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A plate tectonic scenario for the Iapetus and Rheic oceans

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ABSTRACT

The tectonics, dynamics, and biogeographic landscape of the early Paleozoic were dominated by the opening and expansion of one large ocean—the Rheic—and the diminution to terminal closure of another—Iapetus. An understanding of the evolution of these oceans is thus central to an understanding of the early Paleozoic, but their chronicle also presents a rich temporal profile of the Wilson cycle, illustrating continental-scale rifting, microcontinent formation, ocean basin development, arc accretion, and continent–continent collision. Nevertheless, contemporary paleogeographic models of the Iapetus and Rheic oceans remain mostly schematic or spatio-temporally disjointed, which limits their utility and hinders their testing. Moreover, many of the important kinematic and dynamic aspects of the evolution of these oceans are impossible to unambiguously resolve from a conceptual perspective and the existing models unsurprisingly present a host of contradictory scenarios. With the specific aim to resolve some of the uncertainties in the evolution of this early Paleozoic domain, and a broader aim to instigate the application of quantitative kinematic models to the early Paleozoic, I present a new *plate tectonic* model for the Iapetus and Rheic oceans. The model has realistic tectonic plates, which include oceanic lithosphere, that are defined by explicit and rigorously managed plate boundaries, the nature and kinematics of which are derived from geological evidence and plate tectonic principles. Accompanying the presentation and discussion of the plate model, an extensive review of the underlying geological and paleogeographic data is also presented.

1. Introduction

The opening of the Rheic Ocean (McKerrow and Ziegler, 1972) by the rifting of marginal terranes from northwest Gondwana, and the subsequent closure of the Iapetus Ocean (Harland and Gayer, 1972) by means of a three-way continental collision between Baltica, Avalonia, and Laurentia (Cocks and Fortey, 1982; Torsvik et al., 1996), arguably constitute the most dramatic, defining, and well-studied tectonic events of the early Paleozoic. An understanding of the evolution of these oceans is thus central to a broader understanding of the early Paleozoic. Moreover, as their history embodies a temporal cross-section through the transition of two major Wilson cycles, the chronicle of the Iapetus and Rheic oceans is also relevant to the study of global tectonics in general. However, notwithstanding a broad consensus on the first-order narrative (Torsvik and Trench, 1991), many aspects of this important tectonic saga remain unresolved. For example, among contemporary paleogeographic models that depict the opening of the Rheic, there are significant differences in the published number of independent terranes that rifted from northwest Gondwana, the manner in which they rifted, and in how and when those terranes arrived at the margins of Baltica and Laurentia (Cocks and Torsvik, 2002; Nance et al., 2010; van Staal and Hatcher, 2010; Pollock et al., 2011; Waldron et al., 2014). The differing terrane reconstructions in turn result in different ocean basin plans and provide contrasting examples of processes related to rifting, microcontinent formation, and ocean basin development.

Although additional data are (as always) desirable, many of the discrepancies among contemporary early Paleozoic paleogeographic models are driven not by a dearth of available data but by the limited adoption of the data available. In some models, this is partly due to the fact that the model was principally designed to fit the observations of a specific area (i.e. northern Appalachians, southern British Isles, etc.), and only later expanded to a larger region as a correlative exercise. However, a more significant shortcoming is that nearly all of the presently available models are schematic, or at least substantially spatio-temporally disjointed. That means that they are not bound to meet general conditions of tectonic feasibility or kinematic continuity, which greatly loosens a host of constraints that would otherwise be placed on them. Thus, there is a wealth of untapped ‘data’ in the form of practical tectonic considerations, which can greatly enhance our ability to critically evaluate existing models by further limiting the range of permissible tectonic scenarios.

It is extremely challenging to construct an early Paleozoic paleogeographic model on a rigorous plate tectonic framework because the entirety of the pre-Mesozoic oceanic lithosphere has been lost by subduction, save some minor relics preserved as ophiolites. Nevertheless, the kinematics of long-lost ocean basins can still be partly surmised through a careful analysis of the kinematics of the continents and

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terranes that formerly flanked them, together with the geological observations from their continental margins. By further uniting these inferred kinematics within a framework held to obey fundamental tectonic principles, a kinematic model that strictly conforms to both the observational data *and* basic plate tectonic rules can be built (Seton et al., 2012; Domeier and Torsvik, 2014). Such an approach can identify existing paleogeographic concepts that are inherently tectonically untenable, and those which work only in isolation.

Following this approach, this paper presents an early Paleozoic (500–420 Ma) plate tectonic model for the Iapetus and Rheic oceans that has been constructed to meet the available paleomagnetic, paleontological, and geological data, and which evolves in accordance with plate tectonic fundamentals. The result is a 'full-plate' model, wherein plate boundaries and oceanic lithosphere, in addition to the continents, are prescribed and advanced through the modeled interval. Such a full-plate model for the early Paleozoic is seen in the pioneering work of Stampfli and Borel (2002), but their model is based on a relative (Europe-fixed) kinematic network and its details are unfortunately industry confidential. In contrast, the model presented here is built from an absolute continental reconstruction (Torsvik et al., 2014), making it the first absolute, full-plate tectonic model for the early Paleozoic. Furthermore, the details of the presented model are freely distributed. The model should prove useful as a general paleogeographic reference and as an input for other modeling exercises, but should also serve as a shared research platform for the paleogeographic community. Ideally, the model can be tested against new observations and refined when necessary, so as to evolve in parallel with our collective understanding of early Paleozoic tectonics.

2. Methodology

The methodology in this study follows that in Domeier and Torsvik (2014), here reiterated succinctly. The plate tectonic model presented is built upon the continental reconstruction model of Torsvik et al. (2014), which itself is founded upon a global paleomagnetic dataset (Torsvik et al., 2012), a catalog of large igneous province (LIP) and kimberlite distributions (Torsvik et al., 2008, 2010) and a wealth of qualitative to semi-quantitative geological and paleontological data. These data, many of which are reviewed in the following sections and in Appendix A (available from journal website), provide the basis to reconstruct the continents through time. Notably, whereas paleolatitude can (ideally) be unequivocally determined from paleomagnetic data, paleolongitude is mostly ambiguous. Paleontological data can offer insights into the relative proximity of continents, and together with paleomagnetic data they may provide some constraints on relative longitude, but cannot determine absolute paleolongitude. Concerning absolute paleolongitude, Torsvik et al. (2008, 2010) showed that LIP and kimberlite occurrences of the last 320 Myr—when reconstructed to their original positions in a mantle reference frame—coincided with the margins of the large low shear velocity provinces (LLSVPs) in the lowermost mantle. Following the assumption that the LLSVPs have remained stable from the earliest Paleozoic, as they demonstrably have since the Mesozoic, it is possible to construct models with provisional absolute paleolongitude, when and where LIPs and kimberlites are found. This is a major assumption that requires further validation, but, significantly, the model presented herein demonstrates that it is at least *possible* to construct an early Paleozoic plate model under this paradigm.

With the time-dependent motions of the continents established, work proceeds with the reconstruction of ocean basin kinematics and the delineation of plate boundaries. The relative kinematics of the oceans can be inferred through careful integration and analysis of the geology from the margins of the continents, which can provide information about the relative motion (or lack thereof) of the oceanic lithosphere that once flanked them. For example, observations of arc magmatism, HP/UHP metamorphism, ophiolite obduction, etc. can reflect subduction, and thus convergence between a pair of plates, whereas rift-related sedimentation and volcanism, etc., may denote the onset of divergence. Similarly, structural relics can reveal the presence of a transcurrent boundary and determine the sense of motion that once occurred along it. By unifying the relative kinematics inferred from those geological records with the absolute kinematics of the continents, the absolute kinematics of the oceans can be constrained. The specification and temporal management of plate boundaries are likewise realized through the integration of the continental rotation model, continental geology, and basic plate tectonic principles. Plates are assumed to be rigid and their boundaries divisible into segments of divergent, transcurrent, and convergent motion. Along divergent boundaries, spreading is assumed to be symmetrical and orthogonal, and ridge segments themselves are assumed to follow the trace of a great circle passing through the Euler pole that defines the relative motion of the adjoining plates. No assumptions are made about the orientation of continental rifting that precedes seafloor spreading, and it can be highly oblique. Transform boundaries are assumed to follow the trace of a small circle about the Euler pole describing the relative motion of the adjoining plates. No comparably unique assumptions apply for estimating the orientation of subduction zones, but their locations can often be constrained through conservation (of surface area) considerations, and their polarity may be determinable from the geological record. Plate dynamic considerations are not inherent to construction of the model, but are occasionally invoked to discriminate competing scenarios that may be equally kinematically viable; these are discussed in Section 4.

Reconstruction of the ocean basins and the plate boundary network was conducted with the open-source software Gplates (Boyden et al., 2011) (www.gplates.org). The reconstruction of those elements was accomplished via an iterative process, since they are required not only to meet the constraints imposed by a given time but also to evolve in compliance with tectonic rules to fit the observations of other times. Additionally, solutions are often non-unique; in such cases, adoption of the simplest solution that satisfies the existing constraints has been sought. Equipped with the continental reconstruction model, inferred ocean basin kinematics, and the network of plate boundaries, the final plate model was built with continuously closing plate polygons, according to the method of Gurnis et al. (2012). Because the scope of the model is restricted to the domain of the Iapetus and Rheic oceans, it is encircled by an arbitrary perimeter used to close those plate polygons that moved partly beyond the frame of interest. It is important to note that this perimeter is geologically meaningless. Although the plate boundaries were implemented with an arbitrary time-stepping of 1 Myr, the temporal resolution of the plate model can be scaled according to the needs of the user.

3. Geological synopses

The following section presents interpretations of the early Paleozoic geology from the margins of the continents that flanked the Iapetus and Rheic oceans (Fig. 1), with a focus on the features that communicate information about plate interactions. The geological observations from which the interpretations have been drawn are summarized in Appendix A, together with overview maps and many additional references. The principal interpretations of this section are also presented in condensed form in Table 1. In this paper, geochronological units are referenced to the timescale of Walker et al. (2013) and the informal term 'early Cambrian' refers to epochs 1 (Terreneuvian) and 2 (unnamed), 'middle Cambrian' refers to epoch 3 (unnamed), and 'late Cambrian' refers to epoch 4 (Furongian). The informal term 'early Silurian' refers to the Llandovery, 'middle Silurian' refers to the Wenlock, and 'late Silurian' refers to the Ludlow and Pridoli. The term 'terrane' is used in an informal sense to refer to lithological units, presumed to be of the same affinity, that are demonstrated or inferred to cover fragments of continental basement. Some of these 'terranes' comprise yet smaller, possibly distinct units that could be classified as 'terranes' themselves.

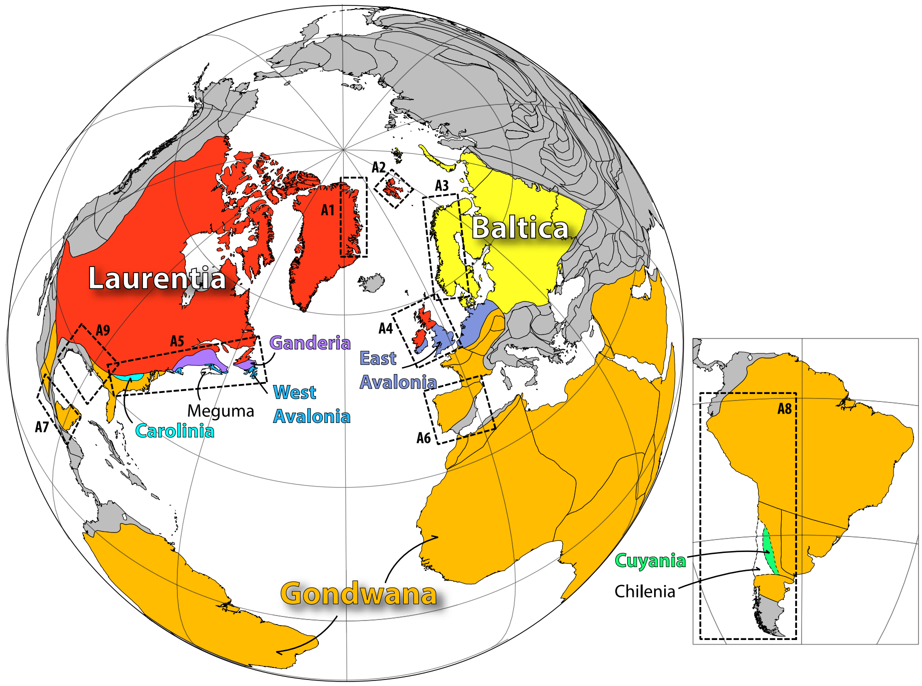


Fig. 1. Modern map showing the present-day distribution of continents and terranes that formerly comprised the margins of the Iapetus and/or Rheic oceans and which are employed in the presented plate model. Warm colors denote the major continents (red = Laurentia, orange = Gondwana, yellow = Baltica) and continental fragments that were coherent with these continents during the early Paleozoic, whereas cool colors denote terranes that were independent at some time during the early Paleozoic. White-colored terranes (Meguma and Chilenia) are discussed in the text but not used in the model, and gray areas are only depicted here for reference. Dashed boxes show the location of overview maps in Appendix A (figure numbers: A1 = northeast Greenland, A2 = Svalbard, A3 = northwest Baltica, A4 = northern British Isles and East Avalonia, A5 = eastern Laurentia, A6 = Iberia, A7 = central America, A8 = proto-Andes, A9 = Ouachita embayment), which also correspond to the topical divisions in Appendix A and in Section 3 of the main text.

Where possible, an endeavor has been made to limit the division of terranes, but not everyone will agree with these simplifications.

3.1. Northeast Laurentia (northeast Greenland and Svalbard)

The highly similar early Cambrian to Middle Ordovician successions of clastic and carbonate platform rocks in the Caledonian allochthons of northeast Greenland and in the northeast of Svalbard (Nordaustlandet and Ny Friesland) suggest that these areas were passive at that time, and probably near each other (Smith and Rasmussen, 2008; Gasser, 2013). The subsequent cessation of passive margin sedimentation and the coeval development of a continental magmatic arc in the Middle Ordovician signify the destruction of that passive margin and the initiation of subduction (Rehnström, 2010; Augland et al., 2012). This subduction later culminated in the Scandian collision between Baltica and Laurentia, in which northeast Greenland and northeast Svalbard were marked by west-vergent folding and thrusting, regional metamorphism, and magmatism. The timing of deformation, metamorphism, and magmatism indicates that collision began in the early to mid-Silurian (~435–430 Ma), but deformation continued, at least locally, beyond 400 Ma (Gee and Teben'kov, 2004; Gilotti et al., 2008; Gasser, 2013). In the latest Silurian to early Middle Devonian, HP metamorphism affected the northeast Greenland eclogite province (NGEP) and Liverpool Land (Gilotti et al., 2008; Augland et al., 2011). That metamorphism was undoubtedly related to the Scandian collision, but its current location on what was then the upper plate reflects complexities in the collision process that are still not fully understood. Still more perplexing is the Late Devonian to early Carboniferous UHP metamorphic event recognized in the NGEP, which is enigmatic both in its location and timing (Gilotti et al., 2008).

