doi.org/10.1130/0016-7606(2001)113<1234:PDOTEL>2.0.CO;2.

Cawood, P.A., Pisarevsky, S.A., 2006. Was Baltica right-way-up or upside-down in the Neoproterozoic? J. Geol. Soc. 163, 753–759.

Cawood, P.A., Dunning, G.R., Lux, D., van Gool, J.A.M., 1994. Timing of peak metamorphism and deformation along the Appalachian margin of Laurentia in Newfoundland: Silurian, not Ordovician. Geology 22, 399–402.

Cawood, P.A., McCausland, P.J.A., Dunning, G.R., 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. Geol. Soc. Am. Bull. 113, 443–453. https://doi.org/10.1130/0016-7606(2001)113<0443:OICFTL>2.0.CO;2.

Cawood, P.A., Nemchin, A.A., Smith, M., Loewy, S., 2003. Source of the Dalradian Supergroup constrained by U-Pb dating of detrital zircon and implications for the East Laurentian margin. J. Geol. Soc. 160, 231–246. https://doi.org/10.1144/0016-764902-039.

Cawood, P.A., Nemchin, A.A., Strachan, R.A., Kinny, P.D., Loewy, S., 2004. Laurentian provenance and an intracratonic tectonic setting for the Moine Supergroup, Scotland, constrained by detrital zircons from the Loch Eil and Glen Urquhart successions. J. Geol. Soc. 161, 861–874.

Cawood, P.A., Nemchin, A.A., Strachan, R., Prave, T., Krabbendam, M., 2007. Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. J. Geol. Soc. 164, 257–275.

Cawood, P.A., Merle, R.E., Strachan, R.A., Tanner, P.W.G., 2012. Provenance of the Highland Border Complex: constraints on Laurentian margin accretion in the Scottish Caledonides. J. Geol. Soc. 169, 575–586. https://doi.org/10.1144/0016-76492011-076.

Channell, J.E.T., McCabe, C., Torsvik, T.H., Trench, A., Woodcock, N.H., 1992. Palaeozoic palaeomagnetic studies, in the Welsh Basin-recent advances. Geol. Mag. 129, 533–542. https://doi.org/10.1017/S0016756800021695.

Channell, J.E.T., McCabe, C., Woodcock, N.H., 1993. Palaeomagnetic study of Llandovery (Lower Silurian) red beds in north-west England. Geophys. J. Int. 115, 1085–1094. https://doi.org/10.1111/j.1365-246X.1993.tb01511.x.

Chew, D.M., 2009. Grampian Orogeny. In: Holland, C.H., Sanders, I.S. (Eds.), The Geology of Ireland. Dunedin, Edinburgh, pp. 69–93.

Chew, D.M., van Staal, C.R., 2014. The Ocean – Continent Transition Zones Along the Appalachian – Caledonian Margin of Laurentia: examples of large-scale hyperextension during the opening of the Iapetus Ocean. Geosci. Can. 165–185 https://doi.org/10.12789/geocanj.2014.41.040.

Chew, D.M., Flowerdew, M.J., Page, L.M., Crowley, Q.G., Daly, J.S., Cooper, M., Whitehouse, M.J., 2008. The tectonothermal evolution and provenance of the Tyrone Central Inlier, Ireland: Grampian imbrication of an outboard Laurentian microcontinent? J. Geol. Soc. 165, 675–685. https://doi.org/10.1144/0016-76492007-120.

Chew, D.M., Daly, J.S., Magna, T., Page, L.M., Kirkland, C.L., Whitehouse, M.J., Lam, R., 2010. Timing of ophiolite obduction in the Grampian orogen. Geol. Soc. Am. Bull. 122, 1787–1799. https://doi.org/10.1130/b30139.1.

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.

Clift, P.D., Carter, A., Draut, A.E., Long, H.V., Chew, D.M., Schouten, H.A., 2009. Detrital U-Pb Zircon dating of Lower Ordovician Syn-Arc-Continent Collision Conglomerates in the Irish Caledonides. Tectonophysics 470, 165–174.

Cocks, L.R.M., Torsvik, T.H., 2011. The Palaeozoic geography of Laurentia and western Laurussia: a stable craton with mobile margins. Earth-Sci. Rev. 106, 1–51. https://doi.org/10.1016/j.earscirev.2011.01.007.

Cocks, L.R.M., McKerrow, W.S., van Staal, C.R., 1997. The margins of Avalonia. Geol. Mag. 134, 627–636.

Cohen, K.M., Harper, D.A.T., Gibbard, P.L., Fan, J.-X., 2013. The ICS International Chronostratigraphic Chart. Episodes 36, 119–204.

Cohen, K.M., Finney, S.M., Gibbard, P.L., Fan, J.-X., 2020. ICS International Chronostratigraphic Chart 2020/03.

Cohen, K.M., Finney, S.M., Gibbard, P.L., Fan, J.-X., 2021. ICS International Chronostratigraphic Chart 2021/05.

Collins, A.S., Buchan, C., 2004. Provenance and age constraints of the South Stack Group, Anglesey, UK: U-Pb SIMS detrital zircon data. J. Geol. Soc. 161, 743–746.

Colman-Sadd, S.P., Dunning, G.R., Dec, T., 1992. Dunnage-Gander relationships and Ordovician orogeny in central Newfoundland; a sediment provenance and U/Pb age study. Am. J. Sci. 292, 317–355.

Coney, P.J., 1978. Mesozoic-Cenozoic Cordilleran plate tectonics. In: Smith, R.B., Eaton, G.P. (Eds.), Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Geological Society of America Memoirs, 152. Geological Society of America, pp. 33–50. https://doi.org/10.1130/MEM152-p33.

Coney, P.J., Jones, D.L., Monger, J.W.H., 1980. Cordilleran suspect terranes. Nature 288, 329–333. https://doi.org/10.1038/288329a0.

Cooper, M.R., Crowley, Q.G., Hollis, S.P., Noble, S.R., Roberts, S., Chew, D., Earls, G., Herrington, R., Merriman, R.J., 2011. Age constraints and geochemistry of the Ordovician Tyrone Igneous Complex, Northern Ireland: implications for the Grampian orogeny. J. Geol. Soc. 168, 837–850. https://doi.org/10.1144/0016-76492010-164.

Cooper, R.A., Sadler, P.M., Hammer, O., Gradstein, F.M., 2012. The Ordovician period. In: Gradstein, F.M., Ogg, J.G., Schmidtz, M., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, Amsterdam, pp. 489–523.

Culshaw, N., Liesa, M., 1997. Alleghenian reactivation of the Acadian fold belt, Meguma zone, southwest Nova Scotia. Can. J. Earth Sci. 34, 833–847.

Culshaw, N.G., Reynolds, P., 1997. 40Ar/ 39Ar age of shear zones in the southwest Meguma Zone between Yarmouth and Meteghan, Nova Scotia. Can. J. Earth Sci. 34, 848–853.

Currie, K.L., 1995. The northeastern end of the Dunnage Zone in Newfoundland. Atl. Geol. 31 https://doi.org/10.4138/2096.

Dallmeyer, R.D., 1989. Terranes in the Circum-Atlantic Paleozoic Orogens. In: Geological Society of America Special Paper, 230. Geological Society of America.

Daly, J.S., 2009. Precambrian. In: Holland, C.H., Sanders, I.S. (Eds.), The Geology of Ireland. Dunedin, Edinburgh, pp. 7–42.

Daly, J.S., McLelland, J.M., 1991. Juvenile Middle Proterozoic crust in the Adirondack Highlands, Grenville province, northeastern North America. Geology 119–122.

Dalziel, I.W.D., 1997. Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Am. Bull. 109, 16–42. https://doi.org/10.1130/0016-7606(1997)109<0016:ONPGAT>2.3.CO;2.

Dalziel, I.W.D., Dewey, J.F., 2019. The classic Wilson cycle revisited. In: Wilson, R.W., Houseman, G.A., McCaffrey, K.J.W., Doré, A.G., Buiter, S.J.H. (Eds.), Fifty Years of the Wilson Cycle Concept in Plate Tectonics, Geological Society, London, Special Publications, vol. 470, pp. 19–38.

De Souza, S., Tremblay, A., Ruffet, G., 2014. Taconian orogenesis, sedimentation and magmatism in the southern Quebec–northern Vermont Appalachians: Stratigraphic and detrital mineral record of Iapetan suturing. Am. J. Sci. 314, 1065–1103.

Deutsch, E.R., 1969. Paleomagnetism and North Atlantic paleogeography. In: North Atlantic—Geology and Continental Drift. American Association of Petroleum Geologists Memoir. https://doi.org/10.1306/M12367C64.

Deutsch, E.R., 1980. Magnetism of the Mid-Ordovician Tramore Volcanics, SE Ireland, and the Question of a Wide Proto-Atlantic Ocean. J. Geomagn. Geoelectr. 32, SIII77–SIII98. https://doi.org/10.5636/jgg.32.Supplement3_SIII77.

Dewey, J.F., 1969. The evolution of the Caledonian/Appalachian orogen. Nature 222, 124–128.

Dewey, J.F., Bird, J.M., 1971. Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland. J. Geophys. Res. 76, 3179–3206.

Dewey, J.F., Casey, J.F., 2013. The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland. J. Geol. Soc. 170, 715–722.

Dewey, J.F., Ryan, P.D., 2016. Connemara; its position and role in the Grampian Orogeny. Can. J. Earth Sci. 53, 1246–1257. https://doi.org/10.1139/cjes-2015-0125.

Dewey, J.F., Shackleton, R.M., 1984. A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. Nature 312, 115–121.

Dewey, J.F., Strachan, R.A., 2003. Changing Silurian–Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. J. Geol. Soc. 160, 219–229. https://doi.org/10.1144/0016-764902-085.

Dietz, R.S., Holden, J.C., 1966. Miogeoclines (miogeosynclines) in space and time. J. Geol. 74, 566–583.

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

Dokken, R.J., Waldron, J.W.F., DuFrane, S.A., 2018. Detrital zircon geochronology of the Fredericton Trough: constraints on the Silurian closure of remnant Iapetus Ocean. Am. J. Sci. 318, 684–725.

Domeier, M., 2016. A plate tectonic scenario for the Iapetus and Rheic oceans. Gondwana Res. 36, 275–295. https://doi.org/10.1016/j.gr.2015.08.003.

Dorais, M.J., Wintsch, R.P., Becker, H., 2001. The Massabesic Gneiss Complex, New Hampshire: a study of a portion of the Avalon terrane. Am. J. Sci. 301, 657–682. https://doi.org/10.2475/ajs.301.7.657.

Dorais, M.J., Wintsch, R.P., Kunk, M.J., Aleinikoff, J., Burton, W., Underdown, C., Kerwin, C.M., 2012a. P-T-t conditions, Nd and Pb isotopic compositions and detrital zircon geochronology of the Massabesic Gneiss Complex, New Hampshire: isotopic and metamorphic evidence for the identification of Gander basement, central New England. Am. J. Sci. 312, 1049–1097. https://doi.org/10.2475/10.2012.01.

Dorais, M.J., Atkinson, M., Kim, J., West, D.P., Kirby, G.A., 2012b. Where is the Iapetus suture in northern New England? A study of the Ammonoosuc Volcanics, Bronson Hill terrane, New Hampshire. Can. J. Earth Sci. 49, 189–205. https://doi.org/10.1139/e10-108.

Dostal, J., Keppie, D.J., Jutras, P., Miller, B.V., Murphy, B.J., 2006. Evidence for the granulite-granite connection: Penecontemporaneous high-grade metamorphism, granitic magmatism and core complex development in the Liscomb Complex, Nova Scotia, Canada. Lithos 86, 77–90.

Dunning, G.R., O'Brien, S.J., 1989. Late Proterozoic - early Paleozoic crust in the Hermitage flexure, Newfoundland Appalachians: U-Pb ages and tectonic significance. Geology 17, 548–551.

Dunning, G.R., O'Brien, S.J., Colman-Sadd, S.P., Blackwood, R.F., Dickson, W.L., O'Neill, P.P., Krogh, T.E., 1990a. Silurian orogeny in the Newfoundland Appalachians. J. Geol. 98, 895–913.

Dunning, G.R., Barr, S.M., Raeside, R.P., Jamieson, R.A., 1990b. U-Pb zircon, titanite, and monazite ages in the Bras d'Or and Aspy terranes of Cape Breton Island, Nova Scotia; implications for igneous and metamorphic history. Geol. Soc. Am. Bull. 102, 322–330. https://doi.org/10.1130/0016-7606(1990)102<0322:upztam>2.3.co;2.

Dunning, G.R., Swinden, H.S., Kean, B.F., Evans, D.E., Jenner, G.A., 1991. A Cambrian island arc in Iapetus: geochemistry and geochronology of the Lake Ambrose Volcanic Belt, Newfoundland Appalachians. Geol. Mag. 128, 1–17.

Dunning, G.R., Barr, S.M., Giles, P.S., McGregor, D.C., Pe-Piper, G., Piper, D.J.W., 2002. Chronology of Devonian to Early Carboniferous rifting and igneous activity in southern Magdalen Basin based on U-Pb (zircon) dating. Can. J. Earth Sci. 39, 1219–1237.

Durling, P.W., Bell, J.S., Fader, G.B.J., 1987. The geological structure and distribution of Paleozoic rocks on the Avalon Platform, offshore Newfoundland. Can. J. Earth Sci. 24, 1412–1420.

Elmore, R.D., Muxworthy, A.R., Aldana, M., 2012. Remagnetization and chemical alteration of sedimentary rocks. In: Elmore, R.D., Muxworthy, A.R., Aldana, M.

(Eds.), Remagnetization and Chemical Alteration of Sedimentary Rocks, Geological Society, London, Special Publications, 371, pp. 1–21.

Escarraga, E.A., Barr, S.M., Murphy, J.B., Hamilton, M.A., 2012. Ordovician A-type plutons in the Antigonish Highlands, Nova Scotia11 This article is one of a series of papers published in CJES Special Issue: in honour of Ward Neale on the theme of Appalachian and Grenvillian geology. Can. J. Earth Sci. 49, 329–345. https://doi.org/10.1139/e11-026.

Escayola, M.P., van Staal, C.R., Davis, W.J., 2011. The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: an accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block. J. S. Am. Earth Sci. 32, 438–459. https://doi.org/10.1016/j.jsames.2011.04.013.

