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A brief history of the Rheic Ocean

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Abstract The Rheic Ocean was one of the most important oceans of the Paleozoic Era. It lay between Laurentia and Gondwana from the Early Ordovician and closed to produce the vast Ouachita-Alleghanian-Variscan orogen during the assembly of Pangea. Rifting began in the Cambrian as a continuation of Neoproterozoic orogenic activity and the ocean opened in the Early Ordovician with the separation of several Neoproterozoic arc terranes from the continental margin of northern Gondwana along the line of a former suture. The rapid rate of ocean opening suggests it was driven by slab pull in the outboard Iapetus Ocean. The ocean reached its greatest width with the closure of Iapetus and the accretion of the peri-Gondwanan arc terranes to Laurentia in the Silurian. Ocean closure began in the Devonian and continued through the Mississippian as Gondwana sutured to Laurussia to form Pangea. The ocean consequently plays a dominant role in the Appalachian-Ouachita orogeny of North America, in the basement geology of

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southern Europe, and in the Paleozoic sedimentary, structural and tectonothermal record from Middle America to the Middle East. Its closure brought the Paleozoic Era to an end.

1. Introduction

During the Paleozoic Era, the interactions between the continents of Laurentia, Baltica and Gondwana were governed by two major oceans: Iapetus and the Rheic Ocean (Fig. 1). The Iapetus Ocean, which opened in the Late Ediacaran/Early Cambrian, gave rise to the extensive Early Paleozoic passive margin of eastern North America and was responsible for the formation of the Caledonide orogen and several accretionary orogenic episodes in the Appalachians. Iapetus was the first pre-Mesozoic ocean to be recognized with the advent of plate tectonics (Wilson, 1966) and its history is both widely known and well documented (e.g., Cocks and Fortey, 1990; Torsvik et al., 1996; Mac Niocaill et al., 1997; van Staal et al., 1998, 2009; Cocks and Torsvik, 2006, 2011).

The Rheic Ocean, on the other hand, opened in the Early Ordovician and although it has not received the same attention as Iapetus, it is arguably the more important ocean of the two. Stretching from Mexico to the Middle East, it was the Rheic Ocean that separated the great paleocontinents of Gondwana and Laurussia as the principal interior ocean of the Paleozoic, and it is the evolution of this ocean that dominates the geology of southern Europe, eastern North America and northern Africa following the closure of Iapetus in the Silurian. It was also the Rheic Ocean that