Southwest Svalbard lacks evidence of Caledonide deformation and magmatism and was probably not assembled with northeast Svalbard until the late stages of the Caledonian orogeny. Nonetheless, it was probably proximal to the early Paleozoic passive margin of northeast Laurentia, based on the occurrence of Cambro–Ordovician platform-type sedimentary rocks bearing fossils of Laurentian affinity in southwest Spitsbergen (Szaniawski, 1994; Gee and Teben'kov, 2004), and was most likely adjacent to the Franklinian margin, which was also largely unaffected by Caledonian orogenesis. Yet more incongruous are the presumed Early Ordovician HP complexes of western Svalbard, which are inconsistent with the picture of an early Cambrian to Middle Ordovician passive margin (Gee and Teben'kov, 2004; Labrousse et al., 2008). However, because those complexes are allochthonous and were probably not emplaced prior to the Middle Ordovician, it is possible that they record an earlier phase of outboard subduction that is otherwise unknown from northeast Greenland and Svalbard (Table 1).

3.2. Northwest Baltica (western Scandinavia)

The early Paleozoic successions from the foreland of Baltica suggest that its northwest margin was passive from the early Cambrian to the latest Ordovician or earliest Silurian (Corfu et al., 2014). The appearance of volcanic ash horizons in the Late Ordovician passive margin strata herald the approach of the active margins of north Avalonia and northeast Laurentia (Torsvik and Rehnström, 2003; Bruton et al., 2010), but, according to stratigraphic constraints and metamorphic ages, the northwest margin of Baltica was not overthrust until the late Llandovery to Wenlock (Andersen et al., 1990; Kirkland et al., 2006; Corfu et al., 2014). Closely following the initial signs of collision, orogenic molasse appeared in the foreland of Baltica in the Wenlock to Ludlow (Bruton et al., 2010), and the Western Gneiss Region of Norway experienced (U)HP metamorphism in the latest Silurian to Early Devonian, reflecting its partial subduction by this time (Hacker et al., 2010; Corfu et al., 2014).

The Caledonian nappe stack above the parautochthonous foreland of Baltica is a complicated juxtaposition of elements telescoped from the pre-collisional margin of Baltica, as well as exotic oceanic and continental assemblages with inferred to demonstrated Iapetan and Laurentian

Table 1
Summarized interpretations of early Paleozoic continental boundaries inferred from the geological data discussed in the main text (Section 3) and Appendix A.

Margin/Terrane *(sub-domain)*	Onset (Ma)	Termination (Ma)	Boundary type	Polarity
Laurentia				
Northeast Greenland and Svalbard				
	Precambrian	470	Passive	–
	Accretion of Sunnhordland and Köli nappe complexes (peri-Laurentia) at 470 Ma			
	470	430	Convergent	West-dipping
	Collision with Baltica at 430 Ma			
North British Isles				
	Precambrian	470	Passive	–
	Accretion of Midland Valley–South Mayo terrane (peri-Laurentia) at 470 Ma			
	470	450	Convergent	Northwest-dipping
	Accretion of Peri-Gondwanan arc(?) at 450 Ma			
	450	430	Convergent	Northwest-dipping
	Collision with East Avalonia (peri-Gondwana) at 430 Ma			
North Appalachians	Early Cambrian	470	Passive	–
	Accretion of Dashwoods terrane (peri-Laurentia) at 470 Ma			
	470	460	Convergent	Northwest-dipping
	Accretion of Popelogan–Victoria arc (peri-Gondwana) at 460–455 Ma			
	460	430	Convergent	Northwest-dipping
	Accretion of Ganderia (peri-Gondwana) at 430 Ma			
	430	420	Convergent	Northwest-dipping
	Accretion of West Avalonia (peri-Gondwana) at 420 Ma			
South Appalachians	Early Cambrian	470	Passive	–
	Accretion of East Piedmont terranes (peri-Laurentia) at 470 Ma?			
	470	455?	Convergent	Northwest-dipping
	Accretion of Carolinia (peri-Gondwana) at 455 Ma?			
	455	440	Transform	Dextral
	440	420	Convergent	Northwest-dipping
South Laurentia (Ouachita embayment)				
	middle Cambrian	320	Passive	–
Baltica				
Northwest Baltica				
	Precambrian	430	Passive	–
	Collision with Laurentia at 430 Ma			
Southwest Baltica	Precambrian	445	Passive	–
	Collision with East Avalonia (peri-Gondwana) at 445–440 Ma			
Gondwana				
Northwest Gondwana				
	500	485	Divergent	–
	485	420	Passive	–
West Gondwana				
	500?	460	Convergent	East dipping
	Accretion of Cuyania at 460 Ma			
	460	420	Passive?	–
Terranes and Island Arcs of Laurentian Affinity				
Sunnhordland and Köli nappe complexes				
	490	470	Convergent	East-dipping
	Accretion to northeast Greenland (Laurentia) at 470 Ma			
Clew Bay-Highland Border suprasubduction ophiolite complexes				
	500	490	Convergent	Northwest-dipping
	Accretion to Midland Valley terrane (peri-Laurentia) at 490 Ma			
Midland Valley–South Mayo terrane				
	490	470	Convergent	Southeast-dipping
	Accretion to north British Isles (Laurentia) at 470 Ma			
Lushs Bight intraoceanic arc				
	510	490	Convergent	Northwest-dipping
	Accretion to Dashwoods terrane (peri-Laurentia) at 490 Ma			
Dashwoods terrane				
	490	470	Convergent	Southeast-dipping
	Accretion to north Appalachians (Laurentia) at 470 Ma			
East Piedmont domain				
	490	470	Convergent	Southeast-dipping
	Accretion to south Appalachians (Laurentia) at 470 Ma?			
Cuyania (Precordillera)				
	middle Cambrian	460	Passive?	–
	Accretion to west Gondwana at 460 Ma			
Terranes and Island Arcs of Gondwanan Affinity				
East Avalonia				
(North margin)	500?	470	Convergent	South-dipping
	470	460	Divergent	–
	460	440	Convergent	South-dipping
	Collision with southwest Baltica and north British Isles (Laurentia) at 445–430 Ma			

Table 1 (*continued*)

Margin/Terrane *(sub-domain)*	Onset (Ma)	Termination (Ma)	Boundary type	Polarity
(South margin)	500	485	Divergent	–
	485	460	Passive	–
	460	450	Divergent	–
	450	440	Passive	–
	440	420	Convergent	North-dipping
Penobscot arc				
	middle Cambrian	485	Convergent	Southeast-dipping
	Accretion to peri-Gondwana at 485–475 Ma			
Popelogan–Victoria arc				
(North side)	475	450	Convergent	Southeast-dipping
	Accretion to north Appalachians and south British Isles? (Laurentia) at 460–450 Ma			
(South side)	475	465	Divergent	–
Ganderia				
(North margin)	500	490	Divergent	–
	490	485	Passive	–
	Accretion of Penobscot arc at 485–475 Ma			
	475	465	Divergent	–
	465	430	Passive	–
	Accretion to north Appalachians (Laurentia) at 430 Ma			
(South margin)	500	485	Divergent	–
	485	440	Passive	–
	440	420	Convergent	Northwest-dipping
	Accretion of West Avalonia (peri-Gondwana) at 420 Ma			
West Avalonia				
(North margin)	500	460	Passive	–
	460	450	Divergent	–
	Accretion to north Appalachians (Laurentia) at 420 Ma			
(South margin)	500	485	Divergent	–
	485	440	Passive	-
	440	420	Convergent?	Northwest-dipping
Carolinia				
	500	485	Divergent	–
	485	455	Passive	–
	Accretion to south Appalachians (Laurentia) at 455 Ma?			

affinities. Among the oceanic assemblages, the Sunnhordland and Köli nappe complexes exhibit evidence of an intraoceanic subduction system that was active by the late Cambrian and continued into the Early to Middle Ordovician (Dunning and Pedersen, 1988; Pedersen and Dunning, 1997; Slagstad et al., 2013). Early to Middle Ordovician fossils of Laurentian affinity in the Støren nappe (Reed, 1932; Pedersen et al., 1992) and Archean to Paleoproterozoic inherited zircons in Early to Middle Ordovician granitoids intruding the Karmøy ophiolite (Pedersen and Dunning, 1997) suggest that this intraoceanic arc was close to Laurentia, at least by the Early Ordovician. The apparent termination of intraoceanic subduction in the late Early to early Middle Ordovician was coincident with HP metamorphism in the Jæren nappe (Smit et al., 2011) and widespread mid-to-Late Ordovician deformation in the Köli and Lyngen nappes (Slagstad et al., 2013; Corfu et al., 2014), possibly signifying collision of the intraoceanic arc with Laurentia at that time. Such a scenario could also explain the Early Ordovician HP complexes presently preserved in western Svalbard, as well as the timing of subduction initiation beneath northeast Greenland–Svalbard in the Middle Ordovician. Accordingly, the appearance of Late Ordovician to early Silurian subduction-related magmatism in the Köli nappe complex (Meyer et al., 2003; Corfu et al., 2014) and the genesis of coeval suprasubduction zone ophiolitic rocks in the Solund–Stavfjord nappe (Furnes et al., 2012) can be related to west-dipping subduction beneath northeast Laurentia, following accretion of the intraoceanic arc to the margin of Laurentia and a consequent reversal in the polarity of subduction. This scenario is further corroborated by the metasedimentary assemblages of Laurentian affinity that structurally overlie the oceanic complexes in the Caledonide nappe stack, which were variably deformed and metamorphosed during the Ordovician, and intruded by Ordovician to Silurian magmatic arc rocks (Barnes et al., 2007; Roberts et al., 2007; Corfu et al., 2014). This subduction-related magmatism ceased in the mid-Silurian, when Baltica and Laurentia collided (Table 1).

3.3. British Isles and the Brabant Massif

The British Isles are bisected by the Iapetan suture and were thus largely assembled by the terminal closure of the Iapetus Ocean during the Caledonian orogeny (Fig. 1). Prior to their Silurian amalgamation, northern Ireland and Scotland (north of the suture) constituted part of northeast Laurentia, whereas southern Ireland, England, and Wales (south of the suture) together comprised part of East Avalonia, a peri-Gondwanan terrane that also included the Brabant Massif and areas further to the east between the Thor suture to the north and the Rheic suture to the south. Controversial correlatives of East Avalonia further to the southeast include the Bruno–Silesia terrane, the Moesian terranes, and the Istanbul terrane (Kalvoda and Bábek, 2010; Mazur et al., 2010), but their early Paleozoic histories and affinities are poorly resolved.

As in northeast Greenland, the northern British Isles were characterized by a southeast-facing passive margin from the early Cambrian to the Early Ordovician (Cawood et al., 2007; Stephenson et al., 2013). The destruction of this passive margin during the late Early to Middle Ordovician Grampian orogeny was due to the accretion of a Cambrian to Early Ordovician intraoceanic arc that is thought to be preserved among the ophiolitic and arc complexes along the south margin of the Grampian terrane of northern Ireland and Scotland, and beneath the younger cover of the Midland Valley graben (Cooper et al., 2011; Chew and Strachan, 2014). Assembly of this Cambrian to Early Ordovician intraoceanic arc complex may have included the incorporation of a minor outboard assemblage based on the occurrence of the Cambro–Ordovician Ballantrae ophiolite to the south of the Midland Valley terrane in Scotland (Chew and Strachan, 2014; Stone, 2014). Following accretion of the intraoceanic arc, a Middle Ordovician to early Silurian accretionary complex was constructed to the southeast of the Midland Valley terrane, indicating that subduction initiated beneath the northern British Isles in the Middle Ordovician and continued into the Silurian (Leggett, 1987; Waldron et al., 2008). An enigmatic episode of deformation and metamorphism subsequently affected the Northern Highlands terrane of Scotland during the Late Ordovician (Bird et al., 2013; Cawood et al., 2014), and possibly also the Grampian terrane (Chew and Strachan, 2014), but terminal closure of the Iapetus Ocean and the collision of East Avalonia did not occur until the mid-Silurian (Goodenough et al., 2011) (Table 1).

East Avalonia was located along the northwest margin of Gondwana at the start of the Paleozoic (McIlroy and Horák, 2006; Nance et al., 2008; Woodcock and Strachan, 2009), but, according to regional subsidence patterns, rifted from that landmass in the latest Cambrian to earliest Ordovician (Prigmore et al., 1997; Linnemann et al., 2012). The subsequent northward drift of East Avalonia and its ultimate collision with Baltica and Laurentia are evident from paleomagnetic data (Table 2; Fig. 2) and the fossil record (Cocks and Fortey, 2009). The appearance of widespread Ordovician arc magmatism across England, Wales, and southeast Ireland implies that the northward drift of East Avalonia was accommodated by subduction directed southward beneath its north margin (Woodcock and Strachan, 2009). Episodes of extension-related volcanism and subsidence in the Middle to Late Ordovician probably reflect one or more instances of backarc extension and/or oceanward migration of the magmatic arc (Prigmore et al., 1997; Woodcock and Strachan, 2009). Magmatism related to southward-directed subduction ultimately ceased by the end of the Ordovician (Millward and Evans, 2003), coincident with the Late Ordovician to early Silurian 'soft docking' of East Avalonia and Baltica (Torsvik and Rehnström, 2003).

3.4. East Laurentia (northern and southern Appalachians)

The early Paleozoic evolution of the eastern margin of Laurentia was marked by a series of complex and diachronous accretionary events wherein peri-Laurentian, Iapetan, and peri-Gondwanan assemblages were progressively amalgamated with Laurentia, such that its eastern margin grew significantly in the Ordovician and Silurian. In the northern Appalachians (north of the New York promontory), the early Paleozoic autochthon of Laurentia is juxtaposed with the Dunnage zone, which comprises allochthonous rocks of Laurentian affinity and tectonically commingled assemblages of Iapetan to Gondwanan affinity. The Dunnage zone, in turn, is flanked to the southeast by three peri-Gondwanan terranes: Ganderia, West Avalonia, and Meguma (Fig. 1).