Ethington, R.L., 2008. Conodonts from the Margie Limestone in the Highland Border Complex, River North Esk. Scott. J. Geol. 44, 75–81. https://doi.org/10.1144/sjg44010075.

Fletcher, T.P., 2006. Bedrock Geology of the Cape St. Mary's Peninsula, Southwest Avalon Peninsula, Newfoundland (includes parts of NTS Map Sheets 1M/1, 1N/4, 1L/16 and 1K/13), Newfoundland and Labrador. Department of Natural Resources. Geological Survey, Report, 06–02.

Fletcher, T.R., Theokritoff, G., Lord, G.S., 2005. The early Paradoxidid harlani trilobite fauna of Massachusetts and its correlatives in Newfoundland, Morocco, and Spain. J. Paleontol. 79, 312–336.

Fyffe, L.R., 2014. The Grand Manan Terrane of New Brunswick: Tectonostratigraphy and relationship to the Gondwanan margin of the Iapetus Ocean. Geosci. Can. 483–502 https://doi.org/10.12789/geocanj.2014.41.051.

Fyffe, L.R., Riva, J., 1990. Revised stratigraphy of the Cookson Group of southwestern New Brunswick and adjacent Maine. Atl. Geol. 26, 271–276.

Fyffe, L.R., Barr, S.M., Johnson, S.C., McLeod, M.J., McNicoll, V.J., Valverde-Vaquero, P., van Staal, C.R., White, C.E., 2009. Detrital zircon ages from Neoproterozoic and Early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: implications for the tectonic evolution of Ganderia. Atl. Geol. 45, 110–144.

Fyffe, L.R., Johnson, S.C., van Staal, C.R., 2011. A review of Proterozoic to Early Paleozoic lithotectonic terranes in the northeastern Appalachian orogen of New Brunswick, Canada, and their tectonic evolution during Penobscot, Taconic, Salinic, and Acadian orogenesis. Atl. Geol. 47, 211–248.

Gerbi, C.C., Johnson, S.E., Aleinikoff, J.N., Bédard, J.H., Dunning, G.R., Fanning, C.M., 2006a. Early Paleozoic development of the Maine–Quebec Boundary Mountains region. Can. J. Earth Sci. 43, 367–389.

Gerbi, C.C., Johnson, S.E., Aleinikoff, J.N., 2006b. Origin and orogenic role of the Chain Lakes massif, Maine and Quebec. Can. J. Earth Sci. 43, 339–366. https://doi.org/10.1139/e05-112.

Geyer, G., 2020. A comprehensive Cambrian correlation chart. Episodes. https://doi.org/10.18814/epiiugs/2019/019026.

Gibbons, W., 1987. Menai Strait fault system; an early Caledonian terrane boundary in North Wales. Geology 15, 744–747.

Gibbons, W., Horak, J., 1990. Contrasting metamorphic terranes in Northwest Wales. Geol. Soc. Spec. Publ. 51, 315–327.

Gibbons, W., Mann, A., 1983. Pre-Mesozoic lawsonite in Anglesey, northern Wales; preservation of ancient blueschists. Geol. Boulder 11, 3–6.

Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), 2012. A Geologic Time Scale 2012. Elsevier, Amsterdam.

Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), 2020. Geologic Time Scale 2020. Elsevier, Amsterdam.

Graham, J.R., Stillman, C.J., 2022. Ordovician of the South. In: Holland, C.H., Saunders, I. (Eds.), The Geology of Ireland. Dunedin Academic Press, Edinburgh, pp. 103–117.

Greenly, E., 1919. The Geology of Anglesey, Geological Survey of Great Britain. Memoir, 1.

Greenough, J.D., Owen, J.V., Ruffman, A., 1993. Noble metal concentrations in shoshonitic lamprophyres: analysis of the Weekend Dykes, Eastern Shore, Nova Scotia, Canada. J. Petrol. 34, 1247–1269. https://doi.org/10.1093/petrology/34.6.1247.

Hall, B.A., 1970. Stratigraphy of the Southern End of the Munsungun Anticlinorium, Maine. Maine Geol. Surv. Bull. 22.

Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. J. Asian Earth Sci. 20, 353±431.

Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics 570–571, 1–41. https://doi.org/10.1016/j.tecto.2012.04.021.

Hamilton, M.A., Murphy, J.B., 2004. Tectonic significance of a Llanvirn age for the Dunn Point volcanic rocks, Avalon Terrane, Nova Scotia, Canada; implications for the evolution of the Iapetus and Rheic oceans. Tectonophysics 379, 199–209.

Harland, W.B., Gayer, R.A., 1972. The Arctic Caledonides and earlier oceans. Geol. Mag. 109, 289–314.

Henderson, B., 2016. What do epsilon hafnium isotopic arrays tell us about Wilson cycle tectonics? Implications for the type area in the Appalachian-Variscan Orogen (PhD thesis). University of Adelaide.

Henderson, B.J., Collins, W.J., Murphy, J.B., Gutierrez-Alonso, G., Hand, M., 2016. Gondwanan basement terranes of the Variscan–Appalachian orogen: Baltican, Saharan and West African hafnium isotopic fingerprints in Avalonia, Iberia and the Armorican Terranes. Tectonophysics 681, 278–304. https://doi.org/10.1016/j.tecto.2015.11.020.

Henderson, B.J., Collins, W.J., Murphy, J.B., Hand, M., 2018. A hafnium isotopic record of magmatic arcs and continental growth in the Iapetus Ocean: The contrasting evolution of Ganderia and the peri-Laurentian margin. Gondwana Res. 58, 141–160. https://doi.org/10.1016/j.gr.2018.02.015.

Hepburn, J.C., Dunning, G.R., Hon, R., 1995. Geochronology and regional tectonic implications of Silurian deformation in the Nashoba Terrane, Southeastern New England, U.S.A. In: Hibbard, J.P., Van Staal, C.R., Cawood, P.A. (Eds.), Current Perspectives in the Appalachian-Caledonian Orogen, Geological Association of Canada Special Paper, 41, pp. 349–366.

Hepburn, J.C., Kuiper, Y.D., McClary, K.J., Loan, M.L., Tubrett, M., Buchwaldt, R., 2021. Detrital zircon ages and the origins of the Nashoba terrane and Merrimack belt in southeastern New England, USA. Atl. Geosci. 57, 343–396. https://doi.org/10.4138/atlgeol.2021.016.

Herbosch, A., Verniers, J., 2011. What is the biostratigraphic value of the ichnofossil Oldhamia for the Cambrian; a review. Geol. Belg. 14, 229–248.

Hibbard, J., 1994. Kinematics of Acadian deformation in the Northern and Newfoundland Appalachians. J. Geol. 102, 215–228.

Hibbard, J., Hall, S., 1993. Early Acadian sinistral shear in north-central Maine, USA. J. Geol. Soc. 150, 815–818. https://doi.org/10.1144/gsjgs.150.5.0815.

Hibbard, J., Waldron, J.W.F., 2009. Truncation and translation of Appalachian promontories: mid-Paleozoic strike-slip tectonics and basin initiation. Geology 37, 487–490. https://doi.org/10.1130/G25614A.1.

Hibbard, J.P., van Staal, C.R., Rankin, D.W., Williams, H., 2006. Lithotectonic Map of the Appalachian Orogen, Canada–United States of America. Geological Survey of Canada Map, 2096A, scale 1: 500 000.

Hibbard, J.P., Van Staal, C.R., Rankin, D.W., 2007. A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen. Am. J. Sci. 307, 23–45. https://doi.org/10.2475/01.2007.02.

Hicks, R.J., Jamieson, R.A., Reynolds, P.H., 1999. Detrital and metamorphic $^{40}$Ar/$^{39}$Ar ages from muscovite and whole-rock samples, Meguma Supergroup, southern Nova Scotia. Can. J. Earth Sci. 36, 23–32.

Hildebrand, R.S., Whalen, J.B., 2021. Arc and slab-failure magmatism of the Taconic Orogeny, western New England, USA. In: Murphy, J.B., Strachan, R.A., Quesada, C. (Eds.), Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region, Geological Society, London, Special Publications, vol. 503, pp. 409–422.

Hillenbrand, I.W., Williams, M.L., Li, C., Gao, H., 2021. Rise and fall of the Acadian altiplano: evidence for a Paleozoic orogenic plateau in New England. Earth Planet. Sci. Lett. 560, 116797 https://doi.org/10.1016/j.epsl.2021.116797.

Hodych, J.P., Bijaksana, S., 1993. Can remanence anisotropy detect paleomagnetic inclination shallowing due to compaction? A case study using Cretaceous deep-sea limestones. J. Geophys. Res. 98, 429. https://doi.org/10.1029/93JB02022.

Hodych, J.P., Buchan, K.L., 1998. Palaeomagnetism of the ca. 440 Ma Cape St Mary's sills of the Avalon Peninsula of Newfoundland: implications for Iapetus Ocean closure. Geophys. J. Int. 135, 155–164.

Hogan, J.P., Sinha, A.K., 1989. Compositional variation of plutonism in the coastal Maine magmatic province; mode of origin and tectonic setting. In: Tucker, R.D. (Ed.), Studies in Maine Geology, 4. Maine Geological Survey, Augusta, ME, pp. 1–33.

Holdsworth, R.E., 1994. Structural evolution of the Gander-Avalon terrane boundary: a reactivated transpression zone in the NE Newfoundland Appalachians. J. Geol. Soc. 151, 629–646. https://doi.org/10.1144/gsjgs.151.4.0629.

Horne, R.J., Dunning, G.R., Jamieson, R.A., 2003. U-Pb age date for the Belle Côte Road orthogneiss, Taylors Barren pluton, and Bothan Brook pluton, southern Cape Breton Highlands (NTS 11K/10, 11K/11): igneous ages and constrains on the age of host and deformational history. In: Mineral Resources Branch, Report of Activities 2002. Nova Scotia Department of Natural Resources Report, 2003–1, pp. 57–68.

Hughes, C.J., 1970. The Late Precambrian Avalonian Orogeny in Avalon, southeast Newfoundland. Am. J. Sci. 269, 183–190.

Hussey, A.M., Berry, H.N., 2002. Bedrock Geology of the Bath 1:100,000 Map Sheet, Coastal Maine, Maine Geological Survey Bulletin, p. 42.

Hussey, A.M., Marvinney, R.G., 2002. Bedrock geology of the Bath 1:100000 quadrangle, Maine. In: Maine Geological Survey Map, 02-152 scale 1:100,000.

Hussey, A.M., Bothner, W.A., Aleinikoff, J., 2010. The tectono-stratigraphic framework and evolution of southwestern Maine and southeastern New Hampshire. In: From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region. Geological Society of America. https://doi.org/10.1130/2010.1206(10.

Hutton, D.H.W., Dewey, J.F., 1986. Palaeozoic terrane accretion in the western Irish Caledonides. Tectonics 5, 1115–1124.

Israel, S.A., 1998. Geochronological, Structural, and Stratigraphic Investigstion of a Precambrian Unconformity between the Harbour Main Group and Conception Group, East Coast Holyrood Bay, Avalon Peninsula. Newfoundland (B.Sc thesis). Memorial University of Newfoundland, St. John's NL.

James, N.P., Stevens, R.K., Barnes, C.R., Knight, I., 1989. Evolution of a lower Paleozoic continental-margin carbonate platform, northern Canadian Appalachians. In: Crevello, P.D., Wilson, J.J., Sarg, J.F., Read, J. Fred (Eds.), Controls on Carbonate Platform and Basin Development, Special Publication Society of Economic Paleontologists and Mineralogists, pp. 123–146.

Jenner, G.A., Dunning, G.R., Malpas, J., Brown, M., Brace, T., 1991. Bay of Islands and Little Port complexes, revisited: age, geochemical and isotopic evidence confirm suprasubduction-zone origin. Can. J. Earth Sci. 28, 1635–1652. https://doi.org/10.1139/e91-146.

Jin, J., Harper, D.A.T., Cocks, L.R.M., McCausland, P.J.A., Rasmussen, C.M.O., Sheehan, P.M., 2013. Precisely locating the Ordovician equator in Laurentia. Geology 41, 107–110. https://doi.org/10.1130/G33688.1.

Johnson, S.C., 2001. Contrasting geology in the Pocologan River and Long Reach areas: implications for the New River belt and correlations in southern New Brunswick and Maine. Atl. Geol. 37 https://doi.org/10.4138/1972.

Johnson, S.C., Barr, S.M., 2004. New chemical data from Precambrian – Cambrian igneous rocks in the Long Reach area, southern New Brunswick. In: Martin, G.L. (Ed.), Geological Investigations in New Brunswick for 2003. New Brunswick Department of Natural Resources, Minerals, Policy and Planning Division, pp. 75–94. Mineral Resource Report, 2004–4.

Johnson, S.C., McLeod, M.J., 1996. The New River Belt; a unique segment along the western margin of the Avalon composite terrane, southern New Brunswick, Canada. Spec. Pap. Geol. Soc. Am. 304, 149–164.

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 the Late Ordovician-Early Silurian Dunn Point volcanics, Nova Scotia. Tectonophysics 178, 193–205. https://doi.org/10.1016/0040-1951(90)90146-Y.

Johnson, S.C., Fyffe, L.R., McLeod, M.J., Dunning, G.R., 2012. U–Pb ages, geochemistry, and tectonomagmatic history of the Cambro-Ordovician Annidale Group: a remnant of the Penobscot arc system in southern New Brunswick? Can. J. Earth Sci. 49, 166–188. https://doi.org/10.1139/e11-031.

Johnson, S.C., Dunning, G.R., Miller, B.V., 2018. U-Pb geochronology and geochemistry from the northeastern New River belt, southern New Brunswick, Canada: significance of the Almond Road Group to the Ganderian platformal margin. Atl. Geol. 54, 147–170.

Jutras, P., Murphy, J.B., Quick, D., Dostal, J., 2020. Evolution of subduction dynamics beneath West Avalonia in Middle to Late Ordovician Times. Lithosphere 2020. https://doi.org/10.2113/2020/8837633, 8837633.

Karabinos, P., Samson, S.D., Hepburn, J.C., Stoll, H.M., 1998. Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc. Geology 26, 215–218.

Karabinos, P., Macdonald, F.A., Crowley, J.L., 2017. Bridging the gap between the foreland and hinterland I: geochronology and plate tectonic geometry of Ordovician magmatism and terrane accretion on the Laurentian margin of New England. Am. J. Sci. 317, 515–554. https://doi.org/10.2475/05.2017.01.