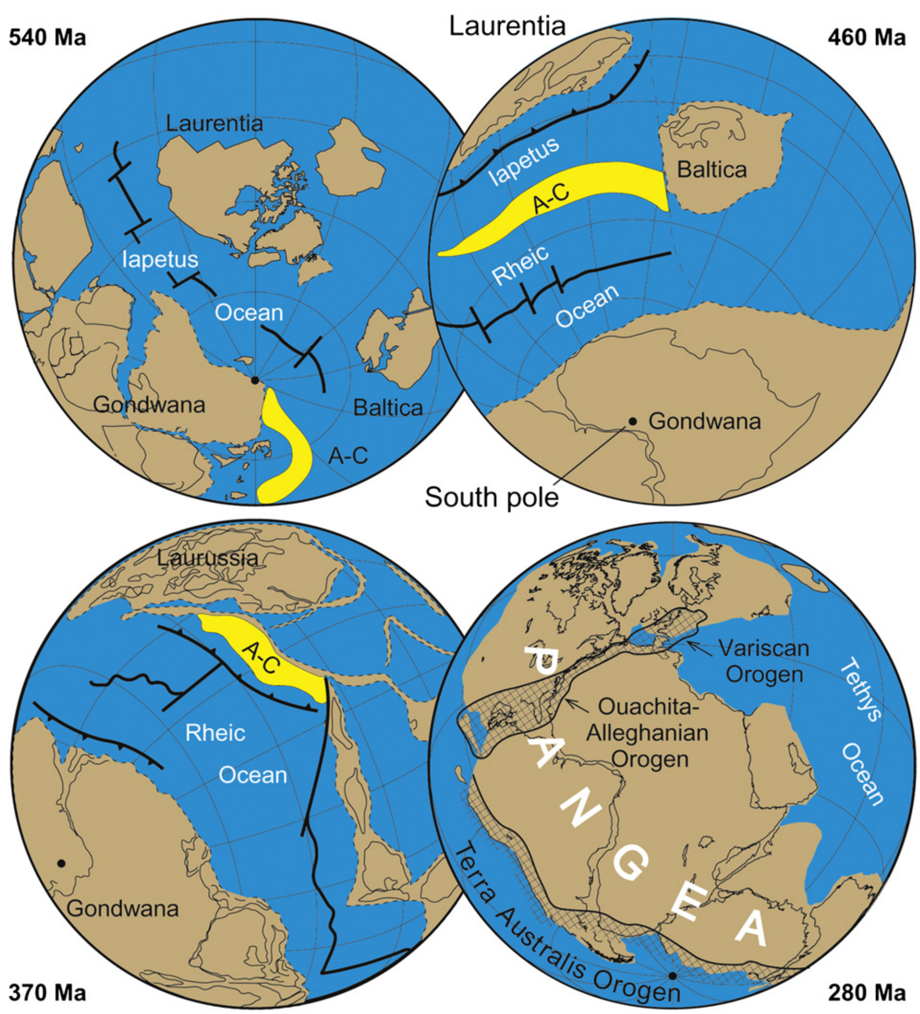

Figure 1 Paleozoic reconstructions (modified from Scotese, 1997; Cocks and Torsvik, 2002; Stampfli and Borel, 2002) at 540 Ma, 460 Ma, 370 Ma and 280 Ma showing the evolution of the Iapetus and Rheic Oceans between Gondwana and Laurentia—Baltica. A-C = Avalonia—Carolinia (from Murphy and Nance, 2008).

created the vast Ouachita-Appalachian-Variscan orogen in the Late Paleozoic and, in doing so, assembled the greater part of Pangea.

The importance of the Rheic Ocean has long been recognized in Europe where its suture, between the Rheno-Hercynian/South Portuguese and Saxo-Thuringian/Ossa-Morena zones, is well defined and well separated from that of Iapetus to the north (Fig. 2). But in North America, the role of the Rheic Ocean has been largely overlooked because its suture is not exposed, having been either buried beneath the sediments of the Coastal Plain or removed with the opening of the Atlantic Ocean and the Gulf of Mexico. As a result, the evolution of the Appalachian-Ouachita orogen is traditionally described in terms of Iapetus, despite the fact that the present structural architecture of this orogenic belt owes its origin to the Rheic Ocean (e.g., Murphy et al., 2009a).

To highlight the importance of the Rheic Ocean and clarify its role in Paleozoic tectonics, this paper provides a brief, illustrative review of the history of this ocean from its initial rifting to its final closure. A more complete treatment of the subject is available in Nance et al. (2010), although this article includes some important updates.

2. Initial rifting

Named for Rhea, the sister of Iapetus in Greek mythology, the Rheic Ocean opened along the southern flank of Iapetus as the result of the separation of several peri-Gondwanan terranes (e.g., Ganderia, Avalonia, Carolinia) from the northern (Avalonian−Cadomian) margin of Gondwana (Fig. 3). Terrane separation took place in the Late Cambrian−Early Ordovician in an apparent continuation of the accretionary tectonic processes that led up to it (e.g., Nance et al., 2008 and references therein). Prior to separation, the Avalonian−Cadomian margin of Gondwana had witnessed a prolonged history of Neoproterozoic subduction and accretion that was followed, in the Late Ediacaran−Early Cambrian, by the diachronous cessation of arc magmatism and the development of a continental transform margin (Murphy and Nance, 1989). This change in tectonic regime has been attributed to ridge-trench collision and likened to the evolution of the Cenozoic Pacific margin of North America (e.g., Nance et al., 2002). If so, the subsequent opening of the Rheic Ocean may have resembled the ongoing separation of Baja California from mainland Mexico, where rifting was similarly facilitated by a preexisting belt of weak volcanic arc crust and strike-slip focused crustal thinning in an oblique-divergent setting (Umhoefer, 2011).