Table 2
Middle Cambrian to Silurian paleomagnetic data from early Paleozoic exotic terranes of the Iapetus and Rheic oceans. Slat/Slon: sampling site latitude/longitude, Age: best-estimate of magnetization age, +/− age: best-estimate of error on estimated age, Dec/Inc: declination/inclination of mean magnetization direction, a95: alpha-95 on mean magnetization, lat: paleolatitude calculated from mean inclination, −lat/+lat: lower/upper error on paleolatitude from mean inclination.

Terrane / Formation	*Slat*	*Slon*	*Age (Ma)*	*+/− Age (Ma)*	*Dec*	*Inc*	*a95*	*lat*	*−lat*	*+lat*	*Reference*
EAST AVALONIA											
Treffgarne volcanics	52.0	−5.0	478 (mid-Early Ordovician)	4	298	75	5.5	61.8	8.6	9.7	a
Stapeley volcanics	52.6	−3.0	467 (early Llanvirn)	4	116	68	4.9	50.9	6.5	7.3	b
Builth igneous and sediments	52.1	−3.3	464 (late Llanvirn)	4	154	70	10.0	53.7	13.0	16.6	c
Tramore volcanics	52.1	−7.4	455 (Caradoc)	6	324	−63	8.5	44.0	9.3	11.6	d
Borrowdale volcanics *	54.4	−3.2	448?	?	347	−62	6.9	43.1	7.6	9.1	e, f
Midlands Minor Intrusives *	52.5	−1.5	442?	?	154	−51	10.4	32.0	8.6	10.9	g
Browgill redbeds #	54.3	−2.5	436 (Telychian)	3	43	−37	12.4	20.4	7.7	9.6	h
Tortworth volcanics	51.7	−2.5	434 (late Telychian)	3	56	−30	4.7	16.1	2.8	3.0	i
Mendips volcanics	51.2	−2.5	432 (early Wenlock)	3	95	−24	8.8	12.6	4.8	5.3	j
Mill Cove redbeds #	52.2	−10.3	428 (Homerian, late Wenlock)	3	219	34	7.9	18.7	4.9	5.5	k
Old Red Sandstone #	51.9	−3.8	410 (Ludlow − Emsian)	17	232	46	8.5	27.5	6.4	7.7	l
Old Red Sandstone *#	51.9	−3.3	410 (Ludlow − Emsian)	17	246	53	7.2	33.5	6.3	7.5	m
DUNNAGE ZONE											
Notre Dame Subzone											
Moreton's Harbour Group igneous rocks	49.5	−55.0	477 (Early Ordovician)	1	171	22	6.5	11.4	3.5	3.8	n
Lawrence Head volcanics	49.5	−54.5	465 (Middle Ordovician)	2	56	23	18.5	12.0	9.7	11.9	o
Exploits Subzone											
Robert's Arm, Chanceport, Summerford volcs.	49.5	−55.2	470 (Early–Middle Ordovician)	12	165	50	6.0	30.8	5.0	5.8	p
Tetagouche Group volcanics	47.0	−66.0	464 (Middle Ordovician)	6	60	69	13.0	52.5	15.9	21.8	q
Stacyville volcanics	46.0	−68.6	464 (Middle Ordovician)	6	90	36	12.4	20.0	7.6	9.4	r
Winterville volcanics	46.8	−68.7	458 (Middle–Late Ordovician)	6	327	−21	9.3	10.9	5.0	5.4	s
Bluffer Pond volcanics	46.5	−69.0	458 (Middle–Late Ordovician)	6	339	−28	11.9	14.9	6.7	7.8	t
Lawrenceton volcanics	49.1	−55.7	433 (Llandovery–Wenlock)	6	16	−27	8.1	14.4	4.6	5.1	u
Springdale and Wigwam redbeds	49.5	−55.0	430 (Wenlock)	6	37	−37	12.4	20.4	7.7	9.6	v
GANDERIA											
Bourinot Group	46.1	−60.4	503 (middle Cambrian)	6	293	−66	8.1	48.3	9.8	12.0	w
WEST AVALONIA											
Nahant intrusives	42.4	−70.9	489 (radiometric)	1	279	−77	3.9	64.7	6.5	7.0	x
Dunn Point volcanics	45.8	−62.1	460 (radiometric)	3	344	−60	4.1	40.9	4.4	4.9	y, z
Cape St. Mary sills	46.8	−54.0	441 (radiometric)	2	344	−51	9.0	31.5	7.4	9.2	aa
CAROLINIA											
Cid Formation metasediments *	35.0	−80.2	455?	?	159	39	5.1	22.3	3.5	3.8	bb
Uwharrie and Cid Formation metaseds. *	35.5	−80.0	455?	?	221	40	14.2	22.8	9.2	12.0	cc
CUYANIA											
Pavon Formation sediments #	−34.6	−68.6	455 (Sandbian)	3	64	57	6.6	37.6	6.4	7.6	dd

References: a. Trench et al. (1992), b. McCabe and Channell (1990), c. (McCabe et al., 1992), d. Trench and Torsvik (1991), e. Channell and McCabe (1992), f. Millward and Evans (2003), g. Vizan et al. (2003), h. Channell et al. (1993), i. Torsvik et al. (1994), j. Torsvik et al. (1993), k. Mac Niocaill (2000), l. Channell et al. (1992), m. Setiabudidaya et al. (1994), n. Johnson et al. (1991), o. Todaro et al. (1996), p. van der Voo et al. (1991), q. Liss et al. (1993), r. Wellensiek et al. (1990), s. Potts et al. (1995), t. Potts et al. (1993), u. Smethurst and McEnroe (2003), v. Stamatakos et al. (1995), w. Johnson and Van der Voo (1985), x. Thompson et al. (2010), y. Johnson and Van Der Voo (1990), z. Hamilton and Murphy (2004), aa. Hodych and Buchan (1998), bb. Vick et al. (1987), cc. Noel et al. (1988), dd. Rapalini and Cingolani (2004)

* Results without upper magnetization age constraints. The magnetization age listed for these results is the oldest *possible* age.

\# Results from sedimentary rocks that were corrected for inclination shallowing, assuming a flattening factor of 0.6 (Torsvik et al., 2012).

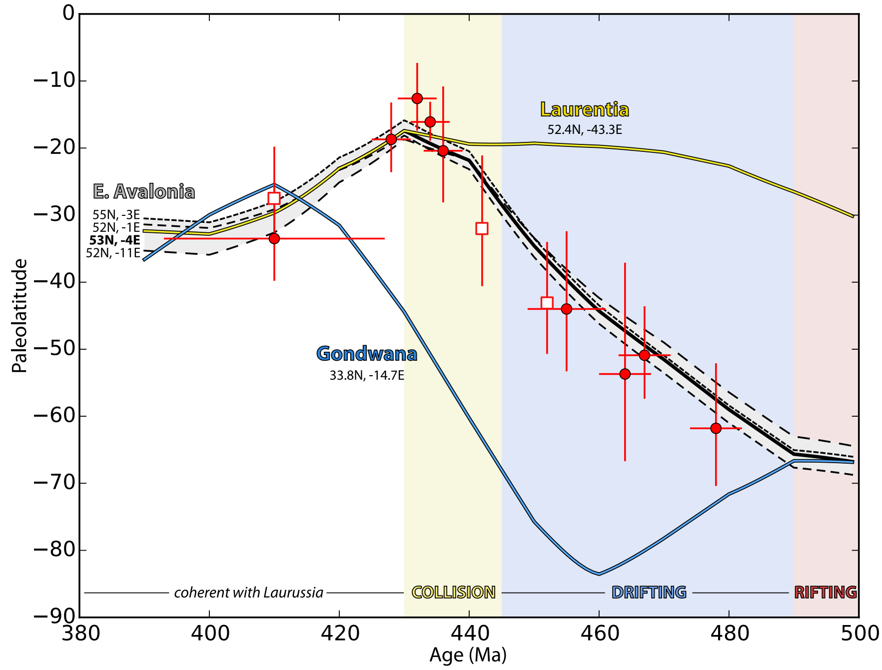


Fig. 2. Early Paleozoic paleomagnetic data from East Avalonia (red symbols; data from Table 2) plotted against paleolatitude reference curves for East Avalonia (black), Laurentia (yellow), and Gondwana (blue) from the presented plate model. The reference point used for each model curve is listed in present-day coordinates. Because vertical axis rotations have affected some of the paleomagnetic data from East Avalonia, a common reference point could not be calculated. Instead, several reference points were selected along the perimeter of East Avalonia, to display the inherent paleolatitude variation (gray area) that could be expected among paleomagnetic data from the different sampling sites there. Age errors on the paleomagnetic results are estimated from constraints provided in the literature. Red squares denote those data without upper age constraints; their placement on the timeline represents their oldest possible age. The background colors highlight the timing of East Avalonia's rifting (red), drifting (blue), and collision with Baltica and Laurentia (yellow), as inferred from geological data reviewed in the main text and Appendix A.

In the southern Appalachians (south of the New York promontory), the Laurentian autochthon is juxtaposed with parautochthonous to allochthonous rocks of the Piedmont zone of Laurentian to Iapetan affinity. The Piedmont zone, in turn, is flanked to the southeast by the Carolinia terrane of Gondwanan affinity.

Following the Neoproterozoic opening of the Iapetus Ocean, late Neoproterozoic rifting continued or resumed along the eastern margin of Laurentia and ultimately cleaved a continental ribbon from the margin by the early Cambrian, thereby opening a minor seaway and commencing a passive margin along east Laurentia (Cawood et al., 2001; Hibbard et al., 2007). By the middle Cambrian, intraoceanic subduction had begun either in Iapetus, to the southeast of the peri-Laurentian continental ribbon, or to its northwest, in the marginal seaway (van Staal et al., 2009; van Staal and Barr, 2012). In either case, this subduction ultimately ended with the accretion of a juvenile island arc onto the continental ribbon, in turn instigating southeast-dipping subduction of the marginal seaway beneath the ribbon terrane (Waldron and van Staal, 2001). Consumption of the marginal seaway culminated in the diachronous re-accretion of the continental ribbon to Laurentia. In the northern Appalachians, this corresponded to the latest Early to Middle Ordovician accretion of the peri-Laurentian Dashwoods terrane (Waldron and van Staal, 2001), whereas in the southern Appalachians, collision of the peri-Laurentian elements of the Piedmont zone occurred in the Middle Ordovician (Hibbard et al., 2007; Merschat, 2009). Following re-accretion of the continental ribbon, subduction jumped outboard of the newly enlarged margin and the polarity of subduction reversed, such that Laurentia then became the upper plate (Zagorevski and Van Staal, 2011). West-dipping subduction beneath the east margin of Laurentia continued until the first peri-Gondwanan assemblages arrived, which occurred in the late Middle to Late Ordovician in the northern Appalachians, as marked by the collision of the peri-Gondwanan Popelogan–Victoria arc (van Staal et al., 2009; Zagorevski and Van Staal, 2011), and at least by the Late Ordovician in the southern Appalachians, when the peri-Gondwanan Carolinia terrane arrived at the Laurentian margin (Hibbard et al., 2010, 2012).

On the far (south) side of the Iapetus Ocean, subduction is interpreted to have initiated beneath northwest Gondwana prior to the start of the middle Cambrian, giving rise to the Penobscot arc which rifted from the margin in the middle to late Cambrian, only to be re-accreted to it in the latest Cambrian to Early Ordovician (Zagorevski et al., 2010). Contemporaneously, a number of peri-Gondwanan terranes directly inboard of the Penobscot arc, namely, Ganderia and West Avalonia, but also possibly Carolinia and Meguma, began to rift from northwest Gondwana in the late middle Cambrian to earliest Ordovician (Pollock et al., 2011; van Staal and Barr, 2012). By the Early Ordovician, that rifting had led to the initial opening of the Rheic Ocean (Table 1), and the subsequent northward drift of those terranes is recorded by paleomagnetic (Table 2; Figs. 3–5) and fossil data (Cocks and Fortey, 2009; Pollock et al., 2011). On the outboard (northwest) side of the rifted terranes, the continuation of southeast-dipping subduction after re-accretion of the Penobscot arc led to the late Early Ordovician development of the Popelogan–Victoria arc on the remnants of the extinct Cambrian arc (Zagorevski et al., 2007, 2010). Coevally, a new phase of intra-arc to backarc extension led to the opening of the Exploits–Tetagouche basin between the arc to the northwest and the peri-Gondwanan terranes to the southeast (Zagorevski et al., 2008; van Staal and Barr, 2012). Here, a note of clarification is needed: with the opening of the Exploits–Tetagouche backarc, part of the basement of Ganderia, which partly floored the Popelogan–Victoria arc, was separated from the remainder of this terrane. This has led to some unfortunate terminological confusion. Here, the term 'Popelogan–Victoria arc' refers both to the arc and the fragments of Ganderian basement traveling with it, whereas 'Ganderia' refers to the crustal fragments left behind the backarc after its opening (the 'Gander margin' of van Staal et al. (2009)). Through the late Early and Middle Ordovician, subduction of Iapetan lithosphere continued beneath the Popelogan–Victoria arc while the Exploits–Tetagouche backarc and

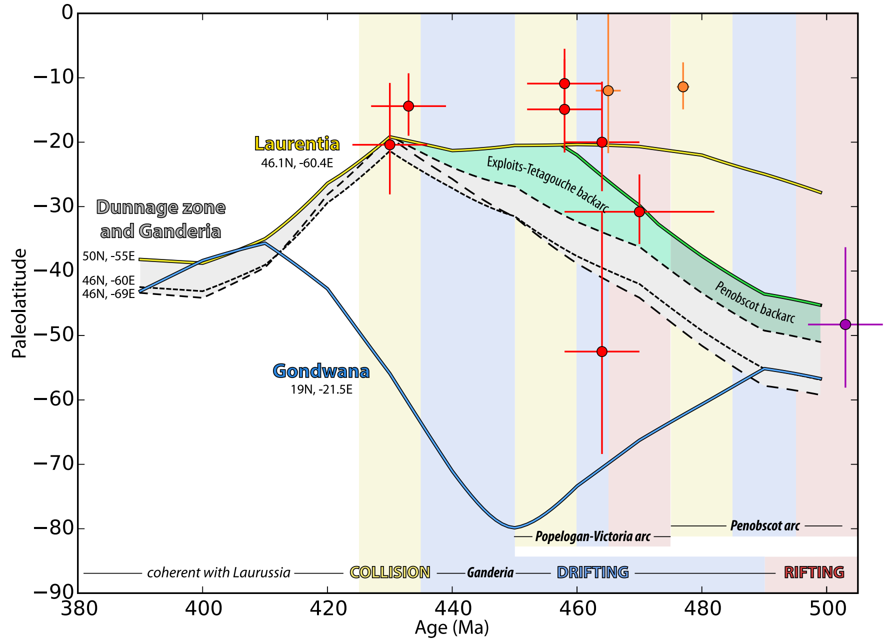


Fig. 3. Early Paleozoic paleomagnetic data (from Table 2) from Ganderia (purple symbols) and the Notre Dame subzone (orange symbols) and Exploits subzone (red symbols) of the Dunnage zone plotted against paleolatitude reference curves for Ganderia (black), Laurentia (yellow), and Gondwana (blue) from the presented plate model. The reference point used for each model curve is listed in present-day coordinates. Several reference points were selected from paleomagnetic sampling sites in 'Ganderia' (as it is simplistically defined in Fig. 1, but note that some of these sampling sites correspond to data categorized as belonging to the Exploits subzone) to display the possible paleolatitude variation (gray area) among different areas of this terrane during its drift. The solid green line depicts the paleolatitude of the approximate northernmost limit of the Penobscot and Popelogan–Victoria arcs from the model. The lighter green area between this green line and the gray area represents the approximate paleolatitude of the Penobscot and Exploits–Tetagouche backarcs (which separated the Penobscot and Popelogan–Victoria arcs from Ganderia) through time. Age errors on the paleomagnetic results are estimated from constraints provided in the literature. The background colors highlight the timing of rifting (red), drifting (blue), and collision (yellow) for the Penobscot arc, Popelogan–Victoria arc, and Ganderia, as inferred from geological data reviewed in the main text and Appendix A.