Kay, M., 1951. North American Geosynclines. In: Geological Society of America Memoir, p. 48.

Kay, A., Hepburn, J.C., Kuiper, Y.D., Baxter, E.F., 2017. Geochemical evidence for a Ganderian arc/back-arc remnant in the Nashoba Terrane, SE New England, USA. Am. J. Sci. 317, 413–448. https://doi.org/10.2475/04.2017.01.

Kellett, D.A., Rogers, N., McNicoll, V., Kerr, A., van Staal, C., McFarlane, C., 2014. New age data refine extent and duration of Paleozoic and Neoproterozoic plutonism at Ganderia–Avalonia boundary, Newfoundland. Can. J. Earth Sci. 51, 943–972. https://doi.org/10.1139/cjes-2014-0090.

Kellett, D.A., Warren, C., Larson, K.P., Zwingmann, H., van Staal, C.R., Rogers, N., 2016. Influence of deformation and fluids on Ar retention in white mica: Dating the Dover Fault, Newfoundland Appalachians. Lithos 254–255, 1–17. https://doi.org/10.1016/j.lithos.2016.03.003.

Kennan, P.S., Kennedy, M.J., 1983. Coticules - a key to correlation along the Appalachian-Caledonian Orogen. In: Schenk, P.E. (Ed.), Regional Trends in the Geology of the Appalachian-Caledonian-Hercynian-Mauretanide Orogen, NATO Advanced Study Institute Series C, pp. 355–361.

Kennedy, M.J., 1979. The continuation of the Canadian Appalachians into the Caledonides of Britain and Ireland. In: Harris, A.L., Holland, C.H., Leake, B.E. (Eds.), The Caledonides of the British Isles – Reviewed, Geological Society Special Publication, vol. 8, pp. 33–64.

Keppie, J.D., 1993. Synthesis of Paleozoic deformational events and terrane accretion in the Canadian Appalachians. Geol. Rundsch. 82, 381–431.

Keppie, J.D., Murphy, J.B., 1988. Anatomy of a telescoped pull-apart basin; an example from the Cambro-Ordovician rocks in the Antigonish Highlands of Nova Scotia. Marit. Sediments Atl. Geol. 24, 123–138.

Keppie, J.D., Shellnutt, J., Dostal, J., Keppie, D.F., 2018. An autochthonous Avalonian basement source for the latest Ordovician Brenton Pluton in the Meguma terrane of Nova Scotia: U–Pb–Hf isotopic constraints and paleogeographic implications. Int. J. Earth Sci. 107, 955–969. https://doi.org/10.1007/s00531-017-1495-4.

Kerr, A., Jenner, G.A., Fryer, B.J., 1995. Sm-Nd isotopic geochemistry of Precambrian to Paleozoic granitoid suites and the deep-crustal structure of the southeast margin of the Newfoundland Appalachians. Can. J. Earth Sci. 32, 224–245. https://doi.org/10.1139/e95-019.

Schoonmaker, A., Kidd, W.S.F., 2006. Evidence for a ridge subduction event in the Ordovician rocks of north-central Maine. Geol. Soc. Am. Bull. 118, 897–912. https://doi.org/10.1130/B25867.1.

Kim, J., Jacobi, R.D., 1996. Geochemistry and tectonic implications of Hawley Formation meta-igneous units. Am. J. Sci. 296, 1126–1174.

King, L.M., 1994. Subsidence analysis of Eastern Avalonian sequences: implications for Iapetus closure. J. Geol. Soc. 151, 647–657.

King, L.H., Fader, G.J., Jenkins, W.A.M., King, E.L., 1986. Occurrence and regional geological setting of Paleozoic rocks on the Grand Banks of Newfoundland. Can. J. Earth Sci. 23, 504–526.

Knight, I., James, N.P., Lane, T.E., 1991. The Ordovician St. George Unconformity, northern Appalachians: the relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe sequence boundary. Geol. Soc. Am. Bull. 103, 1200–1225.

Kokelaar, P., 1988. Tectonic controls of Ordovician arc and marginal basin volcanism in Wales. J. Geol. Soc. 145, 759–775.

Krabbendam, M., Leslie, A.G., Crane, A., Goodman, S., 1997. Generation of the Tay Nappe, Scotland, by large-scale SE-directed shearing. J. Geol. Soc. 154, 15–24. https://doi.org/10.1144/gsjgs.154.1.0015.

Krabbendam, M., Bonsor, H., Horstwood, M.S.A., Rivers, T., 2017. Tracking the evolution of the Grenvillian foreland basin: Constraints from sedimentology and detrital zircon and rutile in the Sleat and Torridon groups, Scotland. Precambrian Res. 295, 67–89. https://doi.org/10.1016/j.precamres.2017.04.027.

Krzywinsky, M., 2022. Designing for Color Blindness [WWW Document]. Des. Color Blind. URL. http://mkweb.bcgsc.ca/colorblind/palettes.mhtml#page-container.

Kuiper, Y.D., Hepburn, J.C., 2021. Detrital zircon populations of the eastern Laurentian margin in the Appalachians. Geology 49, 233–237.

Kuiper, Y.D., Thompson, M.D., Barr, S.M., White, C.E., Hepburn, J.C., Crowley, J.L., 2017. Detrital zircon evidence for Paleoproterozoic West African crust along the eastern North American continental margin, Georges Bank, offshore Massachusetts, USA. Geology 45, 811–814. https://doi.org/10.1130/G39203.1.

Kuiper, Y.D., Murray, D.P., Ellison, S., Crowley, J.L., 2022. U-Pb detrital zircon analysis of sedimentary rocks of the southeastern New England Avalon terrane in the U.S. Appalachians: Evidence for a separate crustal block. 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. https://doi.org/10.1130/2021.2554(05).

Kusky, T.M., Chow, J.S., Bowring, S.A., 1997. Age and origin of the Boil Mountain ophiolite and Chain Lakes massif, Maine: implications for the Penobscottian orogeny. Can. J. Earth Sci. 34, 646–654.

Landing, E., 1988. Lower Cambrian of Eastern Massachusetts: stratigraphy and small Shelly Fossils. J. Paleontol. 62, 661–695.

Landing, E., 1994. Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. Geology 22, 179–182.

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., 2004. Precambrian–Cambrian boundary interval deposition and the marginal platform of the Avalon microcontinent. J. Geodyn. 37, 411–435. https://doi.org/10.1016/j.jog.2004.02.014.

Landing, E., 2005. Early Paleozoic Avalon-Gondwana unity: an obituary - response to “Palaeontological evidence bearing on global Ordovician-Silurian continental reconstructions” by R.A. Fortey and L.R.M. Cocks. Earth-Sci. Rev. 69, 169–175.

Landing, E., 2007. Ediacaran-Ordovician of East Laurentia; S. W. Ford Memorial Volume, Bulletin - New York State Museum, 510. University of The State of New York, State Education Department, Albany, NY, United States, United States.

Landing, E., 2012. The Great American Carbonate Bank in Eastern LaurentiaIts Births, Deaths, and Linkage to Paleooceanic Oxygenation (Early Cambrian–Late Ordovician). In: Derby, J., Fritz, R., Longacre, S., Morgan, W., Sternbach, C. (Eds.), Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian—Ordovician Sauk Megasequence of Laurentia, American Association of Petroleum Geologists Memoir, vol. 98. American Association of Petroleum Geologists, pp. 451–492. https://doi.org/10.1306/13331502M983502.

Landing, E., Murphy, J.B., 1991. Uppermost Precambrian(?)-Lower Cambrian of mainland Nova Scotia; faunas, depositional environments, and stratigraphic revision. J. Paleontol. 65, 382–396.

Landing, E., Westrop, S.R., 2004. Environmental patterns in the origin and diversification loci of Early Cambrian skeletalized Metazoa: Evidence from the Avalon microcontinent. Paleontol. Soc. Pap. 10, 93–106. https://doi.org/10.1017/S1089332600002369.

Landing, E., Bowring, S.A., Davidek, K.L., Westrop, S.R., Gayer, G., Heldmaier, W., 1998. Duration of the Early Cambrian: U-Pb ages of volcanic ashes from Avalon and Gondwana. Can. J. Earth Sci. 35, 329–338.

Landing, E., Johnson, S.C., Geyer, G., 2008. Faunas and Cambrian volcanism on the Avalonian marginal platform, southern New Brunswick. J. Paleontol. 82, 884–905. https://doi.org/10.1666/07-007.1.

Landing, E., Amati, L., Franzi, D.A., 2009. Epeirogenic transgression near a triple junction: the oldest (latest early–middle Cambrian) marine onlap of cratonic New York and Quebec. Geol. Mag. 146, 552–566. https://doi.org/10.1017/S0016756809006013.

Landing, E., Myrow, P.M., Narbonne, G.M., Geyer, G., Buatois, L.A., Mángano, M.G., Kauffman, A., Westrop, S.R., Kröger, B., Laing, B., Gougeon, R., 2017. Ediacaran–Cambrian of Avalonian Eastern Newfoundland (Avalon, Burin, and Bonavista Peninsulas). In: International Symposium on the Ediacaran–Cambrian Transition, Field Trip 4, Newfoundland Department of MInes and Energy, Geological Survey Branch, Open File.

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, 103863. https://doi.org/10.1016/j.earscirev.2021.103863.

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.

Lerouge, C., Cocherie, A., Toteu, S.F., Penaye, J., Milesi, J.P., Tchameni, R., Nsifa, E.N., Fanning, C.M., Deloule, E., 2006. Shrimp U-Pb zircon age evidence for Paleoproterozoic sedimentation and 2.05 Ga syntectonic plutonism in the Nyong Group, south-western Cameroon; consequences for the Eburnean-Transamazonian belt of NE Brazil and Central Africa. J. Afr. Earth Sci. 44, 413–427.

Leslie, A.G., Smith, M., Soper, N.J., 2008. Laurentian margin evolution and the Caledonian orogeny— A template for Scotland and East Greenland. In: Higgins, A.K., Gilotti, J.A., Smith, M.P. (Eds.), The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia, Geological Society of America Memoir, vol. 202, pp. 307–343.

Lin, S., Davis, D.W., Barr, S.M., Van Staal, C.R., Chen, Y., Constantin, M., 2007. U-Pb geochronological constraints on the evolution of the Aspy Terrane, Cape Breton Island: implications for relationships between Aspy and Bras d'Or terranes and Ganderia In the Canadian Appalachians. Am. J. Sci. 307, 371–398. https://doi.org/10.2475/02.2007.03.

Linnemann, U., Pereira, F., Jeffries, T.E., Drost, K., Gerdes, A., 2008. The Cadomian Orogeny and the opening of the Rheic Ocean: The diacrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). Tectonophysics 461, 21–43.

Linnemann, U., Gerdes, A., Hofmann, M., Marko, L., 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—Constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Res. 244, 236–278. https://doi.org/10.1016/j.precamres.2013.08.007.

Liss, M.J., 1993. Avalonian Proximity of the Ordovician Miramichi Terrane, Northern New Brunswick, Northern Appalachians: Paleomagnetic Evidence for Rifting and Back-Arc Basin Formation at the Southern Margin of Iapetus, p. 14.

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.

Lode, S., Piercey, S.J., Cloutier, J., 2017. Provenance of exhalites associated with the Lemarchant volcanogenic massive sulphide (VMS) deposit, central Newfoundland, Canada: insights from Nd isotopes and lithogeochemistry. J. Geol. Soc. 174, 954–967. https://doi.org/10.1144/jgs2017-008.

Lowe, D.G., Arnott, R.W.C., Chiarenzelli, J.R., Rainbird, R.H., 2018. Early Paleozoic rifting and reactivation of a passive-margin rift: Insights from detrital zircon provenance signatures of the Potsdam Group, Ottawa graben. GSA Bull. 130, 1377–1396. https://doi.org/10.1130/B31749.1.

Ludman, A., Hopeck, J., Berry Iv, H.N., 2017. Provenance and paleogeography of post-Middle Ordovician, pre-Devonian sedimentary basins on the Gander composite terrane, eastern and east-central Maine: implications for Silurian tectonics in the northern Appalachians. Atl. Geol. 53, 63–85. https://doi.org/10.4138/atlgeol.2017.003.

Ludman, A., Aleinikoff, J., Berry IV, H.N., Hopeck, J.T., 2018. SHRIMP U–Pb zircon evidence for age, provenance, and tectonic history of early Paleozoic Ganderian rocks, east-central Maine, USA. Atl. Geol. 335–387 https://doi.org/10.4138/atlgeol.2018.012.

Mac Niocaill, C., 2000. A new Silurian palaeolatitude for eastern Avalonia and evidence for crustal rotations in the Avalonian margin of southwestern Ireland. Geophys. J. Int. 141, 661–671.

Mac Niocaill, C., Van der Pluijm, B.A., Van der Voo, R., 1997. Ordovician paleogeography and the evolution of the lapetus ocean. Geology 25, 159–162.

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, 539–542. https://doi.org/10.1130/G35659.1.

Macdonald, F.A., Karabinos, P.M., Crowley, J.L., Hodgin, E.B., Crockford, P.W., Delano, J.W., 2017. Bridging the gap between the foreland and hinterland II: geochronology and tectonic setting of Ordovician magmatism and basin formation on the Laurentian margin from New England to Newfoundland. Am. J. Sci. 317, 555–596.

Mange, M.A., Dewey, J.F., Floyd, J.D., 2005. The origin, evolution and provenance of the Northern Belt (Ordovician) of the Southern Uplands Terrane, Scotland: a heavy mineral perspective. Proc. Geol. Assoc. 116, 251–280.

Massey, M.A., Moecher, D.P., Walker, T.B., O'Brien, T.M., Rohrer, L.P., 2017. The role and extent of dextral transpression and lateral escape on the post-Acadian tectonic evolution of south-central New England. Am. J. Sci. 317, 34–94. https://doi.org/10.2475/01.2017.02.

Massonne, H.-J., Barr, S.M., White, C.E., Miller, B.V., 2018. The Pocologan metamorphic suite of southern New Brunswick, Canada: New constraints on age and conditions of medium- to high-pressure metamorphism on the Ganderian margin of the Rheic Ocean. Tectonophysics 747–748, 177–190. https://doi.org/10.1016/j.tecto.2018.09.006.

Matthews, M., Robinson, A., 2018. Newfoundland Mi'kmaq Place Names. Across the Waters, Qalipu First Nation, Corner Brook NL, Ktaqmkuk.