An elaborate model for the opening of the Rheic Ocean by way of ridge-trench collision has been proposed by Linnemann et al. (2007) for the Saxo-Thuringian zone of the Bohemian Massif in Germany. According to this model, an active Neoproterozoic (Cadomian) continental margin with a back-arc basin like that of the present-day Japan Sea (Fig. 4a) yielded to the development of a retroarc basin in the Late Ediacaran−Early Cambrian as a result of ridge-trench collision, slab break-off, a change to a transform margin and back-arc closure (Fig. 4b). This tectonic regime yielded, in turn, to one of asymmetric rifting in the Early−Middle Cambrian analogous to the present-day Basin and Range Province of western North America (Fig. 4c). Finally, in the Late Cambrian and Early Ordovician, rift incision like that which produced the present-day Gulf of California (Fig. 4d), led to the opening of the Rheic Ocean (Fig. 4e).

Others, however, have argued that the Rheic Ocean originated as a peri-Gondwanan back-arc basin that opened into a major ocean (e.g., van Staal et al., 1998, 2009; Bozkurt et al., 2008). For example, the mechanism favored for the opening of the Rheic Ocean by those working in peri-Gondwanan NW Iberia (e.g., Arenas et al., 2007; Martínez Catalán et al., 2009) is the expansion of a back-arc basin of the Tornquist Sea between Gondwana and Baltica (Fig. 5). Such models do not use ridge-trench collision as a mechanism for ocean initiation, but instead, call upon subduction of the outboard Iapetus/Tornquist Ocean (through either proximal slab roll-back or distal slab pull) as the driving force for Rheic Ocean rifting.

An alternative tectonic setting for the inception of the Rheic Ocean is provided by a model proposed by Waldron et al. (2011) to account for the relatively rapid onset of subduction (only 20−40 m.y. after final rifting) in the Iapetus Ocean. Following the proposal of Murphy et al. (2011) for the Rheic Ocean (see below), these authors submit that the highly depleted mantle source indicated isotopically for many Iapetan ophiolitic complexes points to a history of magmatism that predates the opening of Iapetus, suggesting that the complexes preserve oceanic lithosphere that was captured from the adjacent paleo-Pacific in a manner analogous to the capture of the Caribbean plate by the Atlantic realm in the Mesozoic−Cenozoic. If this was the case and capture occurred between Baltica and Gondwana (Fig. 1), the Avalonian−Cadomian margin of Gondwana would have occupied a tectonic position similar to those along the northern and southern sides of the present-day Caribbean plate and, hence, could have witnessed a diachronous transition from arc to transform as the captured lithosphere moved westward into Iapetus.

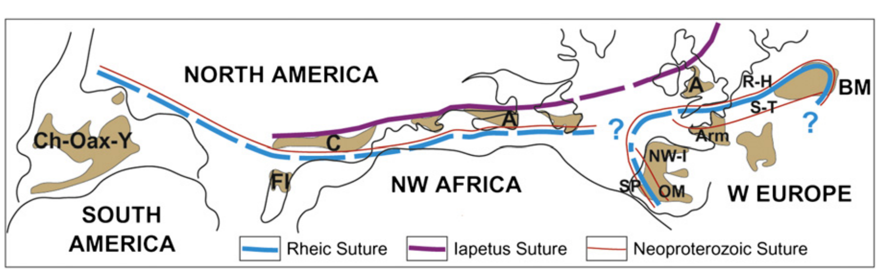

Figure 2 Location of Rheic and Iapetus sutures on an Early Mesozoic reconstruction of the North Atlantic and the close correspondence of the Rheic suture with sutures associated with the accretion of arc terranes to the northern Gondwanan margin in the Late Neoproterozoic (from Murphy et al., 2006). Abbreviations: A = Avalonia, Arm = Armorica, BM = Bohemian Massif, C = Carolinia, Ch = Chortis, Fl = Florida, NW-I = northwest Iberia, Oax = Oaxaquia, OM = Ossa Morena, R-H = Rheno-Hercynian, SP = South Portuguese, S-T = Saxo-Thuringian, Y = Yucatan (modified after Murphy et al., 2006).