Rheic Ocean widened. Terminal closure of the main Iapetus Ocean (excluding the Exploits–Tetagouche backarc basin, which could otherwise be considered part of the Iapetus Ocean) began at least by the late Middle to Late Ordovician, when the Popelogan–Victoria arc arrived at the active margin of Laurentia (van Staal et al., 2009; Zagorevski and Van Staal, 2011) (Table 1).

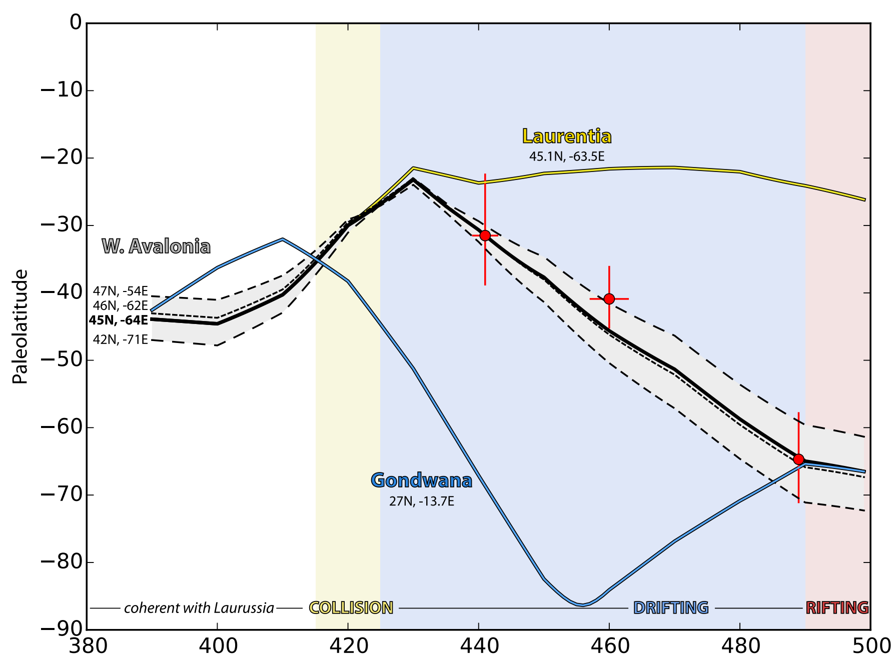


Fig. 4. Early Paleozoic paleomagnetic data from West Avalonia (red symbols; data from Table 2) plotted against paleolatitude reference curves for West Avalonia (black), Laurentia (yellow), and Gondwana (blue) from the presented plate model. The reference point used for each model curve is listed in present-day coordinates. Because vertical axis rotations have affected some of the paleomagnetic data from West Avalonia, a common reference point could not be calculated. Instead, several reference points were selected along the length of West Avalonia, to display the inherent paleolatitude variation (gray area) that could be expected among paleomagnetic data from the different sampling sites there. Age errors on the paleomagnetic results are estimated from constraints provided in the literature. The background colors highlight the timing of West Avalonia's rifting (red), drifting (blue), and collision with Laurussia (yellow), as inferred from geological data reviewed in the main text and Appendix A.

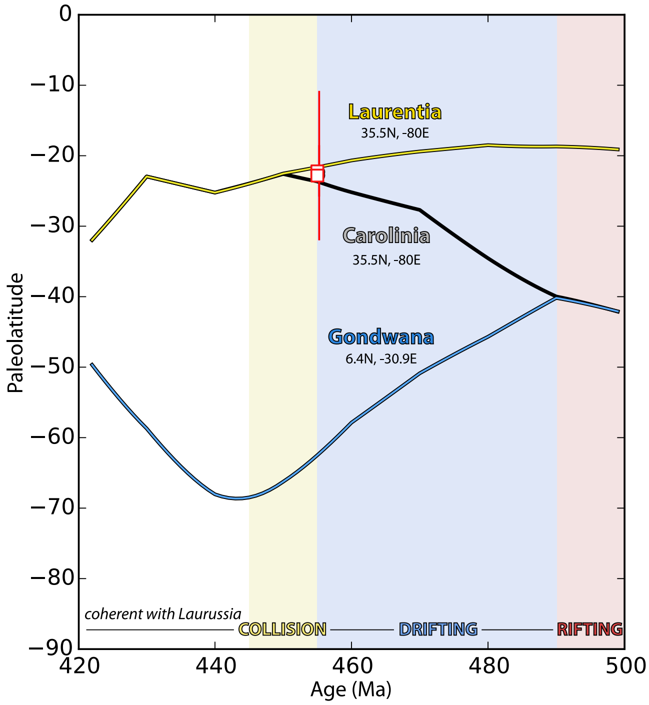


Fig. 5. Early Paleozoic paleomagnetic data from Carolinia (red symbols; data from Table 2) plotted against paleolatitude reference curves for Carolinia (black), Laurentia (yellow), and Gondwana (blue) from the presented plate model. The reference point used for each model curve is listed in present-day coordinates. The paleomagnetic data do not have upper age constraints and their placement on the timeline represents their oldest possible age. The background colors highlight the timing of Carolinia's rifting (red), drifting (blue), and collision with Laurentia (yellow), as inferred from geological data reviewed in the main text and Appendix A.

With the closure of the main Iapetus, the Exploits–Tetagouche backarc began to narrow as west-dipping subduction continued beneath the east margin of Laurentia (van Staal et al., 2008; van Staal and Barr, 2012). The Exploits–Tetagouche basin was entirely consumed by the mid-to-late Silurian, when the Salinic orogeny marked the accretion of (the remaining parts of) Ganderia to the margin of Laurentia (van Staal et al., 2008, 2009). Subsequently, subduction jumped outboard of the enlarged Laurentian margin (to the southeast of accreted Ganderia) and began consuming the basin that apparently separated Ganderia and West Avalonia. This basin was likely narrow, as the latest Silurian to Early Devonian Acadian orogeny that marked the collision of West Avalonia occurred only ~10–15 Myr after the Salinic orogeny (van Staal et al., 2009). The succeeding late Early Devonian to early Carboniferous Neoacadian orogeny is thought to mark the accretion of the Meguma terrane to Laurentia, although the details of how that occurred remain vague (van Staal and Barr, 2012).

3.5. Northwest Gondwana

A broad pattern of late middle Cambrian to Early Ordovician extension is evident among blocks—now dispersed in southern Europe and central America—that once occupied the northwest margin of Gondwana to the north of the cratons of northwest Africa and Amazonia (Murphy et al., 2005; Keppie et al., 2008; Linnemann et al., 2008; Martínez Catalán et al., 2009; Montero et al., 2009; Ortega-Obregon et al., 2010; Sánchez-García et al., 2010; Ballevre et al., 2012; Von Raumer et al., 2013; Žák et al., 2013) (Fig. 1). Following an earlier Neoproterozoic to Cambrian regime of compression to transpression, this margin-wide late middle Cambrian to Early Ordovician extension culminated in the opening of the Rheic Ocean, which established a passive margin along northwest Gondwana that lasted through the rest of the early Paleozoic (Linnemann et al., 2008). Among that multitude of now spatially dispersed records, those from Iberia and central America are further discussed in Appendix A, but an especially remarkable composite record worth mentioning here is that preserved in the allochthonous units of the Galicia-Trás-os-Montes Zone of northwest Iberia, which chronicles i) the initiation of a Cambrian peri-Gondwanan arc, ii) the establishment of a passive margin following its rifting, and iii) the onset of subduction in the mature Rheic Ocean by the end of the Early Devonian (Martínez Catalán et al., 2009; Arenas et al., 2014).

3.6. West Gondwana

Following the final stages of West Gondwana's assembly in the early Cambrian, east-dipping subduction began beneath the proto-Andean margin in the late Cambrian and continued for at least 30 Myr (Pankhurst et al., 2000; Dahlquist et al., 2008). The margin-wide scale of the subduction zone is reflected by the vast Famatinian continental magmatic arc that stretched from central Peru in the north (Chew et al., 2007) to central Argentina in the south (Chernicoff et al., 2010). This active margin was terminated in the Middle to Late Ordovician, when the exotic Cuyania (Precordillera) terrane arrived at the subduction zone (Thomas and Astini, 2003; Astini and Dávila, 2004) (Fig. 1). Prior to its Middle to Late Ordovician collision with Gondwana, lithostratigraphic and fossil records reveal that Cuyania rifted from Laurentia by the middle Cambrian and then began drifting across the Iapetus (Thomas and Astini, 2003; Benedetto, 2004), a scenario that is consistent with the available paleomagnetic data (Rapalini and Astini, 1998) (Table 2; Fig. 6). Following the accretion of Cuyania, another exotic terrane, Chilenia, docked to the outboard (western) margin of Cuyania in the Middle Devonian (Ramos et al., 1986; Álvarez et al., 2011), but much about this terrane is cryptic and the specific Late Ordovician to Middle Devonian kinematics that led to its collision are presently unknown.

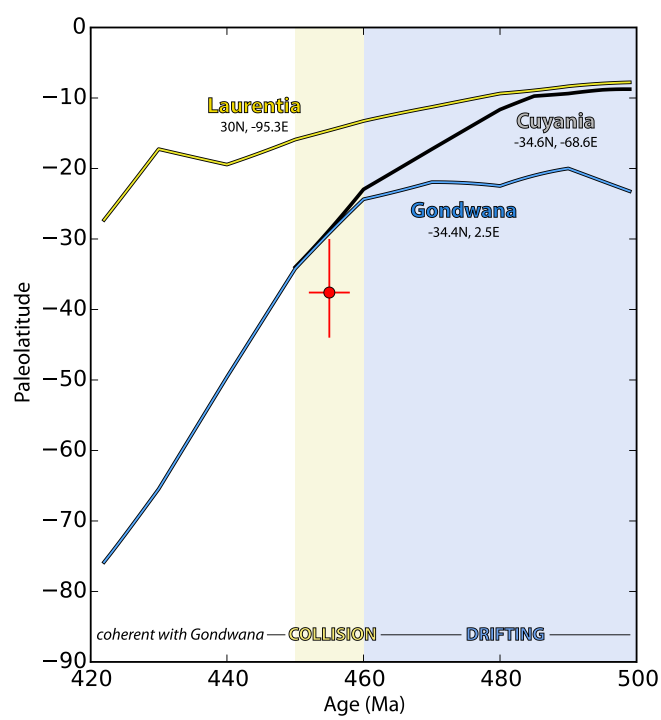


Fig. 6. Early Paleozoic paleomagnetic data from Cuyania (red symbol; data from Table 2) plotted against paleolatitude reference curves for Cuyania (black), Laurentia (yellow), and Gondwana (blue) from the presented plate model. The reference point used for each model curve is listed in present-day coordinates. Age errors on the paleomagnetic result are estimated from constraints provided in the literature. The background colors highlight the timing of Cuyania's drifting (blue) and collision with Gondwana (yellow), as inferred from geological data reviewed in the main text and Appendix A.

3.7. Southeast Laurentia

In the late early Cambrian, southeast Laurentia was affected by an episode of rifting associated with the departure of Cuyania from the Ouachita embayment. This rifting was temporally distinct from the latest Neoproterozoic to earliest Cambrian rifting that affected the proto-Appalachian margin to the northeast, as reflected by discrete syn-rift successions (late Neoproterozoic to earliest Cambrian and late early Cambrian, respectively) in Alabama and Georgia (Thomas, 2011; Read and Repetski, 2012). The younger of these successions, characterized by the late early Cambrian Rome Formation, is correlative with a late early Cambrian syn-rift succession of red beds, evaporites, and carbonates in Cuyania (Thomas and Astini, 2003). The breakaway of Cuyania proceeded via spreading along the Ouachita rift and by transform motion along the Alabama–Oklahoma transform (Thomas, 2011). Rifting must have been complete by the Ordovician, when off-shelf strata were deposited outboard of the Alabama–Oklahoma transform, but was likely already complete by the late Cambrian, when the regional extensional and transcurrent fault systems related to that rifting were first overstepped (Thomas, 2011).

4. Plate model

In the following section, the plate model is presented together with a succinct discussion of the underlying paleogeographic constraints, its accordance with the geological interpretations (Table 1), and the implications of the imposed plate tectonic framework. The presentation of the model is broken into three arbitrary time frames: Cambrian to Early Ordovician (500–470 Ma), Middle to Late Ordovician (470–445 Ma), and Silurian (445–420 Ma). The discussion of each time-frame opens with a review of the paleogeographic constraints of the major continents, as drawn from Torsvik et al. (2012) and Torsvik et al. (2014), and then proceeds with the remaining subtopics that are arranged according to decreasing confidence. Thus, aspects presented earlier in each of the following three sub-sections are better founded than those presented later. Because it is helpful to use both model-based and present-day reference systems in the following presentation, *italics* are used for model-based directions to distinguish them from present-day directions (in normal font). To avoid confusion with the usage of common labels for both oceans and plates (e.g. Iapetus Ocean vs. Iapetan Plate in the same sense as Pacific Ocean vs. Pacific Plate), new terms will be defined as they appear in the text, and used explicitly. The term 'Iapetus Ocean' refers to the entire oceanic realm between Laurentia, Baltica, and Avalonia, including the Exploits–Tetagouche backarc, whereas the 'main Iapetus Ocean' refers to the basins floored by crust generated from the Iapetus ridge (i.e. excluding the Exploits–Tetagouche backarc). The 'Rheic Ocean' refers to the entire oceanic domain between Avalonia and Gondwana.