McCabe, C., Channell, J.E.T., 1990. Paleomagnetic results from volcanic rocks of the Shelve Inlier, Wales: evidence for a wide Late Ordovician Iapetus Ocean in Britain. Earth Planet. Sci. Lett. 96, 458–468. https://doi.org/10.1016/0012-821X(90)90020-X.

McCabe, C., Channell, J.E.T., Woodcock, N.H., 1992. Further paleomagnetic results from the Builth Wells Ordovician Inlier, Wales. J. Geophys. Res. Solid Earth 97, 9357–9370. https://doi.org/10.1029/92JB00638.

McCarron, T., 2020. Petrology and Geochronology of an Inverted Metamorphic Sequence in the Western Cape Breton Highlands, Nova Scotia (Ph.D. thesis). University of New Brunswick, Fredericton, New Brunswick.

McCausland, P.J.A., Van der Voo, R., Hall, C.M., 2007. Circum-Iapetus paleogeography of the Precambrian-Cambrian transition with a new paleomagnetic constraint from Laurentia. Precambrian Res. 156, 125–152. https://doi.org/10.1016/j.precamres.2007.03.004.

McCausland, P.J.A., Hankard, F., Van der Voo, R., Hall, C.M., 2011. Ediacaran paleogeography of Laurentia; paleomagnetism and $^{40}$Ar/ $^{39}$Ar geochronology of the 583 Ma Baie des Moutons Syenite, Quebec. Precambrian Res. 187, 58–78. https://doi.org/10.1016/j.precamres.2011.02.004.

McConnell, B., Gatley, S., 2006. Bedrock Geological Map of Ireland. Geological Survey of Ireland, Dublin scale 1:500,000.

McConnell, B., Riggs, N., Crowley, Q.G., 2009. Detrital zircon provenance and Ordovician terrane amalgamation, western Ireland. J. Geol. Soc. 166, 473–484. https://doi.org/10.1144/0016-76492008-081.

McConnell, B., Crowley, Q.G., Riggs, N., 2010. Laurentian origin of the Ordovician Grangegeeth volcanic arc terrane, Ireland. J. Geol. Soc. 167, 469–474. https://doi.org/10.1144/0016-76492009-139.

McConnell, B., Parkes, M., Crowley, Q., Rushton, A., 2015. No exploits back-arc basin in the Iapetus suture zone of Ireland. J. Geol. Soc. 172, 740–747.

McConnell, B., Rogers, R., Crowley, Q., 2016. Sediment provenance and tectonics on the Laurentian margin: implications of detrital zircons ages from the Central Belt of the Southern Uplands–Down–Longford Terrane in Co. Monaghan, Ireland. Scott. J. Geol. 52, 11–17. https://doi.org/10.1144/sjg2015-013.

McConnell, B., Riggs, N., Sevastopulo, G., 2019. Insight into late Iapetus tectonics from new U–Pb zircon and micropalaeontological data from the Navan area, eastern Ireland. J. Geol. Soc. 176, 440–446. https://doi.org/10.1144/jgs2018-168.

McIlroy, D., Horak, J.M., 2006. Neoproterozoic; the late Precambrian terranes that formed eastern Avalonia. In: Brenchley, P.J., Rawson, P.F. (Eds.), The Geology of England and Wales. The Geological Society, London, pp. 9–23.

McKerrow, W.S., Leggett, J.K., Eales, M.H., 1977. Imbricate thrust model of the Southern Uplands of Scotland. Nature 267, 237–239.

McLennan, S.M., Bock, B., Compston, W., Hemming, S.R., McDaniel, D.K., 2001. Detrital zircon geochronology of Taconian and Acadian foreland sedimentary rocks in New England. J. Sediment. Res. 71, 305–317.

McLeod, M.J., Ruitenberg, A.A., Krogh, T.E., 1992. Geology and U-Pb geochronology of the Annidale Group, southern New Brunswick: Lower Ordovician volcanic and sedimentary rocks formed near the southeastern margin of Iapetus Ocean. Atl. Geol. 28, 181–192.

McNicoll, van Staal, C.R., Lentz, D.R., Stern, R.A., 2002. Uranium-lead geochronology of Middle River rhyolite: implications for the provenance of basement rocks of the Bathurst mining camp, New Brunswick. Geol. Surv. Can. Curr. Res. 2002-F9, 1–11. Radiogenic Age and Isotopic Studies 2002-F9.

Meert, J.G., Pivarunas, A.F., Evans, D.A.D., Pisarevsky, S.A., Pesonen, L.J., Li, Z.-X., Elming, S.-Å., Miller, S.R., Zhang, S., Salminen, J.M., 2020. The magnificent seven: A proposal for modest revision of the Van der Voo (1990) quality index. Tectonophysics 790, 228549. https://doi.org/10.1016/j.tecto.2020.228549.

Miles, A.J., Woodcock, N.H., Hawkesworth, C.J., 2016. Tectonic controls on post-subduction granite genesis and emplacement: the late Caledonian suite of Britain and Ireland. Gondwana Res. 39, 250–260. https://doi.org/10.1016/j.gr.2016.02.006.

Miller, B.V., Barr, S.M., 2000. Petrology and isotopic composition of the Grenvillian Basement Fragment in the Northern Appalachian Orogen: Blair River Inlier, Nova Scotia, Canada. J. Petrol. 41, 1777–1804.

Miller, B.V., Barr, S.M., 2004. Metamorphosed gabbroic dikes related to opening of Iapetus Ocean at the St. Lawrence Promontory: Blair River Inlier, Nova Scotia, Canada. J. Geol. 112, 277–288. https://doi.org/10.1086/382759.

Miller, B.V., Fyffe, L.R., 2002. Geochronology of the Letete and Waweig formations, Mascarene Group, southwestern New Brunswick. Atl. Geol. 38, 29–36.

Miller, B.V., Dunning, G.R., Barr, S.M., Raeside, R.P., Jamieson, R.A., Reynolds, P.H., 1996. Magmatism and metamorphism in a Grenvillian fragment; U-Pb and $^{40}$Ar/$^{39}$Ar ages from the Blair River Complex, northern Cape Breton Island, Nova Scotia, Canada. Geol. Soc. Am. Bull. 108, 127–140.

Miller, B.V., Barr, S.M., Tesfai, F., White, C.E., 2018. Tonian Fe-Ti-P ferronorite and alkali anorthosite in the northern Appalachian orogen, southern New Brunswick, Canada: Amazonian basement in Ganderia? Precambrian Res. 317, 77–88. https://doi.org/10.1016/j.precamres.2018.08.006.

Mills, A.J., Dunning, G.R., Sandeman, H.A., 2021. Lithogeochemical, isotopic, and U–Pb (zircon) age constraints on arc to rift magmatism, northwestern and central Avalon Terrane, Newfoundland, Canada: implications for local lithostratigraphy. Can. J. Earth Sci. 58, 332–354. https://doi.org/10.1139/cjes-2019-0196.

Moench, R.H., Aleinikoff, J.N., 2003. Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England. Phys. Chem. Earth 28, 113–160.

Mueller, P.A., Heatherington, A.L., Wooden, J.L., Shuster, R.D., Nutman, A.P., Williams, I.S., 1994. Precambrian zircons from the Florida basement: a Gondwanan connection. Geology 22, 119–122.

Mueller, P.A., Heatherington, A.L., Foster, D.A., Thomas, W.A., Wooden, J.L., 2013. The Suwannee suture: significance for Gondwana-Laurentia terrane transfer and formation of Pangaea. Gondwana Res. https://doi.org/10.1016/j.gr.2013.06.018.

Müller, R.D., Cannon, J., Qin, X., Watson, R.J., Gurnis, M., Williams, S., Pfaffelmoser, T., Seton, M., Russell, S.H.J., Zahirovic, S., 2018. GPlates: building a virtual Earth through deep time. Geochem. Geophys. Geosyst. 19, 2243–2261. https://doi.org/10.1029/2018GC007584.

Murphy, J.B., Nance, R.D., 2002. Sm-Nd isotopic systematics as tectonic tracers; an example from West Avalonia in the Canadian Appalachians. Earth-Sci. Rev. 59, 77–100.

Murphy, J.B., Fernández-Suárez, J., Keppie, J.D., Jeffries, T.E., 2004a. Contiguous rather than discrete Paleozoic histories for the Avalon and Meguma terranes based on detrital zircon data. Geology 32, 585–588.

Murphy, J.B., Fernandez-Suarez, J., Jeffries, T.E., 2004b. Lithogeochemical and Sm-Nd and U-Pb isotope data from the Silurian-Lower Devonian Arisaig Group clastic rocks, Avalon terrane, Nova Scotia: a record of terrane accretion in the Appalachian-Caledonide orogen. Geol. Soc. Am. Bull. 116, 1183–1201.

Murphy, J.B., Fernandez-Suarez, J., Jeffries, T.E., Strachan, R.A., 2004c. U–Pb (LA–ICP-MS) dating of detrital zircons from Cambrian clastic rocks in Avalonia: erosion of a Neoproterozoic arc along the northern Gondwanan margin. J. Geol. Soc. Lond. 161, 243–254.

Murphy, J.B., McCausland, P.J.A., O'Brien, S.J., Pisarevsky, S., Hamilton, M.A., 2008. Age, geochemistry and Sm–Nd isotopic signature of the 0.76 Ga Burin Group: compositional equivalent of Avalonian basement? Precambrian Res. 165, 37–48. https://doi.org/10.1016/j.precamres.2008.05.006.

Murphy, J.B., Waldron, J.W.F., Kontak, D., Pe-Piper, G., Piper, D.J.W., 2011. Minas Fault Zone: late Paleozoic history of an intra-continental orogenic transform fault in the Canadian Appalachians. J. Struct. Geol. 33, 312–328.

Murphy, J.B., Waldron, J.W.F., Schofield, D.I., Barry, T.L., Band, A.R., 2014. Depleted isotopic compositions evident in Iapetus and Rheic ocean basalts: implications for crustal generation and preservation. Int. J. Earth Sci. 103, 1219–1232.

Murphy, J.B., Nance, R.D., Cawood, P.A., Collins, W.J., Dan, W., Doucet, L.S., Heron, P. J., Li, Z.-X., Mitchell, R.N., Pisarevsky, S., Pufahl, P.K., Quesada, C., Spencer, C.J., Strachan, R.A., Wu, L., 2020. Pannotia: in Defence of Its Existence and Geodynamic Significance. In: Geol. Soc. Lond. Spec. Publ. SP503-2020–96. https://doi.org/10.1144/SP503-2020-96.

Nance, D., Dallmeyer, R.D., 1993. 40Ar/39Ar amphibole ages from the Kingston Complex, New Brunswick: evidence of Silurian-Devonian tectonothermal activity and implications for the accretion of the Avalon composite terrane. J. Geol. Chic. 101, 375–388.

Nance, R.D., Murphy, J.B., 1994. Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens; example from the Neoproterozoic Avalonian-Cadomian Belt. Geology 22, 617–620.

Nance, R.D., Murphy, J.B., 1996. Basement isotopic signatures and Neoproterozoic paleogeography of Avalonian-Cadomian and related terranes in the Circum-North Atlantic. In: Nance, R.D., Thompson, M.D. (Eds.), Special Paper - Geological Society of America, pp. 333–346.

Nance, D., Thompson, M.D. (Eds.), 1996. Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. Geological Society of America Special Paper, 304. The Geological Society of America, Boulder, Colo.

Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutierrez Alonso, G., Fernandez Suarez, J., Quesada, C., Linnemann, U., d'Lemos, R., Pisarevsky, S.A., 2008. Neoproterozoic-early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes; Amazonian v. West African connections. In: Ennih, N., Liégeois, J.-P. (Eds.), The Boundaries of the West African Craton, Geological Society of London Special Publication, pp. 345–383.

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. Gondwana Res. 17, 194–222. https://doi.org/10.1016/j.gr.2009.08.001.

Narbonne, G.M., Myrow, P.M., Landing, E., Anderson, M.M., 1987. A candidate stratotype for the Precambrian- Cambrian boundary, Fortune Head, Burin Peninsula, southeastern Newfoundland. Can. J. Earth Sci. 24, 1277–1293.

Neuman, R.B., 1967. Bedrock Geology of the Shin Pond and Stacyville Quadrangles, Penobscot County, Maine, United States Geological Survey. Professional Paper, 524–1.

Neuman, R.B., 1984. Geology and paleobiology of islands in the Ordovician Iapetus Ocean: review and implications. Geol. Soc. Am. Bull. 95, 1188–1201.

Neuman, R.B., 1987. Type section of the Early Ordovician Shin Brook Formation and evidence of the Penobscot orogeny, northern Penobscot County, Maine. In: Roy, D.C. (Ed.), Centennial Field Guide Volume 5. Northeastern Section of the Geological Society of America. Geological Society of America, pp. 307–309. https://doi.org/10.1130/0-8137-5405-4.307.

Neuman, R.B., Max, M.D., 1989. Penobscottian-Grampian-Finnmarkian orogenies as indicators of terrane linkages. In: Dallmeyer, R.D. (Ed.), Terranes in the Circum-Atlantic Orogens, Geological Society of America Special Paper, vol. 230, pp. 31–45.

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, 835–846. https://doi.org/10.1017/S0016756800023190.

Nowlan, G.S., McCracken, A.D., McLeod, M.J., 1997. Tectonic and paleogeographic significance of Late Ordovician conodonts in the Canadian Appalachians. Can. J. Earth Sci. 34, 1521–1537. https://doi.org/10.1139/e17-124.

O'Brien, B.H., 2003. Geology of the central Notre Dame Bay Region (parts of NTS areas 2E/3,6,11), Northeastern Newfoundland, Newfoundland Department of Mines and Energy, Geological Survey, Report, 03–03. Government of Newfoundland and Labrador, Dept. Mines and Energy, Geological Survey, St. John's, Nfld.

O'Brien, S.J., Wardle, R.J., King, A.F., 1983. The Avalon Zone: a Pan-African terrane in the Appalachian Orogen of Canada. Geol. J. 18, 195–222.

O'Brien, B.H., O'Brien, S.J., Dunning, G.R., 1991. Silurian Cover, Late Precambrian-Early Ordovician basement, and the chronology of Silurian orogenesis in the Hermitage Flexure (Newfoundland Appalachians). Am. J. Sci. 291, 760–799.