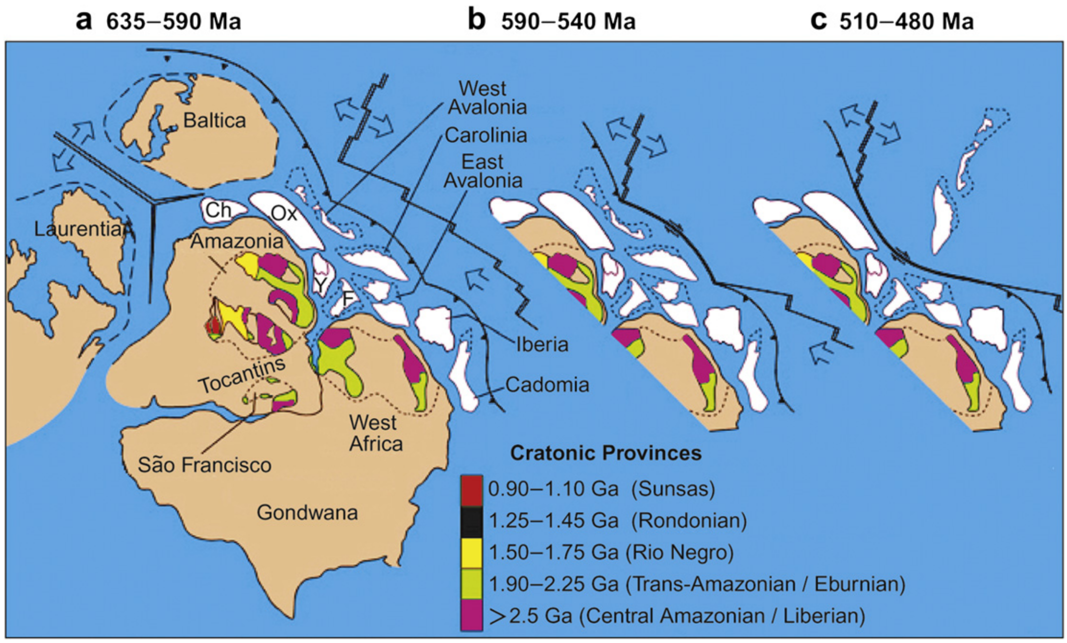

Figure 3 Restoration of Avalonia and related peri-Gondwana terranes relative to the northern margin of Gondwana (from Nance et al., 2002, 2008). a: Late Neoproterozoic (ca. 635–590 Ma) subduction along the periphery of Gondwana (Ch = Chortis Block, Ox = Oaxaquia, Y = Yucatan Block, F = Florida); b: Latest Neoproterozoic (ca. 590–540 Ma) ridge-trench collision with diachronous termination of subduction and generation of continental transform margin; c: Early Paleozoic (ca. 510–480 Ma) continental rifting and separation of Avalonia and Carolinia from Gondwana with the opening of the Rheic Ocean.

An important record of the initial rifting of the Rheic Ocean is preserved in the Ossa-Morena zone of southern Iberia (Fig. 6) where the transition from Cadomian magmatic arc to Rheic Ocean rifting is again attributed to ridge-trench collision (Sánchez-García et al., 2008, 2010). Within the Ossa-Morena Zone, cessation of Cadomian arc magmatism is closely followed by clastic sedimentation accompanied by an episode of largely felsic volcanism dated at ca. 530 Ma and attributed to an early phase of passive rifting. Ensuing subsidence and marine transgression culminated in the development of a shallow-marine carbonate platform that persisted until the end of the Early Cambrian when it broke up with the formation of horst and graben structures. This platform collapse heralds the return of clastic sedimentation and the onset of an episode of bimodal volcanism that marks the main phase of active rifting and was most voluminous in the Middle Cambrian between 512 Ma and 502 Ma. A break-up unconformity occurs at the Cambro-Ordovician boundary and is followed, in the early Ordovician, by the development of a passive margin and outer platform sedimentation that continues until the start of the Variscan orogeny in the Middle Devonian.