The complete digital plate model accompanying this paper can be accessed following the instructions in Appendix B (available from journal website).

4.1. Cambrian to Early Ordovician (500–470 Ma)

4.1.1. Drift of the major continents

Paleomagnetic constraints from Laurentia are strong in the middle Cambrian to Early Ordovician, and Laurentia's paleolatitude and orientation are thus well defined at this time (Torsvik et al., 2012). In the middle Cambrian, Laurentia was positioned at very low *southerly* latitudes and rotated ~90° clockwise from its present-day orientation. During the late Cambrian and Early Ordovician, it rotated ~20° anticlockwise and drifted very slightly *northward*, coming to straddle the Equator by the end of the Early Ordovician (Figs. 7, 8a).

The middle Cambrian to Early Ordovician paleomagnetic record from Gondwana is excellent (Torsvik et al., 2012). The position of Gondwana in the middle Cambrian was such that northwest Africa was at the South Pole while southernmost West Gondwana (South Africa and North Patagonia) reached latitudes of ~30°S. During the late Cambrian and Early Ordovician, Gondwana moved slightly *northward* so that by ~470 Ma southernmost West Gondwana was at ~15–20°S (Figs. 7,8a). By the beginning of the late Cambrian, the apparent position of the South Pole was in northernmost Africa, in the area of present-day northwest Libya, and by the end of the Early Ordovician it had shifted to the area of northwest Algeria.

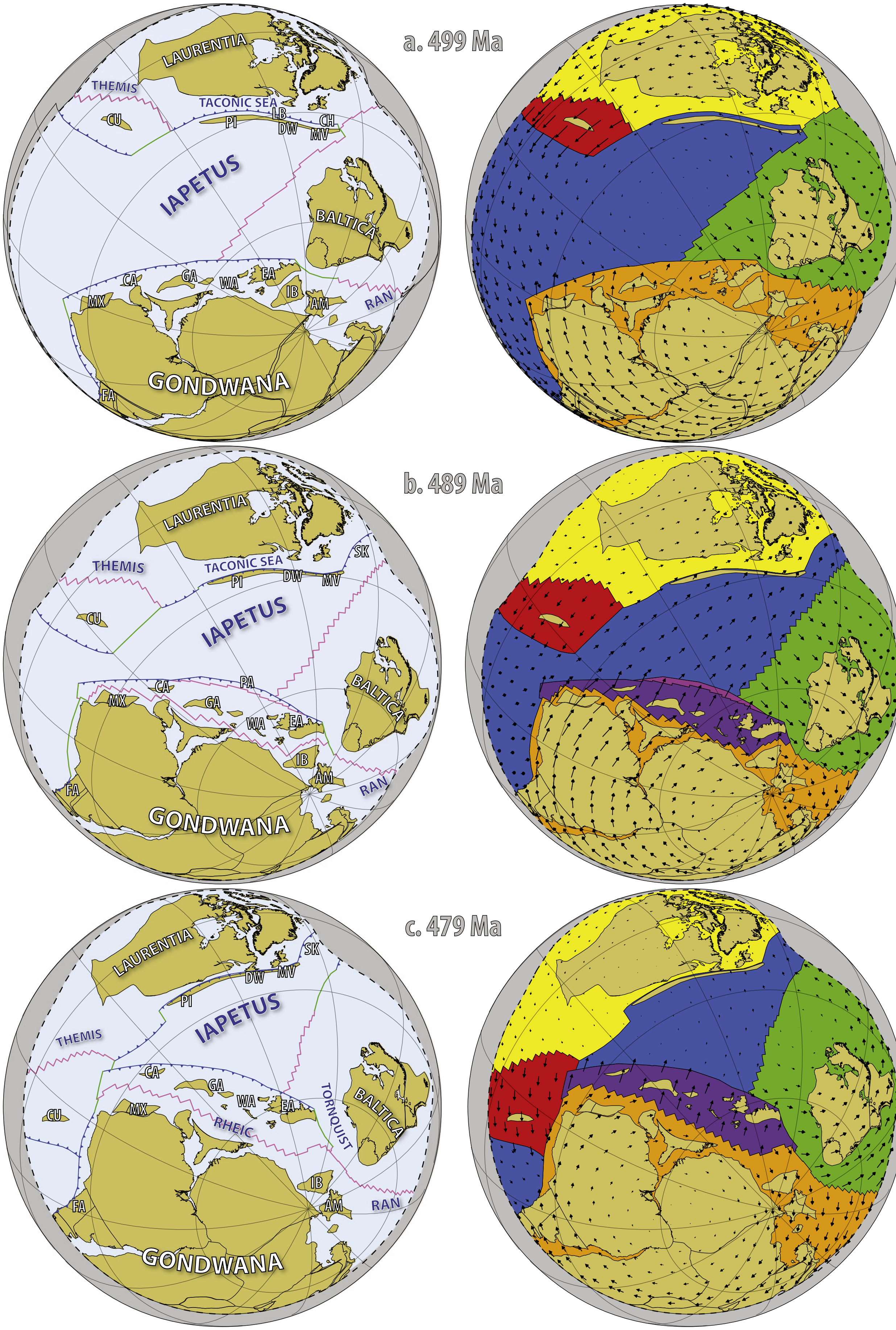
The paleomagnetic data from Baltica are poor for the middle Cambrian to earliest Ordovician, as only two paleomagnetic poles are available between 530 and 480 Ma, and, despite being considered the same age (~500 Ma), they fall ~35° apart (Torsvik et al., 2012). Nevertheless, these data indicate that in the late middle Cambrian, Baltica occupied mid-to-high *southerly* latitudes and was rotated at least 90°clockwise relative to its present-day orientation. Subsequently, between 500 and 470 Ma, Baltica apparently rotated more than ~60° anticlockwise and, after 480 Ma, began drifting *northward* (Figs. 7,8a).

The absolute paleolongitude of the continents is estimated from the restoration of LIPs and kimberlites to the margins of the LLSVPs in the lowermost mantle, following Torsvik et al. (2014). In Gondwana, the Kalkarindji LIP erupted in Australia at ~510 Ma and middle Cambrian kimberlites are known from southern Africa (Torsvik et al., 2014). Together with the middle Cambrian paleomagnetic constraints, these features can be fit to the margins of the African LLSVP, so that the Kalkarindji LIP was positioned above the northeastern margin of the LLSVP and southern Africa was above its southwest margin. Middle Cambrian kimberlites were also emplaced into northwest Canada (Torsvik et al., 2014), but because Gondwana was positioned above the African LLSVP at that time, Laurentia must have been located above the Pacific LLSVP, likely above its northern margin. No LIPs or kimberlites were emplaced into Baltica during the early Paleozoic, so its paleolongitude is not directly constrained. However, because Baltica and Gondwana occupied the same mid-to-high *southern* latitudes in the Cambrian and Early Ordovician, the positioning of Gondwana greatly restricts the range of permissible paleolongitudes for Baltica (Fig. 7).

4.1.2. Opening of the Rheic

The Neoproterozoic to early Cambrian basement and Cambrian faunas of Ganderia, East and West Avalonia and Carolinia clearly establish their affinity to northwest Gondwana in the earliest Paleozoic (Section 3 and Appendix A). Accordingly, middle Cambrian paleomagnetic data from Ganderia and late Cambrian paleomagnetic data from West Avalonia reveal that these terranes occupied mid-to-high *southern* latitudes (~50°S and 65°S, respectively) during the middle to late Cambrian (Table 2; Figs. 2,3). With respect to the middle to late Cambrian position of Gondwana, these paleolatitudes allow the reconstruction of West Avalonia to the northern margin of northwest Africa, and Ganderia to a slightly lower-latitude position, closer to Amazonia (Fig. 7a). Indirect constraints from younger (Early Ordovician) paleomagnetic data from East Avalonia (Table 2; Fig. 4) suggest that its late Cambrian position was along the north margin of northwest Africa, close to West Avalonia, although other configurations are possible (Nance et al., 2008). The specific position of Carolinia is unconstrained by paleomagnetic data, but the placement of Carolinia to the north of

Fig. 7. Cambrian and Early Ordovician paleogeographic reconstructions from the presented plate model for three different times: a. 499 Ma, b. 489 Ma, and c. 479 Ma. For each row, the left panel depicts the reconstruction with schematic plate boundaries (blue = subduction, green = transform, red = spreading ridge) and labels of some major features, whereas the right panel highlights the individual plates (variably colored) and shows the time-dependent plate velocity field. The dashed external boundary in all panels is an arbitrary perimeter marking the outer limit of the domain considered in the presented model. Abbreviations: AM = Armorican Massif, CA = Carolinia, CH = Clew Bay-Highland Border complexes, CU = Cuyania, DW = Dashwoods microcontinent, EA = East Avalonia, FA = Famatina arc, GA = Ganderia, IB = Iberia, LB = Lushs Bight intraoceanic arc, MV = Midland Valley–South Mayo terrane, MX = Mixteca–Oaxaca block, PA = Penobscot arc, PI = Eastern Piedmont, SK = Sunnhordland and Köli nappe complexes, WA = West Avalonia.


a. 499 Ma
LAURENTIA
THEMIS
TACONIC SEA
CU
LB
CH
PI
DW
MV
IAPETUS
BALTICA
CA
GA
WA
EA
IB
MX
AM
RAN
GONDWANA
FA
b. 489 Ma
LAURENTIA
THEMIS
TACONIC SEA
SK
PI
DW
MV
CU
IAPETUS
PA
CA
MX
GA
BALTICA
WA
EA
IB
AM
FA
RAN
GONDWANA
c. 479 Ma
LAURENTIA
SK
DW
MV
PI
IAPETUS
THEMIS
CA
GA
WA
EA
TORNQUIST
BALTICA
CU
MX
RHEIC
IB
AM
FA
RAN
GONDWANA

Amazonia (*north* of Ganderia) allows for a greatly simplified kinematic scenario (see below).

Subduction was already occurring beneath these terranes by the beginning of the middle Cambrian, based on the late early Cambrian onset of the Penobscot arc. Continued subduction below the Penobscot arc led to the opening of a minor backarc in the middle to late Cambrian, but at the Cambrian–Ordovician boundary, the backarc began to close and the arc became extinct (Fig. 7). Closure of the backarc was complete by the mid-Early Ordovician and marked by the obduction of backarc ophiolites (Appendix A). A comparable history is chronicled in the upper allochthonous units of the Galicia-Trás-os-Montes Zone of northwest Iberia—a middle to late Cambrian arc was deformed and metamorphosed in the latest Cambrian to earliest Ordovician—and the arc could constitute a fragment or marginal correlative of the Penobscot arc. Following termination and re-accretion of the Penobscot arc, subduction continued beneath the margin and instigated the late Early Ordovician construction of the Popelogan–Victoria arc on the remains of the Penobscot arc. Beginning at 475 Ma, backarc extension began again behind the new marginal arc and opened the Exploits–Tetagouche backarc (Fig. 8a). Along the margin to the *southeast*, arc magmatism in the Leinster and Welsh basins of East Avalonia initiated in the mid-Early Ordovician, essentially coincident with the onset of the Popelogan–Victoria arc. Speculatively, if the opening of the Exploits–Tetagouche backarc was diachronous, its propagation to the *southeast* toward East Avalonia could have been responsible for the bimodal, extension-related magmatism in the Welsh Basin in the Middle Ordovician (Appendix A).

On the *southwest* side of these terranes (Ganderia, East and West Avalonia, and Carolinia), regional extension—which began perhaps as early as the early Cambrian, but certainly by the late Cambrian—culminated in margin-wide rifting that split them from Gondwana (Fig. 7). The onset of continental breakup, and thus the initial opening of the Rheic Ocean, occurred in the latest Cambrian to earliest Ordovician, as reflected by uplift-induced sedimentary gaps in the conjugate margins of East Avalonia and Iberia, and from the metasedimentary and magmatic records among the basal allochthonous units of the Galicia-Trás-os-Montes Zone (Appendix A). Mid-Early Ordovician and early Middle Ordovician paleomagnetic data from East Avalonia reflect a steady *northward* drift of these terranes following rifting (Fig. 2), such that by the end of the Early Ordovician the Rheic Ocean had reached a width of ~1500 km (Fig. 8a). Correspondingly, the fossil record among these terranes reveals a diminishing Gondwanan signal from the Early to Middle Ordovician, reflecting the emergence of the Rheic Ocean as a barrier to faunal migration (Cocks and Fortey, 2009; Pollock et al., 2011). It is noteworthy that because of the strong clockwise rotation of Gondwana during the latest Cambrian to Early Ordovician, the opening of the Rheic Ocean must have been strongly oblique (Fig. 7). The relative transcurrent motion between Gondwana and its rifted terranes was sinistral and comprised a large part of the total motion during the entire Early Ordovician but was most significant between 490 and 480 Ma.