O'Brien, B.H., O'Brien, S.J., Dunning, G.R., Tucker, R.D., 1993. Episodic reactivation of a Late Precambrian mylonite zone on the Gondwanan margin of the Appalachians, southern Newfoundland. Tectonics 12, 1043–1055. https://doi.org/10.1029/93TC00110.

O'Brien, S.J., O'Brien, B.H., Dunning, G.R., Tucker, R.D., 1996. Late Neoproterozoic Avalonian and related peri-Gondwanan rocks of the Newfoundland Appalachians. 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. 9–28.

Osberg, P.H., Berry, H.N., 2020. Bedrock geology of the Camden quadrangle Maine. In: Maine Geological Survey Open-File, 20-8 scale 1:24,000.

Owen, J.V., Corney, R., Dostal, J., Vaughan, A., 2010. Significance of "gneissic" rocks in the Liscomb Complex, Nova Scotia. Can. J. Earth Sci. 47, 927–940. https://doi.org/10.1139/E10-019.

Palacios, T., Jensen, S., Barr, S.M., White, C.E., 2009. Acritarchs from the MacLean Brook Formation, southeastern Cape Breton Island, Nova Scotia, Canada: new data on Middle Cambrian–Lower Furongian acritarch zonation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 273, 123–141. https://doi.org/10.1016/j.palaeo.2008.12.006.

Palacios, T., Jensen, S., Barr, S.M., White, C.E., Miller, R.F., 2011. New biostratigraphical constraints on the lower Cambrian Ratcliffe Brook Formation, southern New Brunswick, Canada, from organic-walled microfossils. Stratigraphy 8, 16.

Palacios, T., Jensen, S., White, C.E., Barr, S.M., 2012. Cambrian acritarchs from the Bourinot belt, Cape Breton Island, Nova Scotia: age and stratigraphic implications. Can. J. Earth Sci. 49, 289–307.

Palacios, T., Jensen, S., Barr, S.M., White, C.E., Myrow, P.M., 2018. Organic-walled microfossils from the Ediacaran–Cambrian boundary stratotype section, Chapel Island and Random formations, Burin Peninsula, Newfoundland, Canada: global correlation and significance for the evolution of early complex ecosystems. Geol. J. 53, 1728–1742. https://doi.org/10.1002/gj.2998.

Paszkowski, M., Budzyń, B., Mazur, S., Sláma, J., Środoń, J., Millar, I.L., Shumlyanskyy, L., Kędzior, A., Liivamägi, S., 2021. Detrital zircon U-Pb and Hf constraints on provenance and timing of deposition of the Mesoproterozoic to Cambrian sedimentary cover of the East European Craton, part II: Ukraine. Precambrian Res. 362, 106282 https://doi.org/10.1016/j.precamres.2021.106282.

Patchett, P.J., Ruiz, J., 1989. Nd isotopes and the origin of Grenville-age rocks in Texas: implications for Proterozoic evolution of the United States Mid-Continent region. J. Geol. 97, 685–695.

Pauley, J.C., 1990. Sedimentology, structural evolution and tectonic setting of the late Precambrian Longmyndian Supergroup of the Welsh Borderland, UK. Geol. Soc. Lond. Spec. Publ. 51, 341–351. https://doi.org/10.1144/GSL.SP.1990.051.01.22.

Perrot, M., Tremblay, A., David, J., 2017. Detrital zircon U-Pb geochronology of the Magog Group, southern Quebec – stratigraphic and tectonic implications for the Quebec Appalachians. Am. J. Sci. 317, 1049–1094. https://doi.org/10.2475/10.2017.01.

Perrot, M., Tremblay, A., Ruffet, G., David, J., 2018. Detrital U-Pb and 40Ar/39Ar geochronology of the Connecticut Valley-Gaspé trough, southern Quebec and northern Vermont – transitional tectonism from Salinic to Acadian orogenic cycles. Tectonophysics 745, 430–452. https://doi.org/10.1016/j.tecto.2018.08.006.

Pharaoh, T.C., Webb, P.C., Thorpe, R.S., Beckinsale, R.D., 1989. Geochemicalevidencefor the tectonic setting of late Proterozoic volcanic suites in central England. In: Pharaoh, T.C., Beckinsale, R.D., Rickard, D. (Eds.), Geochemistryand Mineralization of Proterozoic Volcanic Suites, Geological Society Special Publication, vol. 33, pp. 541–552.

Phillips, E., 1991. The lithostratigraphy, sedimentology and tectonic setting of the Monian Supergroup, western Anglesey, North Wales. J. Geol. Soc. 148, 1079–1090. https://doi.org/10.1144/gsjgs.148.6.1079.

Phillips, E.R., Smith, R.A., Stone, P., Pashley, V., Horstwood, M., 2009. Zircon age constraints on the provenance of Llandovery to Wenlock sandstones from the Midland Valley terrane of the Scottish Caledonides. Scott. J. Geol. 45, 131–146. https://doi.org/10.1144/0036-9276/01-383.

Pickerill, R.K., Fillion, D., 1983. On the Tremadoc-Arenig and Lower-Upper Tremadoc boundaries in the Bell Island Group, Conception Bay, eastern Newfoundland. Atl. Geol. 19 https://doi.org/10.4138/1561.

Pickering, K.T., Smith, A.G., 1995. Arcs and backarc basins in the early Paleozoic Iapetus Ocean. Island Arc 4, 1–67.

Pickering, K.T., Bassett, M.G., Siveter, D.J., 1988. Late Ordovician - early Silurian destruction of the Iapetus Ocean: Newfoundland, British Isles and Scandinavia: a discussion. Trans. R. Soc. Edinb. Earth Sci. 79, 361–382.

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. GSA Bull. 125, 1930–1942. https://doi.org/10.1130/B30776.1.

Pindell, J.L., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. Geol. Soc. Lond. Spec. Publ. 328, 1–55. https://doi.org/10.1144/sp328.1.

Plint, H.E., Jamieson, R.A., 1989. Microstructure, metamorphism and tectonics of the western Cape Breton Highlands, Nova Scotia. J. Metamorph. Geol. 7, 407–424. https://doi.org/10.1111/j.1525-1314.1989.tb00606.x.

Pollock, J.C., Wilton, D.H.C., Van Staal, C.R., Morrissey, K.D., 2007. U-Pb detrital zircon geochronological constraints on the Early Silurian collision of Ganderia and Laurentia along the Dog Bay Line: The terminal Iapetan suture in the Newfoundland Appalachians. Am. J. Sci. 307, 399–433.

Pollock, J.C., Hibbard, J.P., Sylvester, P.J., 2009. Early Ordovician rifting of Avalonia and birth of the Rheic Ocean: U-Pb detrital zircon constraints from Newfoundland. J. Geol. Soc. 166, 501–515. https://doi.org/10.1144/0016-76492008-088.

Pollock, J.C., Hibbard, J.P., van Staal, C.R., 2012. A paleogeographical review of the peri-Gondwanan realm of the Appalachian orogen. Can. J. Earth Sci. 49, 259–288. https://doi.org/10.1139/e11-049.

Pollock, J.C., Sylvester, P.J., Barr, S.M., 2015. Lu–Hf zircon and Sm–Nd whole-rock isotope constraints on the extent of juvenile arc crust in Avalonia: examples from Newfoundland and Nova Scotia, Canada. Can. J. Earth Sci. 52, 161–181. https://doi.org/10.1139/cjes-2014-0157.

Pollock, J.C., Reusch, D.N., Dunning, G.R., 2022. U–Pb zircon geochronology and implications of Cambrian plutonism in the Ellsworth belt, Maine. Can. J. Earth Sci. https://doi.org/10.1139/cjes-2021-0030 cjes-2021-0030.

Pothier, H.D., Waldron, J.W.F., Schofield, D.I., DuFrane, S.A., 2015a. Peri-Gondwanan terrane interactions recorded in the Cambrian-Ordovician detrital zircon geochronology of North Wales. Gondwana Res. 28, 987–1001. https://doi.org/10.1016/j.gr.2014.08.009.

Pothier, H.D., Waldron, J.W.F., DuFrane, S.A., White, C.E., Jamieson, R.A., 2015b. Stratigraphy, provenance and tectonic setting of the Lumsden Dam and Bluestone Quarry Formations (Lower Ordovician), Halifax Group, Nova Scotia. Atl. Geol. 51, 51–83.

Potter, J., Longstaffe, F.J., Barr, S.M., Thompson, M.D., White, C.E., 2008a. Altering Avalonia: oxygen isotopes and terrane distinction in the Appalachian peri-Gondwanan realm. Can. J. Earth Sci. 45, 815–825. https://doi.org/10.1139/E08-024.

Potter, J., Longstaffe, F.J., Barr, S.M., 2008b. Regional 18O-depletion of Neoproterozoic igneous rocks from Avalonia, Cape Breton Island and southern New Brunswick, Canada. GSA Bull. 120, 347–367. https://doi.org/10.1130/B26191.1.

Potts, S.S., van der Pluijm, B.A., Van der Voo, R., 1993. Paleomagnetism of the Ordovician Bluffer Pond Formation: Paleogeographic implications for the Munsungun terrane of northern Maine. J. Geophys. Res. Solid Earth 98, 7987–7996. https://doi.org/10.1029/93JB00017.

Potts, S.S., van der Pluijm, B.A., Van der Voo, R., 1995. Paleomagnetism of the Pennington Mountain terrane: a near-Laurentian back arc basin in the Maine Appalachians. J. Geophys. Res. Solid Earth 100, 10003–10011. https://doi.org/10.1029/94JB03013.

Pratt, B.R., Waldron, J.W.F., 1991. A Middle Cambrian trilobite faunule from the Meguma Group of Nova Scotia. Can. J. Earth Sci. 28, 1843–1853.

Price, J.R., Barr, S.M., Raeside, R.P., Reynolds, P.H., 1999. Petrology, tectonic setting, and 40Ar/ 39Ar (hornblende) dating of the Late Ordovician - Early Silurian Belle Côte Road orthogneiss, western Cape Breton Highlands, Nova Scotia. Atl. Geol. 35 https://doi.org/10.4138/2021.

Pu, J.P., Bowring, S.A., Ramezani, J., Myrow, P., Raub, T.D., Landing, E., Mills, A., Hodgin, E., Macdonald, F.A., 2016. Dodging snowballs: geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. Geology 44, 955–958. https://doi.org/10.1130/G38284.1.

Raine, R.J., Smith, M.P., 2012. Sequence stratigraphy of the Scottish Laurentian margin and recognition of the Sauk Megasequence. AAPG Mem. 98, 575–596. https://doi.org/10.1306/13331657M983507.

Ranger, M.J., Pickerill, R.K., Fillon, D., 1984. Lithostratigraphy of the Cambrian? - Lower Ordovician Bell Island and Wabana groups of Bell, Little Bell, and Kellys islands, Conception Bay, eastern Newfoundland. Can. J. Earth Sci. 21, 1245–1261.

Reusch, D.N., 1987. Silurian stratigraphy and melanges, New World Island, north central Newfoundland. In: Roy, D.C. (Ed.), Geological Society of America Centennial Field Guide, Northeastern Section, pp. 463–466.

Reusch, D.N., 2003. Bedrock Geology of the Mainland Portion of the Newbury Neck and Salsbury Cove 7.5-minute Quadrangles. Maine Geological Survey Open-File, 03–92.

Reusch, D.N., Rust, K.L., 2001. Post-rifting fate of the peri-Gondwanan Ellsworth Schist, Newbury Neck, Maine. In: Abstracts with Programs - Geological Society of America, vol. 33, p. 79.

Reusch, D.N., van Staal, C.R., 2012. The Dog Bay-Liberty Line and its significance for Silurian tectonics of the northern Appalachian orogen. Can. J. Earth Sci. 49, 239–258. https://doi.org/10.1139/e11-024.

Reusch, D.N., Holm-Denoma, C.S., Slack, J.F., 2018. U–Pb zircon geochronology of Proterozoic and Paleozoic rocks, North Islesboro, coastal Maine (USA): links to West Africa and Penobscottian orogenesis in southeastern Ganderia? Atl. Geol. 54, 189–221.

Reynolds, P.H., Jamieson, R.A., Barr, S.M., Raeside, R.P., 1989. An 40Ar/39Ar study of the Cape Breton Highlands, Nova Scotia: thermal histories and tectonic implications. Can. J. Earth Sci. 26, 2081–2091.

Reynolds, P.H., Barr, S.M., White, C.E., 2009. Provenance of detrital muscovite in Cambrian Avalonia of Maritime Canada: $^{40}$Ar/ $^{39}$Ar ages and chemical compositions. Can. J. Earth Sci. 46, 169–180. https://doi.org/10.1139/E09-013.

Riggs, N., McConnell, B., Graham, J., 2022. Sedimentary provenance of Silurian basins in western Ireland during Iapetus closure. 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. https://doi.org/10.1130/2021.2554(16).

Rippon, J., Read, W.A., Park, R.G., 1996. The Ochil Fault and the Kincardine basin: key structures in the tectonic evolution of the Midland Valley of Scotland. J. Geol. Soc. 153, 573–587. https://doi.org/10.1144/gsjgs.153.4.0573.

Robert, B., Domeier, M., Jakob, J., 2021. On the origins of the Iapetus ocean. Earth-Sci. Rev. 103791 https://doi.org/10.1016/j.earscirev.2021.103791.

Robinson, P., 2003. Tectonic-stratigraphic-metamorphic perspective of the New England Caledonides, west-central Massachusetts. In: Brady, J.B., Cheney, J.T. (Eds.), Guidebook for Field Trips in the Five College Region, Annual Meeting of the New England Intercollegiate Geological Conference, vol. 95 pp. A1-1-A1-54.

Robinson, P., Tucker, R.D., Bradley, D., Berry IV, H.N., Osberg, P.H., 1998. Paleozoic orogens in New England, USA. GFF 120, 119–148.

Rogers, N., van Staal, C.R., McNicoll, V., Pollock, J., Zagorevski, A., Whalen, J., 2006. Neoproterozoic and Cambrian arc magmatism along the eastern margin of the Victoria Lake Supergroup: a remnant of Ganderian basement in central Newfoundland? Precambrian Res. 147, 320–341.

de Roo, J.A., van Staal, C.R., 1994. Transpression and extensional collapse; steep belts and flat belts in the Appalachian central mobile belt, northern New Brunswick, Canada. Geol. Soc. Am. Bull. 106, 541–552.

van Rooyen, D., Barr, S.M., White, C.E., Hamilton, M.A., 2019. New U–Pb age constraints on the geological history of the Ganderian Bras d'Or terrane, Cape Breton Island, Nova Scotia. Can. J. Earth Sci. 56, 829–847. https://doi.org/10.1139/cjes-2018-0248.