3. Ocean opening

Regardless of the mechanism by which it was achieved, rifting of the Rheic Ocean took place along the northern margin of Gondwana in the mid- to Late Cambrian, by which time Iapetus was already a wide ocean (Fig. 1). The terranes that separated from Gondwana as the ocean opened in the Early Ordovician, such as Avalonia and Carolinia (Fig. 3), were in large part the same terranes that had accreted to this margin in the Late Neoproterozoic, leading Murphy et al. (2006) to suggest that rifting occurred along the line of a former Neoproterozoic suture (Fig. 2).

Terrane separation is likely to have been diachronous because the onset of passive margin sedimentation in Mexico, at the western end of the Rheic Ocean, occurs in the latest Cambrian (e.g., Landing et al., 2007), whereas in Europe to the east, separation in the Arenig (Floian) is supported by paleomagnetic data (e.g., Cocks and Torsvik, 2002, 2006) and the widespread deposition of the Armorican Quartzite (e.g., Young, 1990). Views differ, however, as to whether terrane separation occurred more-or-less en masse (e.g., Murphy et al., 1999, 2004; Keppie et al., 2003) or independently at intervals during the Cambro-Ordovician (e.g., van Staal et al., 1998, 2009; Hibbard et al., 2007).

Throughout the Ordovician, the Rheic Ocean widened at the expense of Iapetus as the departing peri-Gondwanan terranes drifted northward toward Baltica and Laurentia (Fig. 1). Replacement of the endemic fauna of these terranes by those of Baltic and Laurentian affinities by the end of the Middle Ordovician (e.g., Fortey and Cocks, 2003) suggests increasing proximity to these continents and a widening gap with Gondwana. Paleomagnetic data likewise suggest increasing separation from Gondwana, with Avalonia lying at least 2000 km to the north by the end of the Middle Ordovician (Hamilton and Murphy, 2004). This would necessitate a relatively rapid spreading rate (8–10 cm/y) for the opening Rheic Ocean, which suggests the involvement of slab pull (e.g., Murphy et al., 2006).

Conversely, European Cadomia, which also formed part of the active Neoproterozoic margin of Gondwana, probably remained attached to Gondwana to form the southern margin of the Rheic Ocean until its Variscan collision with Baltica in the uppermost Devonian. Although some uncertainty exists regarding the relationship between Gondwana and Cadomia during the Early Paleozoic (e.g., Robardet, 2003), Nd isotopic data and detrital zircon ages, coupled with widespread evidence for a shared Late Ordovician glaciation (e.g., Linnemann et al., 2004; Martínez