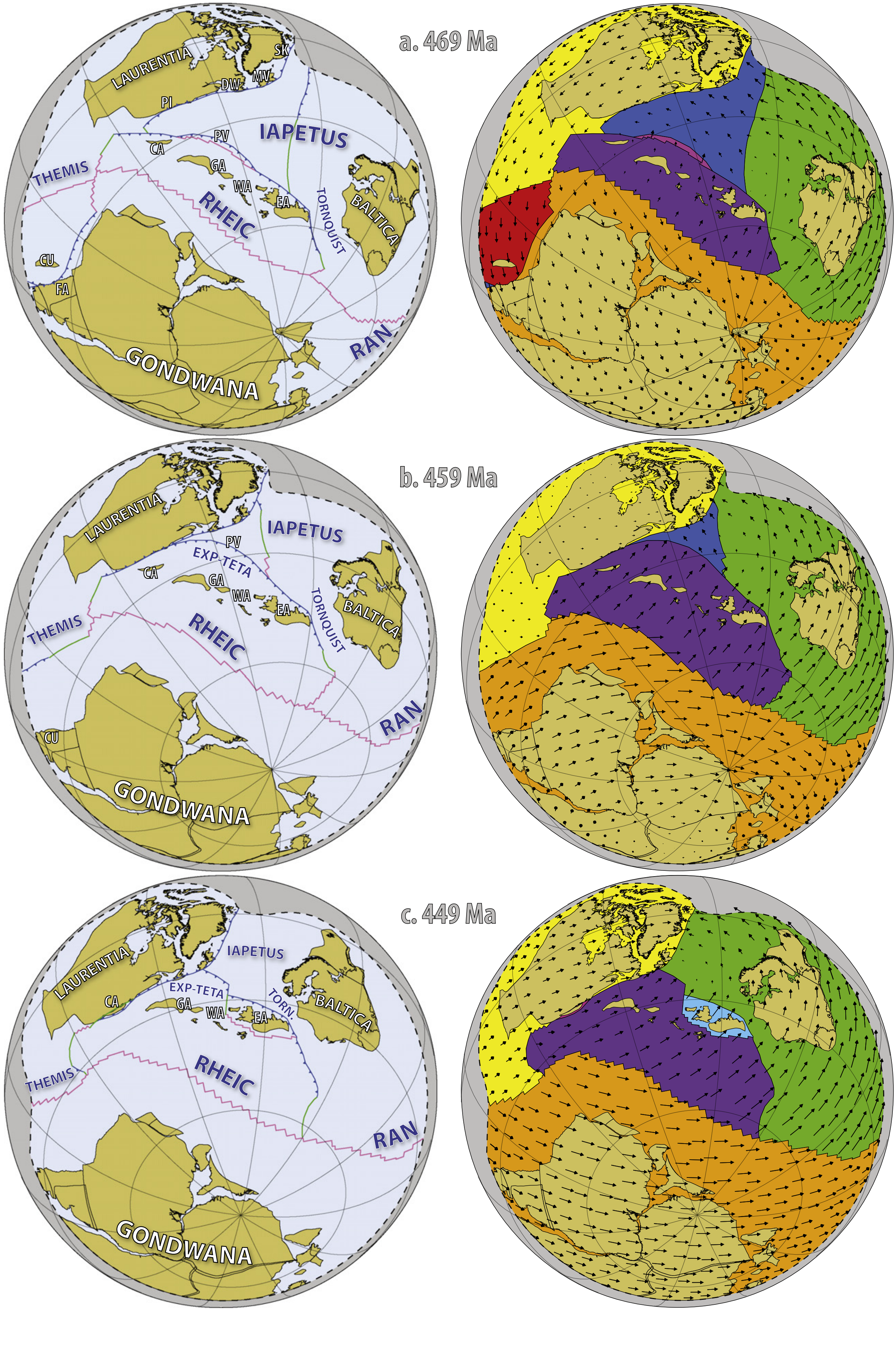
To the *east* of East Avalonia, the Cambrian to Early Ordovician motion between Baltica and the north margin of Gondwana was characterized by oblique divergence (Fig. 7). From 500 to 480 Ma, the respective rotations of Baltica and Gondwana were such that the relative motion between them was partly transcurrent, but to the *east*, their shared transform boundary probably gave way to a spreading ridge that formed the Ran Ocean (Hartz and Torsvik, 2002). By 480 Ma, the relative motion between Baltica and Gondwana became more purely divergent, and from then on the Ran ridge extended continuously along their shared boundary, connecting to the Rheic ridge in the *west*. Thus, the *southern* halves of the Rheic and Ran oceans both occupied the Gondwanan Plate and formed a continuous basin. The *northern* halves of these oceans occupied two different plates (the Avalonian and Baltic plates), but also effectively formed a continuous basin. Nevertheless, the term 'Ran Ocean' is retained here to describe the oceanic realm between Baltica and Gondwana until the mid-Silurian, when Baltica merges with Laurentia. By the end of the Early Ordovician, the Ran Ocean was more than ~1500 km wide along its narrowest region in the *west*, and widened substantially to the *east* (Fig. 8a).

4.1.3. The Famatina arc and the drift of Cuyania

Along the west of Gondwana, subduction of the Iapetus Ocean (or possibly Panthalassa) beneath the proto-Andean margin began at least by the late Cambrian, and perhaps as early as the late middle Cambrian. The apparently diachronous development of the Famatina continental magmatic arc suggests that subduction initiation was earlier in the southern segment of the margin, or that subduction was more highly oblique in the north during the late Cambrian to earliest Ordovician (Fig. 7a,b). However, by the mid-Early Ordovician, the entire proto-Andean margin was active and the Famatina continental magmatic arc stretched from central Peru to south-central Argentina (Figs. 7c–8a).

On the opposite side of the Iapetus Ocean, along the southeast margin of Laurentia, the late early Cambrian rifting of Cuyania established a new ocean that continued to widen through the Cambrian and Early Ordovician (Fig. 7). Previously referred to as the 'Ouachtia Ocean', I prefer to follow the practice of applying mythological labels to large Paleozoic oceans to distinguish and dissociate them from younger geologic and physiologic features, and suggest the term 'Themis Ocean' (Themis is the sister of Iapetus and Rhea in Greek mythology). By 470 Ma, Cuyania was close to the central proto-Andean margin, consistent with the appearance of Gondwanan faunas in Cuyania in the late Early to Middle Ordovician (Fig. 8a). Because the late Cambrian to Early Ordovician strata of Cuyania typify platform deposits along a passive margin (Appendix A), the rifting and drifting of Cuyania has conventionally been assumed to relate to slab-pull from the far side of the Iapetus Ocean, along the proto-Andean margin (Thomas and Astini, 1996). However, there are several problems with this assumption. Firstly, the proto-Andean margin was evidently not active until the late middle Cambrian (at the earliest), and so subduction there could not have been responsible for the rifting of Cuyania from Laurentia in the late Early Cambrian. Second, and more importantly, the rifting of Cuyania was not associated with rifting elsewhere along the east margin of Laurentia, indicating that the ridge must have terminated at a transform boundary between Cuyania and the southern proto-Appalachians. If the rifting of Cuyania was driven by slab-pull from the far side of the Iapetus Ocean, this transform boundary must have spanned the width of Iapetus, as in the sense of Thomas and Astini (1996) (see their Fig. 3). Consequently, it is here speculated that, by the late early Cambrian, Cuyania occupied the remote backarc position of a plate that was distinct from, and overriding, oceanic lithosphere of the main Iapetus Ocean (Fig. 7a). In such a scenario, Cuyania's rifting would be related to the oceanward migration of a subduction zone that originated on the Laurentian side of the Iapetus, and the length of the requisite transform to the northeast would thus be minimized. With regard to the apparent late Cambrian to Early Ordovician passive margin of Cuyania, it should be noted that Ganderia also appears to have an Ordovician succession essentially devoid of subduction-related relics because it was separated from the active margin by a substantial backarc (Appendix A). Therefore, although the late Cambrian to Early Ordovician platform

Fig. 8. Middle–Late Ordovician paleogeographic reconstructions from the presented plate model for three different times: a. 469 Ma, b. 459 Ma, and c. 449 Ma. For each row, the left panel depicts the reconstruction with schematic plate boundaries (blue = subduction, green = transform, red = spreading ridge) and labels of some major features, whereas the right panel highlights the individual plates (variably colored) and shows the time-dependent plate velocity field. The dashed external boundary in all panels is an arbitrary perimeter marking the outer limit of the domain considered in the presented model. Abbreviations: CA = Carolinia, CU = Cuyania, DW = Dashwoods microcontinent, EA = East Avalonia, FA = Famatina arc, GA = Ganderia, MV = Midland Valley–South Mayo terrane, PV = Popelogan–Victoria arc, PI = Eastern Piedmont, SK = Sunnhordland and Köli nappe complexes, WA = West Avalonia.


a. 469 Ma
LAURENTIA
SK
DW
MV
PI
PV
CA
IAPETUS
THEMIS
GA
WA
EA
RHEIC
TORNQUIST
BALTICA
CU
FA
RAN
GONDWANA
b. 459 Ma
LAURENTIA
IAPETUS
PV
EXP-TETA
CA
GA
WA
EA
THEMIS
RHEIC
TORNQUIST
BALTICA
RAN
CU
GONDWANA
c. 449 Ma
LAURENTIA
IAPETUS
CA
EXP-TETA
GA
WA
EA
TORN.
BALTICA
THEMIS
RHEIC
RAN
GONDWANA

succession of Cuyania is compelling, it is not considered to be exclusive of a scenario wherein Cuyania occupies an upper plate position relative to the Iapetus, which is preferred here.

4.1.4. Dynamics of a peri-Laurentian seaway

The Neoproterozoic rifting along the east and northeast margins of Laurentia that gave rise to the Iapetus Ocean was followed by a distinct latest Neoproterozoic to earliest Cambrian episode of rifting that culminated in the excision of an elongate continental sliver and the opening of a marginal seaway, the Taconic seaway (Fig. 7a). The elongate continental ribbon, which later re-accreted to Laurentia in the late Early to Middle Ordovician following collapse of the Taconic seaway, is recognized in allochthonous blocks with Laurentian basement in the Dunnage and Piedmont zones of the northern and southern Appalachians, respectively. Relics of the same briefly independent peri-Laurentian terrane may also be preserved in the northern British Isles (beneath the Midland Valley Graben and in the Tyrone Central Inlier and Slishwood Division) and among the exotic allochthons of the Scandinavian Caledonides (Appendix A). The middle Cambrian Lushs Bight oceanic tract in the Dunnage zone of the northern Appalachians preserves the earliest evidence of subduction outboard of the east Laurentian margin, but it is uncertain whether this subduction occurred within the Taconic seaway or in the main Iapetus Ocean. Zagorevski and Van Staal (2011) tentatively concluded that subduction was more likely initiated within the marginal seaway, and that interpretation is adopted in the model (Fig. 7a), although the choice is largely speculative and alternative scenarios have been developed (Waldron et al., 2014). Because this subduction was interrupted in the late Cambrian by the obduction of the Lushs Bight oceanic tract onto the Dashwoods microcontinent, the microcontinent must have initially occupied the lower plate and thus subduction was *north-dipping*.

Following the obduction of the Lushs Bight oceanic tract in the late Cambrian, the subduction polarity in the marginal seaway reversed so that it then dipped below the microcontinent (Fig. 7b). The continuation of this subduction culminated in the closure of the Taconic seaway and the re-accretion of the Dashwoods microcontinent with the Laurentian autochthon in the latest Early to Middle Ordovician (Figs. 7c-8a). In the southern Appalachians, latest Cambrian to Ordovician arc magmatic rocks in the eastern Piedmont and late Middle Ordovician HP metamorphic rocks in the western Piedmont reveal a similar history of marginal seaway closure by southeast-dipping subduction beneath an outboard terrane, but final closure of the seaway was perhaps slightly younger than in the north (Appendix A).

In the northern British Isles, possibly that same collisional event was marked by the late Early to early Middle Ordovician Grampian orogeny. The ophiolitic–accretionary complexes along the Highland Border Fault and correlative Clew Bay-Fair Head Line moreover preserve evidence of ophiolite obduction prior to Grampian orogenesis, and probably represent a diachronous reflection of the late Cambrian collision between the Lushs Bight oceanic tract and Dashwoods microcontinent, as seen in the northern Appalachians (Appendix A). Late Cambrian to Early Ordovician southeast-dipping subduction was likewise manifest, as preserved in the South Mayo Trough, Tyrone Igneous Complex, and Midland Valley terrane. From the northern British Isles, the late Cambrian to Early Ordovician subduction zone continued further to the northeast, outboard of northeast Greenland, based on intraoceanic subduction relics in the allochthonous assemblages of oceanic affinity in the Scandinavian Caledonides (Sunnhordland, Støren, Lyngen and more; see Appendix A) (Fig. 7b,c). As in the northern British Isles, the collision of this subduction system with the margin of northeast Greenland (or offshore microcontinents of Laurentian origin) probably occurred in the late Early to Middle Ordovician, when the Köli nappes were deformed and the Jæren nappe of Laurentian affinity was subjected to HP metamorphism (Appendix A) (Fig. 7c). If of Early Ordovician age as supposed, the allochthonous HP complexes in Svalbard might also relate to this outboard subduction system and its late Early to Middle Ordovician convergence with the Laurentian margin (or outboard blocks derived from it).

4.1.5. The Iapetus

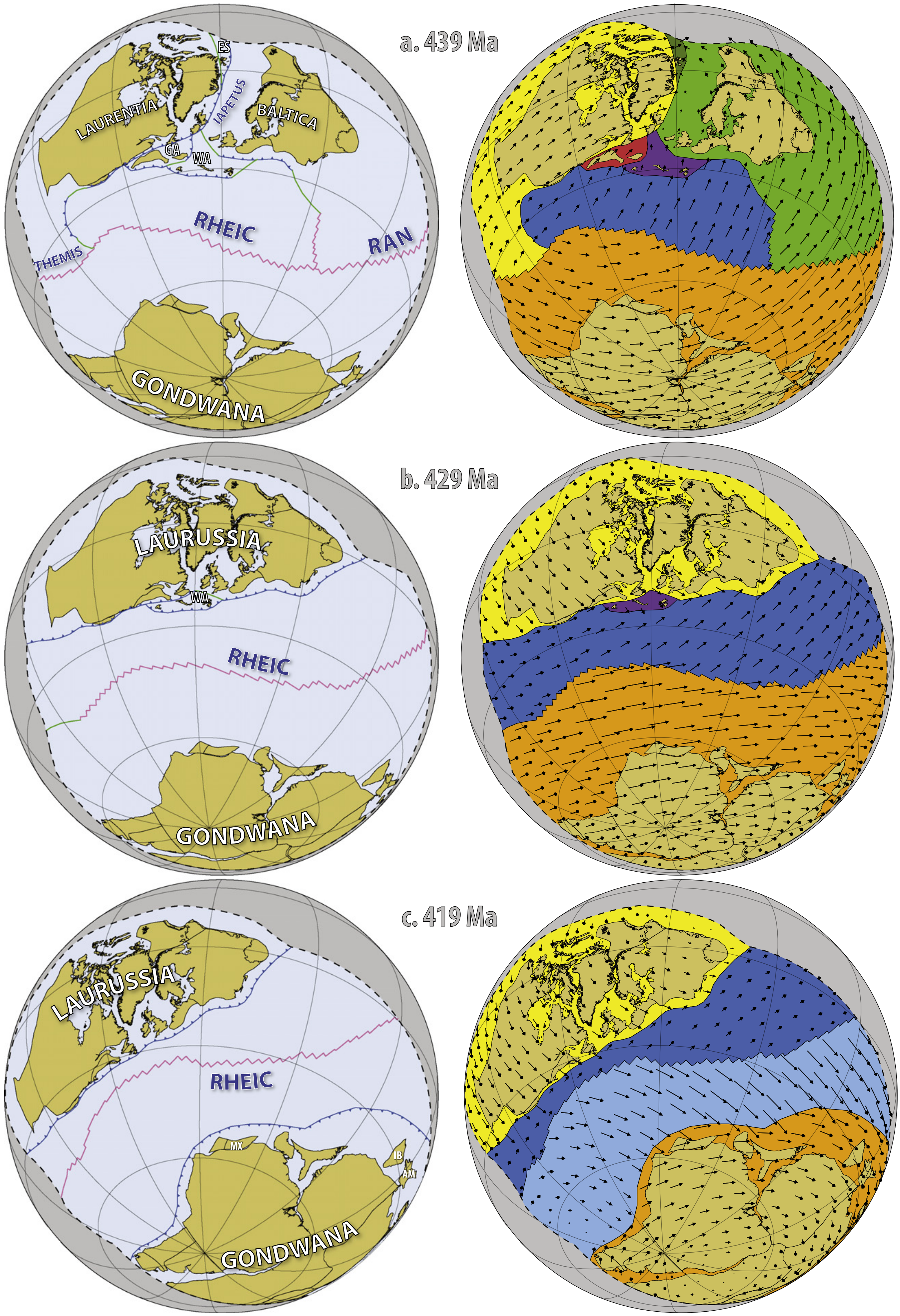
The kinematics of the Iapetus Ocean can be only indirectly inferred, and only after both the motion of the adjacent continents and the nature of their boundaries with the Iapetus lithosphere have been defined. Thus, the modeled kinematics of the Iapetus realm are inherently bound to both the uncertainties in the kinematic model of the continents and the interpretations of the geology along their margins. Furthermore, the constraints imposed by the neighboring continents generally do not allow a truly unique solution, and the modeled kinematics are typically the simplest among a family of possible alternatives. For example, in most instances, a direction or range of motion is established by the topology of the tectonic boundaries surrounding a plate, but the rate of motion is not absolutely constrained. In such cases, the scenario that minimized plate speeds was adopted.