Ross, G.M., 1991. Tectonic setting of the Windermere Supergroup revisited. Geology 19, 1125–1128. https://doi.org/10.1130/0091-7613(1991)019<1125:TSOTWS>2.3.CO;2.

Rushton, A.W.A., Brück, P.M., Molyneux, S.G., Williams, M., Woodcock, N.H., 2011. A Revised Correlation of the Cambrian Rocks in the British Isles. Geological Society Special Report, vol. 25.

Samson, S.D., Barr, S.M., White, C.E., 2000. Nd isotopic characteristics of terranes within the Avalon Zone, southern New Brunswick. Can. J. Earth Sci. 37, 14.

Santos, J.O.S., Hartmann, L.A., Bossi, J., Campal, N., Schipilov, A., Piñeyro, D., McNaughton, N.J., 2003. Duration of the Trans-Amazonian cycle and its correlation within South America based on U-Pb SHRIMP geochronology of the La Plata Craton, Uruguay. Int. Geol. Rev. 45, 27–48. https://doi.org/10.2747/0020-6814.45.1.27.

Satkoski, A.M., Barr, S.M., Samson, S.D., 2010. Provenance of late Neoproterozoic and Cambrian sediments in Avalonia; constraints from detrital zircon ages and Sm-Nd isotopic compositions in southern New Brunswick, Canada. J. Geol. 118, 187–200. https://doi.org/10.1086/649818.

Scallion, K.-L., Jamieson, R.A., Barr, S.M., White, C.E., Erdmann, S., 2011. Texture and composition of garnet as a guide to contamination of granitoid plutons: an example from the Governor Lake area, Meguma Terrane, Nova Scotia. Can. Mineral. 49, 441–458. https://doi.org/10.3749/canmin.49.2.441.

Schenk, P.E., 1971. Southeastern Atlantic Canada, northwestern Africa, and continental drift. Can. J. Earth Sci. 8, 1218–1251.

Schenk, P.E., 1973. Nova Scotia, Morocco and continental drift. In: Hood, P.J. (Ed.), Earth Sciences Symposium on Offshore Eastern Canada, Geological Survey of Canada Paper, vol. 71–23, pp. 219–222.

Schofield, D.I., Horstwood, M.S.A., Pitfield, P.E.J., Crowley, Q.G., Wilkinson, A.F., Sidaty, H.C.O., 2006. Timing and kinematics of Eburnean tectonics in the central Reguibat Shield, Mauritania. J. Geol. Soc. Lond. 163, 549–560. https://doi.org/10.1144/0016-764905-097.

Schofield, D.I., Millar, I.L., Wilby, P.R., Evans, J.A., 2009a. A new, high precision U–Pb date from the oldest known rocks in southern Britain. Geol. Mag. 147, 145. https://doi.org/10.1017/s001675680999063x.

Schofield, D.I., Aspden, J.A., Kemp, S.J., Merriman, R.J., Wilby, P.R., 2009b. Basement controls on Acadian thrusting and fault reactivation along the southern margin of the Welsh Basin. Geol. J. 44, 526–536.

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. Gondwana Res. 35, 257–271. https://doi.org/10.1016/j.gr.2015.06.001.

Schofield, D.I., Leslie, A.G., Wilby, P.R., Dartnall, R., Waldron, J.W.F., Kendall, R.S., 2020. Tectonic evolution of Anglesey and adjacent mainland North Wales. Geol. Soc. Lond. Spec. Publ. https://doi.org/10.1144/SP503-2020-9. SP503-2020–9.

Schulz, K.J., Stewart, D.B., Tucker, R.D., Pollock, J.C., Ayuso, R.A., 2008. The Ellsworth terrane, coastal Maine: geochronology, geochemistry, and Nd-Pb isotopic composition – implications for the rifting of Ganderia. Geol. Soc. Am. Bull. 120, 1134–1158. https://doi.org/10.1130/B26336.1.

Shellnutt, J.G., Dostal, J., Keppie, J.D., Keppie, D.F., 2020. Formation of Anorthositic Rocks within the Blair River Inlier of Northern Cape Breton Island, Nova Scotia (Canada). Lithosphere 2020. https://doi.org/10.2113/2020/8825465.

Skehan, J.W., Rast, N., 1990. Pre-Mesozoic evolution of Avalon terranes of southern New England. In: Socci, A.D., Skehan, J.W., Smith, G.W. (Eds.), Geology of the Composite Avalon Terrane of Southern New England, Geological Society of America Special Paper, pp. 13–53.

Skulski, T., Castonguay, S., McNicoll, V., van Staal, C.R., Kidd, W., Rogers, N., Morris, W., Ugalde, H., Slavinski, H., Spicer, W., Moussallam, Y., Kerr, I., 2010. Tectonostratigraphy of the Baie Verte Oceanic Tract and its ophiolite cover sequence on the Baie Verte Peninsula. Curr. Res. Nfld. Labrador Geol. Surv. 315–335.

Slaman, L.R., Barr, S.M., White, C.E., van Rooyen, D., 2017. Age and tectonic setting of granitoid plutons in the Chéticamp belt, western Cape Breton Island, Nova Scotia, Canada. Can. J. Earth Sci. 54, 88–109. https://doi.org/10.1139/cjes-2016-0073.

Smith, M.P., Rasmussen, J.A., 2008. Cambrian–Silurian development of the Laurentian margin of the Iapetus Ocean in Greenland and related areas. In: Higgins, A.K., Gilotti, J.A., Smith, M.P. (Eds.), The Greenland Caledonides: Evolution of the Northeast Margin of Laurentia, Geological Society of America Memoir, vol. 202, pp. 137–167.

Smith, N.J.P., Rushton, A.W.A., 1993. Cambrian and Ordovician stratigraphy related to structure and seismic profiles in the western part of the English Midlands. Geol. Mag. 130, 665–671. https://doi.org/10.1017/S0016756800020975.

Snyder, M.E., Waldron, J.W.F., 2021. Deformation of soft sediments and evaporites in a tectonically active basin: Bay St. George sub-basin, Newfoundland, Canada. Atl. Geol. 57, 275–304. https://doi.org/10.4138/atlgeol.2021.013.

Socci, A.D., Skehan, J.W., Smith, G.W., 1990. Geology of the Composite Avalon Terrane of Southern New England. In: Geological Society of America Special Paper, vol. 245.

Soper, N.J., Hutton, D.H.W., 1988. Timing and geometry of collision, terrane accretion and sinistral strike-slip events in the British Caledonides. In: Harris, A.J., Fettes, D.J. (Eds.), The Caledonian-Appalachian Orogen, Geological Society of London Special Publication, vol. 38, pp. 481–492.

Stanley, R.S., Ratcliffe, N.M., 1985. Tectonic synthesis of the Taconian orogeny in western New England. Geol. Soc. Am. Bull. 96, 1227–1250.

Steinberger, B., Torsvik, T.H., 2008. Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature 452, 620–623.

Stephan, T., Kroner, U., Romer, R.L., 2019. The pre-orogenic detrital zircon record of the Peri-Gondwanan crust. Geol. Mag. 156, 281–307. https://doi.org/10.1017/S0016756818000031.

Stephens, M.B., 2020. Chapter 22 Upper and uppermost thrust sheets in the Caledonide orogen, Sweden: outboard oceanic and exotic continental terranes. In: Stephens, M. B., Bergman Weihed, J. (Eds.), Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources, Geological Society, London, Memoirs, vol. 50, pp. 549–575.

Stephenson, D., Mendum, J.R., Fettes, D.J., Leslie, A.G., 2013. The Dalradian rocks of Scotland: an introduction. Proc. Geol. Assoc. 124, 3–82. https://doi.org/10.1016/j.pgeola.2012.06.002.

Stern, R.J., Bloomer, S.H., 1992. Subduction zone infancy: examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs. Geol. Soc. Am. Bull. 104, 1621–1636.

Stevens, R.K., 1970. Cambro-Ordovician flysch sedimentation and tectonics in West Newfoundland and their possible bearing on a Proto-Atlantic Ocean. In: Lajoie, J. (Ed.), Flysch Sedimentology in North America, Geological Association of Canada Special Paper, vol. 7, pp. 165–177.

Stockmal, G.S., Colman-Sadd, S.P., Keen, C.E., Marillier, F., O'Brien, S.J., Quinlan, G.M., 1990. Deep seismic structure and plate tectonic evolution of the Canadian Appalachians. Tectonics 9, 45–62.

Stone, P., 2014. A review of geological origins and relationships in the Ballantrae Complex, SW Scotland. Scott. J. Geol. 50, 1–25.

Stone, P., Merriman, R.J., 2004. Basin thermal history favours an accretionary origin for the Southern Uplands Terrane, Scottish Caledonides. J. Geol. Soc. Lond. 161, 829–836.

Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M., Lawrence, D.J.D., 2010. British regional geology: Northern England, 5th ed. British Geological Survey, Keyworth, Nottingham.

Stone, P., McMillan, A.A., Floyd, J.D., Barnes, R.P., Phillips, E.R., 2012. British Regional Geology: South of Scotland. British Geological Survey, Keyworth, Nottingham.

Strachan, R.A., Collins, A.S., Buchan, C., Nance, R.D., Murphy, J.B., D'Lemos, R.S., 2007. Terrane analysis along a Neoproterozoic active margin of Gondwana; insights from U-Pb zircon geochronology. J. Geol. Soc. Lond. 164, 57–60.

Strachan, R.A., Linnemann, U., Jeffries, T., Drost, K., Ulrich, J., 2014. Armorican provenance for the melange deposits below the Lizard Ophiolite (Cornwall, UK); evidence for Devonian obduction of Cadomian and lower Palaeozoic crust onto the southern margin of Avalonia. Int. J. Earth Sci. 103, 1359–1383. https://doi.org/10.1007/s00531-013-0961-x.

Swanson-Hysell, N.L., Macdonald, F.A., 2017. Tropical weathering of the Taconic orogeny as a driver for Ordovician cooling. Geology 45, 719–722. https://doi.org/10.1130/G38985.1.

Swinden, H.S., Jenner, G.A., Szybinski, Z.A., 1997. Magmatic and tectonic evolution of the Cambrian-Ordovician Laurentian margin of Iapetus: geochemical and isotopic constraints from the Notre Dame Subzone, Newfoundland. In: Sinha, A.K., Whalen, J.B., Hogan, J.P. (Eds.), The Nature of Magmatism in the Appalachian Orogen, Geological Society of America Memoir, vol. 191, pp. 337–365.

Tan, X., Kodama, K.P., 2003. An analytical solution for correcting palaeomagnetic inclination error. Geophys. J. Int. 152, 228–236.

Tanner, P.W.G., 2014. A kinematic model for the Grampian Orogeny, Scotland. In: Corfu, F., Gasser, D., Chew, D.M. (Eds.), New Perspectives on the Caledonides of Scandinavia and Related Areas, Geological Society, London, Special Publications, vol. 390, pp. 467–511.

Tanner, P.W.G., Sutherland, S., 2007. The Highland Border Complex, Scotland; a paradox resolved. J. Geol. Soc. Lond. 164, 111–116. https://doi.org/10.1144/0016-76492005-188.

Tanoli, S.K., Pickerill, R.K., 1988. Lithostratigraphy of the Cambrian-Lower Ordovician Saint John Group, southern New Brunswick. Can. J. Earth Sci. 25, 669–690.

Taylor, G.K., Gascoyne, J., Colley, H., 2000. Rapid rotation of Fiji: Paleomagnetic evidence and tectonic implications. J. Geophys. Res. Solid Earth 105, 5771–5781. https://doi.org/10.1029/1999JB900305.

Thomas, W.A., 1977. Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin. Am. J. Sci. 277, 1233–1278.

Thompson, M.D., Bowring, S.A., 2000. Age of the Squantum "tillite," Boston Basin, Massachusetts; U-Pb zircon constraints on terminal Neoproterozoic glaciation. Am. J. Sci. 300, 630–655.

Thompson, M.D., Crowley, J.L., 2020. Avalonian arc-to-platform transition in southeastern New England: U-Pb geochronology and stratigraphy of Ediacaran Cambridge "argillite," Boston Basin, Massachusetts, USA. Am. J. Sci. 320, 405–449. https://doi.org/10.2475/05.2020.01.

Thompson, M.D., Hermes, O.D., 2003. Early rifting in the Narragansett Basin, Massachusetts-Rhode Island: Evidence from Late Devonian bimodal volcanic rocks. J. Geol. 111, 597–604.

Thompson, M.D., Grunow, A.M., Ramezani, J., 2010a. 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.

Thompson, M.D., Ramezani, J., Barr, S.M., Hermes, O.D., 2010b. High-precision U-Pb zircon dates for Ediacaran granitoid rocks in SE New England; revised magmatic chronology and correlation with other Avalonian terranes. In: Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., Karabinos, P.M. (Eds.), From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region, Geological Society of America Memoir, pp. 231–250.

Thomas, W.A., Astini, R.A., 2003. Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review. J. S. Am. Earth Sci. 16, 67–79. https://doi.org/10.1016/S0895-9811(03)00019-1.

Thompson, M.D., Barr, S.M., Grunow, A.M., 2012. Avalonian perspectives on Neoproterozoic paleogeography: evidence from Sm-Nd isotope geochemistry and detrital zircon geochronology in SE New England, USA. Geol. Soc. Am. Bull. 124, 517–531. https://doi.org/10.1130/b30529.1.

Thompson, M.D., Ramezani, J., Crowley, J.L., 2014. U-Pb zircon geochronology of Roxbury Conglomerate, Boston Basin, Massachusetts: Tectono-stratigraphic implications for Avalonia in and beyond SE New England. Am. J. Sci. 314, 1009–1040. https://doi.org/10.2475/06.2014.02.

Thompson, M.D., Ramezani, J., Grunow, A.M., 2018. Within-plate setting of paleozoic alkalic suites in southeastern New England, USA: Constraints from chemical abrasion–TIMS U-Pb geochronology and paleomagnetism. J. Geol. 126, 41–61. https://doi.org/10.1086/694867.

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. https://doi.org/10.1130/2022.2554(03).