At 500 Ma, the Iapetus Ocean was subducting to the *southwest* and *south*, beneath the northwest and west margins of Gondwana, and to the *northeast*, beneath Cuyania (Fig. 7a). Because the model follows Zagorevski and Van Staal (2011) in presuming that middle to late Cambrian subduction associated with the Lushs Bight oceanic tract was occurring in the Taconic seaway, oceanic lithosphere of the main Iapetus Ocean was separated from the Laurentian Plate by subduction within the seaway. To the *southeast*, the Iapetus Ocean flanked the south passive margin of Baltica. As determined from preliminary paleogeographic modeling for times prior to 500 Ma, the main Iapetus ridge was probably located between Laurentia and Baltica in the *northeast* and was subducting below north Gondwana to the *southwest*. Thus, to the *southeast*, oceanic lithosphere of the main Iapetus Ocean comprised part of the Baltic plate, whereas to the *northwest* of the main Iapetus ridge, the oceanic lithosphere of the main Iapetus may have constituted an independent plate, possibly including the Dashwoods microcontinent and its lateral correlatives (Fig. 7a). That plate is here referred to as the 'Iapetan Plate'.

These tectonic boundaries constrain the modeled kinematics of the Iapetan Plate from 500 to 485 Ma, at which time the opposed subduction zones outboard of Cuyania and Carolinia passed by one another and divided the Iapetan Plate into two smaller pieces (the East and West Iapetan plates) (Fig. 7b,c). Both of these plates grew progressively smaller during the Early Ordovician, in step with the drift of Cuyania and the peri-Gondwanan terranes and the oceans that widened behind them. By 470 Ma, the smaller, West Iapetan Plate had been subducted and the larger, East Iapetan Plate had narrowed to ~500 km in the *west*, although its width to the *east* was still substantial (<3000 km). Owing to the strong anticlockwise rotation of Baltica in the mid-Early Ordovician, the Iapetus ridge may have partly converted to a transform boundary at this time, although spreading probably continued to the *south* (Fig. 7c). Due to the respective motions of Baltica and East Avalonia during the Early Ordovician, a minor oceanic corridor was preserved between them, termed the Tornquist Sea (Cocks and Fortey, 1982; Torsvik and Rehnström, 2003). Thus, the Tornquist Sea was not genetically distinct from the main Iapetus Ocean but was a remnant corridor of Iapetus trapped between East Avalonia and Baltica as the latter rotated.

In the latest Early to Middle Ordovician, the peri-Laurentian continental ribbon that comprised the northern limit of the East Iapetan Plate collided with the Laurentian autochthon, perhaps diachronously (Figs. 7c, 8a). With the subsequent onset of north-dipping subduction

Fig. 9. Silurian paleogeographic reconstructions from the presented plate model for three different times: a. 439 Ma, b. 429 Ma, and c. 419 Ma. For each row, the left panel depicts the reconstruction with schematic plate boundaries (blue = subduction, green = transform, red = spreading ridge) and labels of some major features, whereas the right panel highlights the individual plates (variably colored) and shows the time-dependent plate velocity field. The dashed external boundary in all panels is an arbitrary perimeter marking the outer limit of the domain considered in the presented model. Abbreviations: ES = East Svalbard, GA = Ganderia, WA = West Avalonia.


a. 439 Ma
ES
LAURENTIA
IAPETUS
BALTICA
GA
WA
RHEIC
RAN
THEMIS
GONDWANA
b. 429 Ma
LAURUSSIA
WA
RHEIC
GONDWANA
c. 419 Ma
LAURUSSIA
RHEIC
MX
IB
AM
GONDWANA

beneath that terrane after its accretion, it became separate from the East Iapetan Plate, which from then was composed entirely of oceanic lithosphere.

4.2. Middle to Late Ordovician (470–444 Ma)

4.2.1. The major continents

The Middle to Late Ordovician paleomagnetic record for Laurentia, Gondwana, and Baltica is generally poor (Torsvik et al., 2012). Laurentia has one ~470 Ma pole, but then no younger data until the early Silurian. Interpolating between these Early–Middle Ordovician and early Silurian data, Laurentia drifted ~5° south and rotated ~10° anticlockwise. Middle and Late Ordovician kimberlites in northwest Canada are interpreted to indicate that Laurentia remained above the northern margin of the Pacific LLSVP throughout the Ordovician (Torsvik et al., 2014).

Gondwana has two Middle Ordovician paleomagnetic poles, but only one from the Late Ordovician (Torsvik et al., 2012). Although sparse, these data reveal that Gondwana's position during the Middle and Late Ordovician was such that northwest Africa remained close to the South Pole. Specifically, the apparent location of the South Pole moved from its position in the area of present-day northwest Algeria at 470 Ma to southern Morocco at 460 Ma and then to northeast Guinea by the end-Ordovician (Fig. 8). Accordingly, southernmost West Gondwana drifted from ~15–20°S at 470 Ma *southward* to ~30–35°S by the end of the Ordovician.

Baltica is well-constrained by paleomagnetic data in the Middle Ordovician, with five poles, but lacks Late Ordovician and early Silurian data (Torsvik et al., 2012). Interpolating between the Middle Ordovician and middle Silurian constraints, Baltica drifted ~30° *north* and rotated ~30° anticlockwise from 470 to 444 Ma (Fig. 8).

4.2.2. The drift of the peri-Gondwanan terranes

Middle to Late Ordovician paleomagnetic data from East and West Avalonia confirm that these terranes drifted *northward* at that time, moving from ~50°–55°S at 470 Ma to ~30°–35°S by the end-Ordovician (Table 2; Figs. 2,4,8). Middle Ordovician paleomagnetic data from relics of the Exploits–Tetagouche backarc are unfortunately too imprecise to derive a meaningful interpretation, and Ganderia is not otherwise constrained by paleomagnetic data in the Middle to Late Ordovician (Table 2; Fig. 3). However, the continued *northward* drift of these terranes can be inferred from i) the arrival of the Popelogan–Victoria arc to the east margin of Laurentia by the latest Middle Ordovician, and ii) the presumption that spreading of the Rheic Ocean persisted.

As in the Early Ordovician, the *northward* motion of the peri-Gondwanan terranes was accommodated by *southward* subduction of the Iapetan Plate beneath their *northern*, active margin. In the *northwest*, that active margin was represented by the Popelogan–Victoria arc, which became increasingly distant from Ganderia during the Middle Ordovician by the widening of the Exploits–Tetagouche backarc (Fig. 8a,b). To the *southeast*, in East Avalonia, the appearance of bimodal, extension-related magmatism in the Welsh Basin in the Middle Ordovician, coupled with the coeval occurrence of arc-related magmatism in the outboard Bellewstown terrane to the north, could reflect the *southeast* propagation of the Exploits–Tetagouche backarc at that time (Appendix A). However, continental arc magmatism resumed in East Avalonia in the early Late Ordovician, indicating that the backarc had already locally collapsed by then. By comparison, the margins of Ganderia remained passive through the Middle and Late Ordovician, suggesting that the Exploits–Tetagouche backarc continued to widen to the *northwest* (Fig. 8b). Speculatively, the apparent *southeast* narrowing of the backarc could have been due to the location of the Iapetus ridge to the *north* of East Avalonia, preventing the subduction zone there from rolling back.

In the latest Middle to early Late Ordovician, the Popelogan–Victoria arc collided with the active margin of east Laurentia, thereby marking the first contact between Laurentia and the peri-Gondwanan terranes (Fig. 8b). However, due to the orientation of the Popelogan–Victoria arc relative to the east margin of Laurentia, their collision was oblique and the terminal subduction of the East Iapetan Plate was thus diachronous, younging to the *east*. By ~450 Ma, the Popelogan–Victoria arc reached the southern margin of the northern British Isles at the same time that the former Iapetus ridge was subducted there, marking the final destruction of the East Iapetan Plate (Fig. 8c). This oblique collision of the arc with the northern British Isles, and/or the subduction of the former Iapetus ridge beneath them, might have been responsible for the enigmatic Late Ordovician phase of deformation and metamorphism reported from the Northern Highlands and Grampian terranes (Bird et al., 2013; Cawood et al., 2014; Chew and Strachan, 2014). Following the collision of the Popelogan–Victoria arc with Laurentia, subduction of the Exploits–Tetagouche basin began beneath them. At 455 Ma, Carolinia reached the eastern margin of Laurentia, as constrained by its oldest paleomagnetic data (Table 2; Fig. 5). After its initial collision, Carolinia continued to move relative to Laurentia by dextral transpression until the early Silurian (Fig. 8c), as reflected in the structures described by Hibbard et al. (2012). *East* of Carolinia, the expanse of the Exploits–Tetagouche backarc was greatly reduced by subduction beneath Laurentia in the Late Ordovician, such that it was less than 1000 km wide by the end-Ordovician.

Weak latest Ordovician to earliest Silurian deformation and metamorphism in East Avalonia is thought to denote its convergence and collision with southwest Baltica, which also experienced weak metamorphism at that time (Appendix A). Likewise, the cessation of subduction-related magmatism in East Avalonia by the end-Ordovician presumably reflects the effective closure of the narrow Tornquist Sea by that time (Figs. 8c, 9a). Although a latest Ordovician to earliest Silurian timing for this collision is permissible according to the available paleomagnetic constraints, it requires that the *northward* drift of East Avalonia accelerated slightly in the Late Ordovician (Fig. 2). Coincident with this inferred *northward* acceleration, the Welsh Basin and Brabant Massif experienced an episode of pronounced subsidence in the early Late Ordovician that could have marked the opening of a backarc basin between East and West Avalonia (Fig. 8c). Correspondingly, bimodal, rift-related volcanism appeared in West Avalonia in the latest Middle Ordovician to earliest Late Ordovician (Appendix A).

4.2.3. The accretion of Cuyania

In the late Early to early Middle Ordovician, platform carbonate deposition in Cuyania was diachronously supplanted by black shale sedimentation, signifying the progressive drowning of the platform as Cuyania approached the active margin of west Gondwana (Appendix A). In turn, the black shales were succeeded by coarse Middle to Late Ordovician clastic rocks of magmatic arc derivation, reflecting the incursion of Gondwana's forearc onto Cuyania when the latter reached the margin and began to subduct (Fig. 8a,b). Independent evidence from paleomagnetic, paleontological, and lithostratigraphic data from Cuyania confirm its proximity to southwest Gondwana by that time (Appendix A) (Table 2; Fig. 6). Ultimately, the subduction of Cuyania was unsuccessful and it accreted to the margin of Gondwana. Contemporaneously, and probably as a result of that collision, subduction and continental arc magmatism ceased all along the west margin of Gondwana. As discussed below, this cessation in subduction may have also coincided with the linking of the Rheic ridge with the ridge behind Cuyania (Themis ridge), which may have further contributed to the termination of convergence along the western margin of Gondwana.

4.2.4. Middle to Late Ordovician oceans

As in the Early Ordovician, the Rheic Ocean grew rapidly at the expense of the Iapetus Ocean during the Middle Ordovician and continued to do so through the Late Ordovician (Fig. 8). The expanse of the Iapetus Ocean was substantially reduced in the Middle to Late Ordovician, and the *western* half of the main Iapetus Ocean was closed in the Late

Ordovician, when the Popelogan–Victoria arc collided diachronously with the Appalachian margin of Laurentia. With the complete subduction of the Iapetus ridge by 450 Ma, the independent East Iapetan Plate ceased to exist, and the main Iapetus Ocean persisted only as the oceanic extension of the Baltic plate (Fig. 8c), which survived until the mid-Silurian Scandian collision between Baltica and Laurentia. To the *southeast*, the Iapetus Ocean continued into the narrow corridor of the Tornquist Sea, which effectively closed by the end-Ordovician. Following the consumption of the *western* half of the main Iapetus Ocean (i.e. the East Iapetan Plate), subduction of the Exploits–Tetagouche backarc beneath Laurentia allowed the Rheic Ocean to continue to expand throughout the Ordovician. By the end-Ordovician, the Rheic Ocean between northwest Gondwana and West Avalonia reached a width greater than 3000 km.

Baltica and Gondwana continued to drift apart through the Middle and Late Ordovician, so the Ran ridge—which first formed a thoroughgoing feature connected to the Rheic in the Early Ordovician—persisted through the Middle and Late Ordovician. As in the Early Ordovician, Baltica was rotating anticlockwise relative to East Avalonia during the Middle to Late Ordovician, so their shared boundary was probably complex, with a *northeast-facing* subduction zone in the *north* that likely passed *southward* into a transform and a ridge (Fig. 8a,b). For most of the Ordovician to mid-Silurian, a triple-junction of ridges may have formed the intersection of the Gondwanan, Baltic, and Avalonian plates.

In the earliest Ordovician, Cuyania and its inferred outboard subduction zone passed by the directionally opposed subduction zone along the leading edge of the peri-Gondwanan terranes, and a transform boundary was established between them in wake of their passage (Fig. 7c). Subsequently, in the late Early Ordovician, the continued relative motion between Cuyania and the peri-Gondwanan terranes led the Rheic and Themis ridges to pass by one another (Fig. 8a). At the beginning of the Middle Ordovician, these ridges may have become partly linked by spreading along the transform boundary that formerly separated them, and by the beginning of the Late Ordovician, the former plate boundary between Cuyania and Gondwana became inactive and the ridges became further coupled (Fig. 8b). Thus, the shutdown of subduction along the proto-Andean margin by the beginning of the Late Ordovician could have been a combined consequence of the collision of Cuyania and a coincident plate reorganization event associated with that ridge coupling. From the start of the Late Ordovician, the *southern* half of the Themis Ocean was thus part of the Gondwanan Plate, while the *northern* half remained part of the Laurentian Plate.

4.3. Silurian (444–420 Ma)

4.3.1. The major continents

Paleomagnetic constraints are poor for Laurentia and Baltica between 444 and 430 Ma, but after 430 Ma, following the Scandian collision between these continents, their data-sets can be combined and their paleomagnetic constraints become excellent (Torsvik et al., 2012). During the early to mid-Silurian, Laurentia remained essentially stationary at equatorial latitudes, whereas Baltica continued to drift rapidly *north* while rotating anticlockwise (Fig. 9a). By 430 Ma, the western Scandinavian margin of Baltica and the northeast Greenland margin of Laurentia were opposed at equatorial latitudes and colliding, the ultimate consequence of which was the fusion of Baltica and Laurentia and the formation of Laurussia (Fig. 9b). Subsequently, in the late Silurian, Laurussia began rotating anticlockwise and drifting *southward* so that by the end of the Silurian, the bulk of Laurussia was *south* of the Equator (Fig. 9c). Early Silurian kimberlites in northwest Canada again provide the only constraints on paleolongitude and are interpreted to indicate that Laurentia was still above the northern margin of the Pacific LLSVP at this time (Torsvik et al., 2014).

There are no paleomagnetic or paleolongitude constraints from Gondwana for the Silurian, so its motion is entirely interpolated for this time (Torsvik et al., 2012). According to this interpolation, Gondwana's drift during the Silurian was such that the apparent position of the South Pole migrated—from the area of present-day northeast Guinea at 444 Ma—south through Brazil to reach northern Argentina by the end of the Silurian (Fig. 9). Southernmost West Gondwana thus moved *southward* from ~30–35°S to 65–70°S during the Silurian, while West Africa moved from the South Pole to mid-*southerly* latitudes.

4.3.2. The formation of Laurussia

From the late Cambrian to the end-Ordovician, East Avalonia and Baltica were separated by the narrow Tornquist Sea, which only reached ~1000 km in width but nonetheless posed a barrier to faunal migration prior to the Late Ordovician (Cocks and Fortey, 1982). Subduction of that seaway beneath East Avalonia eventually led to its complete disappearance in the latest Ordovician to earliest Silurian, at which time East Avalonia and Baltica amalgamated (Figs. 8c, 9a). Notably, their merger was associated with only very weak latest Ordovician to earliest Silurian deformation and metamorphism, and the event is often termed a 'soft docking' (Torsvik and Rehnström, 2003). From the kinematics of the present model, this soft docking can be explained by the fact that East Avalonia and Baltica had very similar Late Ordovician trajectories—such that their relative motion at that time was small compared with their total motion—and that their final convergence was significantly oblique.

With the closure of the Tornquist Sea and the collision of East Avalonia and Baltica, subduction beneath East Avalonia ceased and Baltica and East Avalonia drifted, passively and in concert, toward Laurentia (Fig. 9a). Along the active margin of northeast Laurentia, oblique subduction of the oceanic extension of the Baltic plate during the early Silurian led to northward, margin-parallel displacement of East Svalbard toward West Svalbard, which was located along the Franklinian margin of northern Greenland. By the mid-Silurian, the last vestiges of the Iapetus Ocean that separated Baltica and Laurentia were subducted below the active margin of the latter, and the continents were brought together in a direct collision that represented the climax of the Caledonian orogeny (Fig. 9b). During this collision, Laurentia, Baltica, and East Avalonia were fused into a single tectonic entity, Laurussia. Accordingly, by the late early Silurian, the paleomagnetic data from East Avalonia are indistinguishable from those of Baltica and Laurentia (Table 2; Fig. 2).

4.3.3. The accretion of Ganderia and West Avalonia

In addition to the subduction of the last remnants of the main Iapetus Ocean beneath northeast Greenland during the early to mid-Silurian, the Exploits–Tetagouche backarc to the *southwest* continued to subduct *northward* at that time, beneath the northern Appalachians and northern British Isles. The closure of this basin was complete by the mid-Silurian, and at 430 Ma, Ganderia, which was passive on the *south* side of the Exploits–Tetagouche basin, collided with the northern Appalachians during the Salinic orogeny (Fig. 9a,b). This collision was broadly coeval with the Scandian collision to the *northeast*, and so peak Caledonian orogenesis during the mid-Silurian was expansive, affecting a composite collision zone that ran a length of more than 5000 km.

At the start of the Silurian, both the *north* and *south* margins of Ganderia were passive. However, as Ganderia approached and entered the subduction zone along the east margin of Laurentia, its *northward* drift slowed and its *southern* passive margin collapsed to become an active margin by 440 Ma (Fig. 9a), at which time a magmatic arc was erected along the entire margin, from southern Newfoundland to Massachusetts (Appendix A). Because the accretion of Ganderia to Laurentia is distinguishable from the accretion of West Avalonia, the subduction zone that formed along the *south* margin of Ganderia probably continued to the *east* as a nascent plate boundary between Ganderia and West Avalonia. That boundary between Ganderia and West Avalonia could have persisted as an oblique (dextral) convergent boundary from 440 Ma until the latest Silurian to early Devonian, when

West Avalonia amalgamated with Laurentia during the Acadian orogeny (Fig. 9b,c). Coincident with the onset of subduction along the *south* margin of Ganderia at 440 Ma, *north-dipping* subduction also initiated to the *south* of East Avalonia (Appendix A), perhaps along the former ridge that separated it from West Avalonia, and along the *south* of West Avalonia, such that the latter then formed a minor, independent plate (Fig. 9a,b).

4.3.4. Zenith of the Rheic

At the dawn of the Silurian, the Rheic Ocean comprised an enormous domain, separating Gondwana in the *south* from Laurentia, Baltica, and the peri-Gondwanan terranes to the *north*, and the continuous Themis-Rheic-Ran ridge spanned nearly a hemisphere (Fig. 9a). The basin continued to widen through the early Silurian, as the remnant Iapetus Ocean was subducted, reaching a maximum width of more than 4000 km in the mid-Silurian (Fig. 9b). Until 440 Ma, the Rheic Ocean was passive on both sides. However, at 440 Ma, the *southern* margins of Ganderia, West Avalonia, and East Avalonia all became active and *northward* subduction of oceanic lithosphere of the Rheic Ocean commenced. With the onset of subduction along the *southern* margins of these terranes, the *northern* half of the Rheic Ocean became an independent tectonic plate (the 'North Rheic Plate'). The new plate's *east* and *west* tectonic boundaries with the oceanic extensions of the Laurentian and Baltic plates briefly endured, but at 430 Ma, subduction initiated along the entire *southern* margin of Laurussia, and the *northern* half of the Themis, Rheic, and Ran basins became kinematically united. By the end of the Silurian, parts of the *northern* Rheic Ocean basin were reduced to a width of >500 km, whereas the *southern* Rheic Ocean remained wide because the west and northwest margins of Gondwana remained passive until the end-Silurian (Fig. 9c).

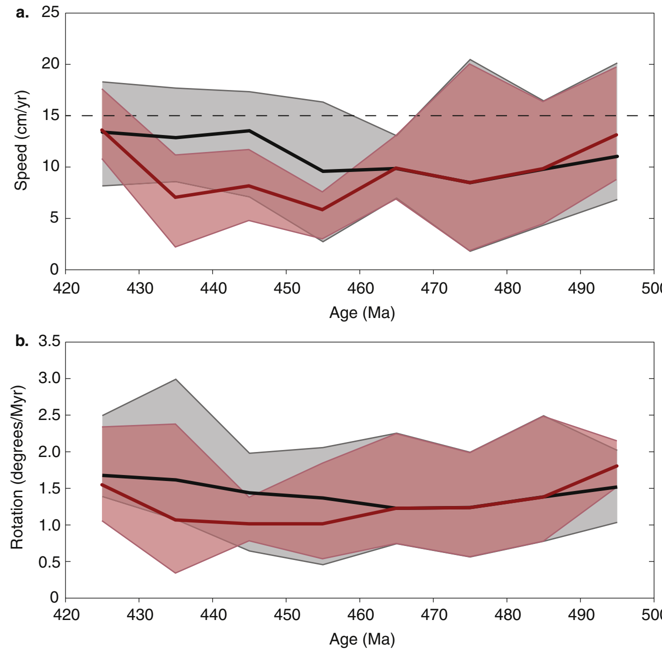


Fig. 10. The range (red and gray areas) of (a) plate speeds and (b) rotations from the plate model, as averaged in 10-Myr intervals between 500 and 420 Ma. In both panels, red denotes values calculated from the model after true polar wander (TPW) correction (Torsvik et al., 2014), whereas gray values are without TPW correction. Plate speeds were calculated from the approximate centroid of each independent plate. The thick lines represent (a) the average plate speed (*not* the average surface velocity) and (b) the average plate rotation.

5. Discussion

5.1. Model aspects and comparisons

Through the 500–420 Ma interval, the number of constituent plates in the presented model ranges between 4 and 8. The average speeds of these plates without true polar wander (TPW) correction, as calculated at 10-Myr intervals from the approximate centroids of the individual plates, range between ~2 and 20 cm/yr, with an overall average range between ~8 and 13 cm/yr (Fig. 10a). With TPW correction (Torsvik et al., 2014), plate speeds generally decrease and the overall average ranges between ~6 and 13 cm/yr. The maximum speed of ~20 cm/yr was reached only briefly by two minor plates composed predominantly of oceanic lithosphere, the Cuyania and Popelogan–Victoria plates. The average plate speeds are mostly higher than those determined from Cenozoic kinematics, but they are not inconsistent with observational evidence of high plate speeds or the approximate thresholds derived from geodynamic considerations (Meert et al., 1993; Gurnis and Torsvik, 1994), and they are moreover similar to those inferred from a global plate model of the late Paleozoic (Domeier and Torsvik, 2014). Although plate speeds (in cm/yr) communicate an intuitive measure of plate movement, a more representative metric is a plate's rotation (Fig. 10b). As with plate speed, the average plate rotations from the model are generally higher than those estimated from Cenozoic kinematics, but the largest rotations are associated with Baltica and Gondwana, whose movements are underpinned by paleomagnetic data.

In comparison to other paleogeographic reconstructions for the Iapetus and Rheic oceans, one of the notable aspects of the present model is that a comparatively simple framework of 4–8 plates can evidently satisfy the bulk of the paleomagnetic, geological, and kinematic constraints. In particular, East and West Avalonia, Ganderia (except the basement rifted with the Popelogan–Victoria arc), and Carolinia can be modeled together as a single plate from their latest Cambrian to earliest Ordovician departure from northwest Gondwana until ~455 Ma, when Carolinia first arrives to the Laurentian margin. Moreover, the collective paleomagnetic and geological data from these different blocks, when used to formulate scenarios which are tectonically viable and kinematically continuous, reveal that East Avalonia, West Avalonia, and Ganderia must have been close during their Early to Middle Ordovician drift. Thus, the discrete arrival times of these respective blocks (to the margins of Baltica and Laurentia) were probably a reflection of the late-stage tectonic dissection of a formerly united plate as it approached Baltica and Laurentia, and not an indication that they were originally independent and separated by large interior oceans.

5.2. Future directions

Among the avenues for future work on the plate model, perhaps the most obvious is a spatial expansion of the model to include the other parts of the globe. The outer perimeter in the model is an entirely arbitrary frame that divides the tectonic plates once they move beyond the scope of this paper. That arbitrary boundary limits the utility of the model as an input for global geodynamic modeling, and also forms an artificial break with the regions beyond the domain of the Iapetus and Rheic oceans, which may otherwise present additional constraints on the kinematics of these oceans. A global expansion of the plate model would also allow it to be fully integrated with younger global plate models (Domeier and Torsvik, 2014).

Among the simplifications made, the omission of the Meguma and Chilenia terranes is perhaps the most significant. The reason for their omission is simply that they utterly lack early Paleozoic paleomagnetic data and their histories are extremely poorly known. For example, according to van Staal et al. (2009), the arrival of Meguma to the margin of Laurussia was marked by the Neoacadian orogeny, but the event may have spanned more than 50 Myr (~395–340 Ma) and the relative kinematics associated with it are not yet adequately resolved (van Staal and Barr, 2012). The pre-accretionary history of Chilenia is likewise unclear, although Domeier and Torsvik (2014) speculated that Chilenia could have resided along the margin of southeast Laurentia until being transferred to southwest Gondwana in the Devonian. The model here is not entirely incompatible with that scenario, but such a positioning would nonetheless suggest that Chilenia was subjected to much early Paleozoic tectonism.

6. Conclusion

The opening of the Rheic Ocean and the closing of the Iapetus Ocean were the prevailing tectonic events of the early Paleozoic, reflecting the changeover between two major Wilson cycles and culminating in the major continental collision that forged Laurussia. However, despite a consensus on this basic narrative, published tectonic models of the early Paleozoic reveal gross differences in the conceptualized kinematics and dynamics that gave rise to this tectonic history and provide contrasting portrayals of important tectonic processes, such as rifting, microcontinent formation, and ocean basin development. The source of many of these significant discrepancies can be traced to the conceptual framework of the models, which thwarts the use of a host of practical plate tectonic constraints. Here an early Paleozoic (500–420 Ma) plate tectonic scenario for the Iapetus and Rheic oceans is presented that conforms both to the available paleogeographic data and to plate tectonic principles. In merging absolute continental reconstructions with geologically derived, kinematically viable plate boundaries, the model presented represents the first absolute, full-plate tectonic model for the early Paleozoic. Among the implications proffered by the model, it is demonstrated that the peri-Gondwanan terranes of East and West Avalonia, Ganderia, and Carolinia could have rifted and drifted as a single plate until just prior to their accretion to Laurentia and Baltica. This model will hopefully prove useful as a paleogeographic reference and as an input for further modeling, as well as serving as a shared platform for future testing and further improvement.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2015.08.003.

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