Tietzsch-Tyler, D., Phillips, E., 1989. Correlation of the Monian Supergroup in NW Anglesey with the Cahore Group in SE Ireland. J. Geol. Soc. 146, 417–418.

Torsvik, T.H., Rehnström, E.F., 2003. The Tornquist Sea and Baltica–Avalonia docking. Tectonophysics 362, 67–82. https://doi.org/10.1016/s0040-1951(02)00631-5.

Torsvik, T.H., Trench, A., Svensson, I., Walderhaug, H.J., 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain – major revision of the apparent polar wander path for eastern Avalonia. Geophys. J. Int. 113, 651–668.

Torsvik, T.H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A., Cocks, L.R.M., 2012. Phanerozoic polar wander, palaeogeography and dynamics. Earth-Sci. Rev. 114, 325–368. https://doi.org/10.1016/j.earscirev.2012.06.007.

Traynor, J.-J., 1988. The Arenig in South Wales: Sedimentary and volcanic processes during the initiation of a marginal basin. Geol. J. 23, 275–292. https://doi.org/10.1002/gj.3350230401.

Tremblay, A., Pinet, N., 2016. Late Neoproterozoic to Permian tectonic evolution of the Quebec Appalachians, Canada. Earth-Sci. Rev. 160, 131–170. https://doi.org/10.1016/j.earscirev.2016.06.015.

Trench, A., Torsvik, T.H., 1991. A revised Palaeozoic apparent polar wander path for Southern Britain (Eastern Avalonia). Geophys. J. Int. 104, 227–233.

Trench, A., Torsvik, T.H., McCabe, C., Channell, J.E.T., 1991. Palaeomagnetic results from volcanic rocks of the Shelve Inlier, Wales; evidence for a wide Late Ordovician Iapetus Ocean in Britain; discussion and reply [modified]. Earth Planet. Sci. Lett. 104, 535–544.

Trench, A., Torsvik, T.H., Dentith, M.C., Walderhaug, H., Traynor, J.-J., 1992. A high southerly palaeolatitude for Southern Britain in Early Ordovician times: palaeomagnetic data from the Treffgarne Volcanic Formation SW Wales. Geophys. J. Int. 108, 89–100. https://doi.org/10.1111/j.1365-246X.1992.tb00840.x.

Tucker, R.D., Robinson, P., 1990. Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England. Geol. Soc. Am. Bull. 102, 1404–0419.

Tucker, R.D., Osberg, P.H., Berry, H.N., 2001. The geology of part of Acadia and the nature of the Acadian orogeny across central and eastern Maine. Am. J. Sci. 301, 205–260.

Underhill, J.R., Monaghan, A.A., Browne, M.A.E., 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. Mar. Pet. Geol. 25, 1000–1022. https://doi.org/10.1016/j.marpetgeo.2007.12.002.

Valverde-Vaquero, P., van Staal, C.R., McNicoll, V., Dunning, G.R., 2006a. Mid–Late Ordovician magmatism and metamorphism along the Gander margin in central Newfoundland. J. Geol. Soc. 163, 347–362.

Valverde-Vaquero, P., Dunning, G.R., O'Brien, S.J., 2006b. Polycyclic evolution of the Late Neoproterozoic basement in the Hermitage Flexure region (southwest Newfoundland Appalachians): new evidence from the Cinq-Cerf gneiss. Precambrian Res. 148, 1–18. https://doi.org/10.1016/j.precamres.2006.03.001.

Van der Voo, R., 1990. The reliability of paleomagnetic data. Tectonophysics 184, 1–9. https://doi.org/10.1016/0040-1951(90)90116-P.

Van der Voo, R., 1993. Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge University Press, Cambridge, United Kingdom.

Van der Voo, R., Johnson, R.J.E., 1985. Paleomagnetism of the Dunn Point Formation (Nova Scotia); high paleolatitudes for the Avalon Terrane in the Late Ordovician. Geophys. Res. Lett. 12, 337–340. https://doi.org/10.1029/GL012i006p00337.

van Staal, C.R., 1987. Tectonic setting of the Tetagouche Group in northern New Brunswick: implications for plate tectonic models of the northern Appalachians. Can. J. Earth Sci. 24, 1329–1351.

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., 2005. North America; Northern Appalachians. In: Selley, R.C., Cocks, L.R.M., Plimer, I.R. (Eds.), Encyclopedia of Geology, vol. 4, pp. 81–91.

van Staal, C.R., 2007. Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians. In: Goodfellow, W.D. (Ed.), Mineral Resources of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, Geological Association of Canada, Mineral Deposits Division, Special Publication, vol. 5, pp. 793–818.

van Staal, C.R., Barr, S.M., 2012. Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin. In: Percival, J.A., Cook, F.A., Clowes, R.M. (Eds.), Tectonic Styles in Canada: The LITHOPROBE Perspective, Geological Association of Canada, Special Paper, vol. 49, pp. 41–95.

van Staal, C.R., de Roo, J.A., 1996. Mid-Paleozoic tectonic evolution of the Appalachian central mobile belt in northern New Brunswick, Canada: Collision, extensional collapse and dextral transpression. In: Hibbard, J.P., van Staal, C.R., Cawood, P.A. (Eds.), Current Perspectives in the Appalachian-Caledonian Orogen, Geological Association of Canada Special Paper, vol. 41, pp. 367–389.

van Staal, C., Zagorevski, A., 2020. Accretion, soft and hard collision: similarities, differences and an application from the Newfoundland Appalachian Orogen. Geosci. Can. 47, 103–118. https://doi.org/10.12789/geocanj.2020.47.161.

van Staal, C.R., Ravenhurst, C.E., Winchester, J.A., Roddick, J.C., 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., Sullivan, R.W., Whalen, J.B., 1996. Provenance and tectonic history of the Gander Zone in the Caledonian/Appalachian Orogen; implications for the origin and assembly of Avalon. 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. 347–367.

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 of London Special Publication, vol. 143, pp. 199–242.

van Staal, C.R., Wilson, R.A., Rogers, N., Fyffe, L.R., Langton, J.P., McCutcheon, S.R., McNicoll, V.J., Ravenhurst, C.E., 2003. Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp, and its relationship to coeval rocks in southwestern New Brunswick and adjacent Maine – a synthesis. In: Goodfellow, W. D., McCutcheon, S.R., Peter, J.M. (Eds.), Massive Sulphide Deposits of the Bathurst Mining Camp, New Brunswick, and Northern Maine, Economic Geology Mongraph, vol. 11, pp. 37–60.

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. In: Hatcher, R.D., Carlson, M.P., McBride, J.H., Martinez Catalan, J.R. (Eds.), 4-D Framework of Continental Crust, Geological Society of America Memoirs, vol. 200, pp. 511–552.

van Staal, C.R., Currie, K.L., Rowbotham, G., Rogers, N., Goodfellow, W., 2008. Pressure-temperature paths and exhumation of Late Ordovician-Early Silurian blueschists and associated metamorphic nappes of the Salinic Brunswick subduction complex, northern Appalachians. Geol. Soc. Am. Bull. 120, 1455–1477. https://doi.org/10.1130/b26324.1.

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, 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, vol. 327. Geological Society of London Special Publication, pp. 271–316.

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. https://doi.org/10.1130/g33302.1.

van Staal, C.R., Chew, D.M., Zagorevski, A., McNicoll, V., Hibbard, J., Skulski, T., Castonguay, S., Escayola, M.P., Sylvester, P.J., 2013. Evidence of Late Ediacaran Hyperextension of the Laurentian Iapetan Margin in the Birchy Complex, Baie Verte Peninsula, Northwest Newfoundland: Implications for the Opening of Iapetus, Formation of Peri-Laurentian Microcontinents and Taconic – Grampian Orogenesis. Geosci. Can. vol. 94–117 https://doi.org/10.12789/geocanj.2013.40.006.

van Staal, C.R., Zagorevski, A., McNicoll, V.J., Rogers, N., 2014. Time-Transgressive Salinic and Acadian Orogenesis, Magmatism and Old Red Sandstone Sedimentation in Newfoundland. Geosci. Can. 41, 138. https://doi.org/10.12789/geocanj.2014.41.031.

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.

van Staal, C.R., Barr, S.M., McCausland, P.J.A., Thompson, M.D., White, C.E., 2020. Tonian-Ediacaran tectonomagmatic evolution of West Avalonia and its Ediacaran-Early Cambrian interactions with Ganderia: an example of complex terrane transfer due to arc-arc collision? Geol. Soc. Lond. Spec. Publ. https://doi.org/10.1144/SP503-2020-23. SP503-2020–23.

van Staal, C.R., Barr, S.M., Waldron, J.W.F., 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. Gondwana Res. 98, 212–243. https://doi.org/10.1016/j.gr.2021.05.025.

Van Wagoner, N.A., 2002. Late Silurian bimodal volcanism of southwestern New Brunswick, Canada: Products of continental extension. Geol. Soc. Am. Bull. 114, 400–418.

Vermeesch, P., 2018. IsoplotR: A free and open toolbox for geochronology. Geoscience Frontiers 9, 1479–1493. https://doi.org/10.1016/j.gsf.2018.04.001.

Waldron, J.W.F., 1992. The Goldenville-Halifax transition, Mahone Bay, Nova Scotia: relative sea-level change in the Meguma source terrane. Can. J. Earth Sci. 29, 1091–1105.

Waldron, J.W.F., van Staal, C.R., 2001. Taconian orogeny and the accretion of the Dashwoods block: a peri-Laurentian microcontinent in the Iapetus Ocean. Geology 29, 811–814.

Waldron, J.W.F., Stockmal, G.S., Corney, E., Stenzel, S.R., 1993. Basin development and inversion at the Appalachian structural front, Port au Port Peninsula, western Newfoundland Appalachians. Can. J. Earth Sci. 30, 1759–1772.

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

Waldron, J.W.F., Floyd, J.D., Simonetti, A., Heaman, L.M., 2008. Ancient Laurentian detrital zircon in the closing Iapetus Ocean, Southern Uplands terrane, Scotland. Geology 36, 527–530.

Waldron, J.W.F., White, C.E., Barr, S.M., Simonetti, A., Heaman, L.M., 2009. Provenance of the Meguma terrane, Nova Scotia: rifted margin of early Paleozoic Gondwana. Can. J. Earth Sci. 46, 1–9.

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., McNicoll, V.J., van Staal, C.R., 2012. Laurentia-derived detritus in the Badger Group of central Newfoundland: deposition during closing of the Iapetus Ocean. Can. J. Earth Sci. 49, 207–221.

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

Waldron, J.W.F., Schofield, D.I., Murphy, J.B., Thomas, C.W., 2014b. How was the Iapetus Ocean infected with subduction? Geology 42, 1095–1098. https://doi.org/10.1130/G36194.1.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., Hibbard, J.P., 2015. Late Paleozoic strike-slip faults in Maritime Canada and their role in the reconfiguration of the northern Appalachian orogen. Tectonics 34, 1661–1684. https://doi.org/10.1002/2015TC003882.

Waldron, J.W.F., Schofield, D.I., Pearson, G., Sarkar, C., Luo, Y., Dokken, R., 2019a. Detrital zircon characterization of early Cambrian sandstones from East Avalonia and SE Ireland: implications for terrane affinities in the peri-Gondwanan Caledonides. Geol. Mag. 156, 1217–1232. https://doi.org/10.1017/S0016756818000407.

Waldron, J.W.F., Schofield, D.I., Murphy, J.B., 2019b. Diachronous Paleozoic accretion of peri-Gondwanan terranes at the Laurentian margin. In: Wilson, R.W., Houseman, G.A., McCaffrey, K.J.W., Doré, A.G., Buiter, S.J.H. (Eds.), Fifty Years of the Wilson Cycle Concept in Plate Tectonics, Geological Society London Special Publications, vol. 470, pp. 289–310. https://doi.org/10.1144/SP470.11.

Wallace, L.M., McCaffrey, R., Beavan, J., Ellis, S., 2005. Rapid microplate rotations and backarc rifting at the transition between collision and subduction. Geology 33, 857. https://doi.org/10.1130/G21834.1.

Wallace, L.M., Ellis, S., Mann, P., 2009. Collisional model for rapid fore-arc block rotations, arc curvature, and episodic back-arc rifting in subduction settings. Geochem. Geophys. Geosyst. 10 https://doi.org/10.1029/2008GC002220.

Walsh, G.J., Aleinikoff, J.N., Wintsch, R.P., 2007. Origin of the Lyme Dome and implications for the timing of multiple Alleghanian deformational and intrusive events in southern Connectiut. Am. J. Sci. 307, 168–215. https://doi.org/10.2475/01.2007.06.

Walsh, G.J., Aleinikoff, J.N., Ayuso, R.A., Wintsch, R.P., 2021. Age and tectonic setting of the Quinebaug-Marlboro belt and implications for the history of Ganderian crustal fragments in southeastern New England, USA. Geosphere 17, 1038–1100. https://doi.org/10.1130/GES02295.1.

Wang, C., 2019. Bedrock geology of the Jack Mountain quadrangle, Maine. Maine Geol. Surv. Open File 19-6, 1.

Warsame, H.S., McCausland, P.J.A., White, C.E., Barr, S.M., Dunning, G.R., Waldron, J. W.F., 2021. Meguma terrane orocline: U–Pb age and paleomagnetism of the Silurian Mavillette gabbro, Nova Scotia, Canada. Can. J. Earth Sci. 58, 315–331. https://doi.org/10.1139/cjes-2020-0089.

Weil, A., Gutiérrez-alonso, G., Conan, J., 2010. New time constraints on lithospheric-scale oroclinal bending of the Ibero-Armorican Arc: a palaeomagnetic study of earliest Permian rocks from Iberia. J. Geol. Soc. 167, 127–143. https://doi.org/10.1144/0016-76492009-002.

Welford, J.K., Shannon, P.M., O'Reilly, B.M., Hall, J., 2012. Comparison of lithosphere structure across the Orphan Basin-Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3D gravity inversions. J. Geol. Soc. Lond. 169, 405–420. https://doi.org/10.1144/0016-76492011-114.

Wellensiek, M.R., van der Pluijm, B.A., Johnson, R.J.E., 1990. Tectonic history of the Lunksoos composite terrane in the Maine Appalachians. Tectonics 9, 719–734.

West, D.P., Ludman, A., Lux, D.R., 1992. Silurian age for the Pocomoonshine gabbro-diorite, southeastern Maine and its regional tectonic implications. Am. J. Sci. 292, 253–273.

West, D.P., Beal, H.M., Grover, T.W., 2003. Silurian Deformation and Metamorphism of Ordovician Arc Rocks of the Casco Bay Group, South-Central Maine, vol. 40, p. 20.

West, D.P., Peterman, E.M., Chen, J., 2021. Silurian-Devonian tectonic evolution of mid-coastal Maine, U.S.A.: details of polyphase orogenic processes. Am. J. Sci. 321, 458–489. https://doi.org/10.2475/04.2021.03.

White, C.E., 2017. Bedrock geology map of the Antigonish Highlands area, Antigonish and Pictou counties, Nova Scotia. Department of Natural Resources, Geoscience and Mines Branch, Nova Scotia. Open File Map, ME 2017-34, scale 1:75 000.

White, C.E., Barr, S.M., 1998. Stratigraphy and tectonic significance of the Lower to Middle Devonian McAdams Lake Formation, Cape Breton Island, Nova Scotia. Atl. Geol. 34, 133–145.

White, C.E., Barr, S.M., 2012. Meguma Terrane revisited: stratigraphy, metamorphism, paleontology, and provenance. Geosci. Can. 39, 8–12.

White, C.E., Scallion, K.-L., 2011. Bedrock Geology Map of the Governor Lake Area, Part of NTS Sheets 21E/01, 02, 07, and 08, Colchester, Guysborough, Halifax, and Pictou counties, Nova Scotia. Nova Scotia Department of Natural Resources, Mineral Resources Branch. Open File Map, ME 2011-013, scale 1:50,000.

White, S.E., Waldron, J.W.F., 2019. Inversion of Taconian extensional structures during Acadian orogenesis in western Newfoundland. In: Wilson, R.W., Houseman, G.A., McCaffrey, K.J.W., Doré, A.G., Buiter, S.J.H. (Eds.), Tectonic Evolution: 50 Years of the Wilson Cycle Concept, Geological Society London Special Publications, 470, pp. 311–336.

White, S.E., Waldron, J.W.F., 2022. Along-strike variations in the deformed Laurentian margin in the Northern Appalachians: Role of inherited margin geometry and colliding arcs. Earth-Sci. Rev. 226, 10391.

White, C.E., Barr, S.M., Bevier, M.L., Deveau, K.A., 1990. Field relations, petrography, and age of plutonic units in the Saint John area of southern New Brunswick. Atl. Geol. 26 https://doi.org/10.4138/1708.

White, C.E., Barr, S.M., Bevier, M.L., Kamo, S., 1994. A revised interpretation of Cambrian and Ordovician rocks in the Bourinot Belt of central Cape Breton Island, Nova Scotia. Atl. Geol. 30, 123–142.

White, C.E., Barr, S.M., Jamieson, R.A., Reynolds, P.H., 2001. Neoproterozoic high-pressure/low-temperature metamorphic rocks in the Avalon terrane, southern New Brunswick, Canada. J. Metamorph. Geol. 19, 519–530. https://doi.org/10.1046/j.0263-4929.2001.00326.x.

White, C.E., Barr, S.M., Reynolds, P.H., Grace, E., McMullin, D.W.A., 2006. The Pocologan metamorphic suite; high-pressure metamorphism in a Silurian fore-arc complex, Kingston Terrane, southern New Brunswick. Can. Mineral. 44, 905–927.

White, C.E., Palacios, T., Jensen, S., Barr, S.M., 2012. Cambrian–Ordovician acritarchs in the Meguma terrane, Nova Scotia, Canada: resolution of early Paleozoic stratigraphy and implications for paleogeography. Geol. Soc. Am. Bull. 124, 1773–1792.

White, C.E., Barr, S.M., Davis, D.W., Swanton, D.S., Ketchum, J.W.F., Reynolds, P.H., 2016a. Field relations, age, and tectonic setting of metamorphic and plutonic rocks in the Creignish Hills – North Mountain area, southwestern Cape Breton Island, Nova Scotia, Canada. Atl. Geol. 52, 037–059.

White, C.E., Barr, S.M., van Rooyen, D., McCarron, T., Slaman, L.R., Shute, J.M., 2016b. New age controls on rock units in the Chéticamp area, western Cape Breton Island, Nova Scotia, Canada. In: Report of Activities 2015. Nova Scotia Department of Natural Resources Report, ME 2016-001, pp. 131–142.

White, C.E., Sombini dos Santos, G., Moning, A., Barr, S.M., van Rooyen, D., 2018a. Geological and geochronological studies in the Middle River - Leonard MacLeod Brook area, central Cape Breton Island, Nova Scotia, in. In: Geoscience and Mines Branch, Report of Activities 2016. Nova Scotia Department of Natural Resources, Report, ME 2018-001, pp. 89–97.

White, C.E., Barr, S.M., Linnemann, U., 2018b. 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, 589–603. https://doi.org/10.1139/cjes-2017-0196.

White, S.E., Waldron, J.W.F., Dunning, G.R., DuFrane, S.A., 2019. Provenance of the Newfoundland Appalachian foreland basins. Am. J. Sci. 319, 694–735.

White, S.E., Waldron, J.W.F., Harris, N.B., 2020. Anticosti foreland basin offshore of western Newfoundland: Concealed record of northern Appalachian Orogen development. Basin Res. 32, 25–50. https://doi.org/10.1111/bre.12364.

White, C.E., Barr, S.M., Hamilton, M.A., Murphy, J.B., 2021. Age and tectonic setting of Neoproterozoic granitoid rocks, Antigonish Highlands, Nova Scotia, Canada: implications for Avalonia in the northern Appalachian orogen. Can. J. Earth Sci. 58, 396–412. https://doi.org/10.1139/cjes-2020-0110.

White, C.E., Barr, S.M., Crowley, J.L., van Rooyen, D., MacHattie, T.G., 2022. U-Pb zircon ages and Sm-Nd isotopic data from the Cobequid Highlands, Nova Scotia, Canada: new contributions to understanding the Neoproterozoic geologic history of Avalonia. 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. Geological Society of America, pp. 135–172. https://doi.org/10.1130/2021.2554(07).

Williams, H., 1964. The Appalachians in northeastern Newfoundland – a two-sided symmetrical system. Am. J. Sci. 262, 1137–1158.

Williams, H., 1978a. Geological development of the northern Appalachians: its bearing on the evolution of the British Isles. In: Bowes, D.L., Leake, B.E. (Eds.), Crustal Evolution in Northwestern Britain and Adjacent Regions, Geological Journal Special Issue, vol. 10, pp. 1–22.

Williams, H., 1978b. Tectonic Lithofacies Map of the Appalachian Orogen. In: Memorial University of Newfoundland Map, 1.

Williams, H., 1979. Appalachian Orogen in Canada. Can. J. Earth Sci. 16, 792–807.

Williams, H., Hatcher, R.D., 1982. Suspect terranes and accretionary history of the Appalachian orogen. Geology 10, 530–536.

Williams, H., Hatcher, R.D., 1983. Appalachian suspect terranes. In: Hatcher, R.D., Williams, H., Zietz, I. (Eds.), Contribution to the Tectonics and Geophysics of Mountain Chains, Geological Society of America Memoir, vol. 158, pp. 33–53.

Williams, H., Hiscott, R.N., 1987. Definition of the lapetus rift-drift transition in western Newfoundland. Geology 15, 1044–1047.

Williams, H., Stevens, R.K., 1974. The ancient continental margin of eastern North America. In: Burk, C.A., Drake, C.L. (Eds.), Geology of Continental Margins. Springer-Verlag, New York, pp. 781–796.

Williams, H., Colman-Sadd, S.P., Swinden, H.S., 1988. Tectonic-stratigraphic subdivisions of central Newfoundland. In: Current Research Part B. Geological Survey of Canada Paper, 88–1B, pp. 91–98.

Williams, H., Currie, K.L., Piasecki, M.A.J., 1993. The Dog Bay Line: a major Silurian tectonic boundary in northeast Newfoundland. Can. J. Earth Sci. 30, 2481–2494.

Willner, A.P., Barr, S.M., Gerdes, A., Massonne, H.-J., White, C.E., 2013. Origin and evolution of Avalonia: evidence from U–Pb and Lu–Hf isotopes in zircon from the Mira terrane, Canada, and the Stavelot–Venn Massif, Belgium. J. Geol. Soc. 170, 769–784.

Willner, A.P., Gerdes, A., Massonne, H.-J., Van Staal, C.R., Zagorevski, A., 2014. Crustal Evolution of the northeast Laurentian margin and the peri-Gondwanan microcontinent Ganderia prior to and during closure of the Iapetus Ocean: Detrital zircon U–Pb and Hf isotope evidence from Newfoundland. Geosci. Can. 41, 345. https://doi.org/10.12789/geocanj.2014.41.046.

Wilson, J.T., 1966. Did the Atlantic close and then re-open. Nature 211, 676–681.

Wilson, R.A., 2003. Geochemistry and petrogenesis of Ordovician arc-related mafic volcanic rocks in the Popelogan Inlier, northern New Brunswick. Can. J. Earth Sci. 40, 1171–1189. https://doi.org/10.1139/e03-034.

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.

Wintsch, R.P., Aleinikoff, J.N., Walsh, G.J., Bothner, W.A., Hussey, A.M., Fanning, C.M., 2007. Shrimp U-Pb evidence for a Late Silurian age of metasedimentary rocks in the Merrimack and Putnam-Nashoba terranes, eastern New England. Am. J. Sci. 307, 119–167.

Wintsch, R.P., Yi, K., Dorais, M.J., 2014. Crustal thickening by tectonic wedging of the Ganderian rocks, southern New England, USA: evidence from cataclastic zircon microstructures and U–Pb ages. J. Struct. Geol. 69, 428–448. https://doi.org/10.1016/j.jsg.2014.07.019.

Wonderly, P.F., Neuman, R.B., 1984. The Indian Bay Formation: fossiliferous Early Ordovician volcanogenic rocks in the northern Gander Terrane, Newfoundland, and their regional significance. Can. J. Earth Sci. 21, 525–532.

Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, James G., Clapham, M.E., 2003. Paleoenvironmental analysis of the late Neoproterozoic Mistaken Point and Trepassey formations, southeastern Newfoundland. Can. J. Earth Sci. 40, 1375–1391.

Woodcock, N.H., Strachan, R.A., 2000. Geological history of Britain and Ireland. Blackwell Science, Chichester, U.K.

Woodcock, N.H., Soper, N.J., Brenchley, P.J., Rawson, P.F., 2006. The Acadian Orogeny; the Mid-Devonian phase of deformation that formed slate belts in England and Wales. In: The Geology of England and Wales. The Geological Society, London, pp. 131–164.

Woodcock, N.H., Soper, N.J., Strachan, R.A., 2007. A Rheic cause for the Acadian deformation in Europe. J. Geol. Soc. Lond. 164, 1023–1036. https://doi.org/10.1144/0016-76492006-129.

Woodcock, N.H., Jack Soper, N., Miles, A.J., 2019. Age of the Acadian deformation and Devonian granites in northern England: a review. Proc. Yorks. Geol. Soc. 62, 238–253. https://doi.org/10.1144/pygs2018-009.

Wu, L., Kravchinsky, V.A., Gu, Y.J., Potter, D.K., 2017. Absolute reconstruction of the closing of the Mongol-Okhotsk Ocean in the Mesozoic elucidates the genesis of the slab geometry underneath Eurasia. J. Geophys. Res. Solid Earth 122, 4831–4851.

Wu, L., Murphy, J.B., Quesada, C., Li, Z.-X., Waldron, J.W.F., Williams, S., Pisarevsky, S., Collins, W.J., 2021. The amalgamation of Pangea: paleomagnetic and geological observations revisited. Geol. Soc. Am. Bull. 133, 625–646. https://doi.org/10.1130/B35633.1.

Wu, L., Murphy, J.B., Collins, W.J., Waldron, J.W.F., Li, Z.-X., Pisarevsky, S.A., Halverson, G.P., 2022. A trans-Iapetus transform fault control for the evolution of the Rheic Ocean: Implications for an early Paleozoic transition of accretionary tectonics. Geol. Soc. Am. Bull. https://doi.org/10.1130/B36158.1 in press.

Yin, Q.-Z., Wimpenny, J., Tollstrup, D.L., Mange, M., Dewey, J.F., Zhou, Q., Li, X.-H., Wu, F.-Y., Li, Q.-L., Liu, Y., others, 2012. Crustal evolution of the South Mayo Trough, western Ireland, based on U–Pb ages and Hf–O isotopes in detrital zircons. J. Geol. Soc. 169, 681–689.

Zagorevski, A., Van Staal, C.R., McNicoll, V., Rogers, N., 2007. Upper Cambrian to Upper Ordovician peri-Gondwanan Island arc activity in the Victoria Lake Supergroup, Central Newfoundland: tectonic development of the northern Ganderian margin. Am. J. Sci. 307, 339–370. https://doi.org/10.2475/02.2007.02.

Zagorevski, A., van Staal, C.R., McNicoll, V., Rogers, N., Valverde-Vaquero, P., 2008. Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians. In: Draut, A., Clift, P.D., Scholle, D.W. (Eds.), Formation and Applications of the Sedimentary Record in Arc Collision Zones, Geological Society of America Special Paper, vol. 436, pp. 309–333.

Zagorevski, A., Lissenberg, C.J., van Staal, C.R., 2009. Dynamics of accretion of arc and backarc crust to continental margins: inferences from the Annieopsquotch accretionary tract, Newfoundland Appalachians. Tectonophysics 479, 150–164. https://doi.org/10.1016/j.tecto.2008.12.002.

Zagorevski, A., van Staal, C.R., Rogers, N., McNicoll, V.J., Pollock, J., 2010. Middle Cambrian to Ordovician Arc-Backarc Development on the Leading Edge of Ganderia, Newfoundland Appalachians. In: Geological Society of America Memoirs, vol. 206. Geological Society of America, pp. 367–396.

Zahirovic, S., Seton, M., Müller, R.D., 2014. The Cretaceous and Cenozoic tectonic evolution of Southeast Asia. Solid Earth 5, 227–273. https://doi.org/10.5194/se-5-227-2014.

Zen, E., 1983. Bedrock Geological Map of Massachusetts. In: U.S. Geological Survey Map scale 1:250,000.

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 Publications in Biology and Geology, 2, pp. 1–21.