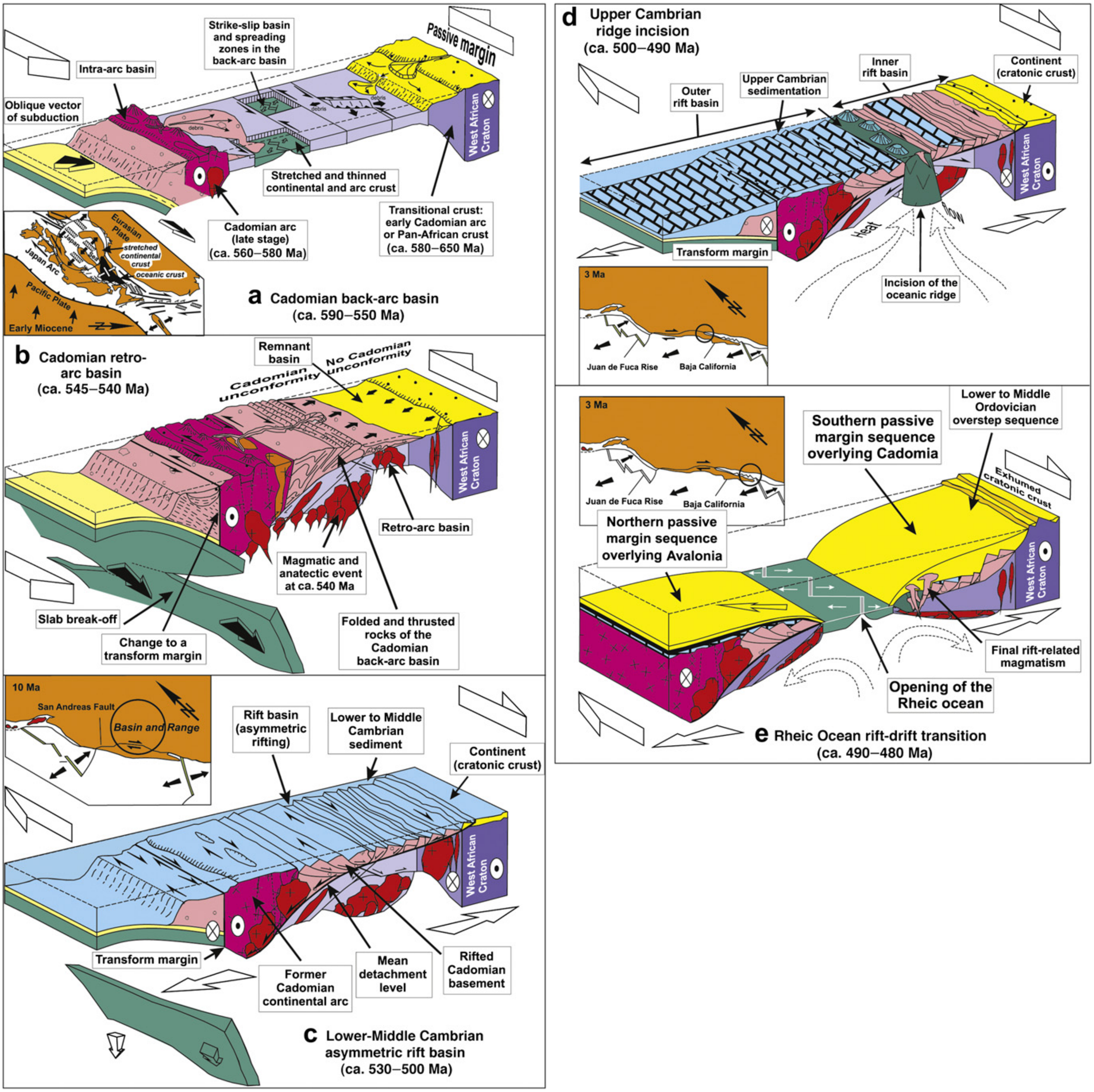

Figure 4 Model for the plate-tectonic transition from Cadomian arc to Rheic Ocean in the Saxo-Thuringian zone of the Bohemian Massif (simplified from Linnemann et al., 2007). a: Cadomian back-arc basin development at ca. 590–550 Ma; b: Cadomian retroarc basin development at 545–540 Ma; c: Early to Middle Cambrian asymmetric rifting at ca. 530–500 Ma; d: upper Cambrian oceanic ridge incision at ca. 500–490 Ma; and e: Early Ordovician Rheic rift-drift transition at ca. 490–480 Ma. Inset in (a) shows analogous setting illustrated by the opening of the Japan Sea in the Early Miocene. Insets in (c)–(e) show analogous settings (circled) illustrated by the Miocene–Pliocene evolution of the Pacific margin of North America.

Catalán et al., 2004) and the continuous Cambrian to Devonian record of passive margin sedimentation in Iberia (e.g., Quesada, 1991; Sánchez-García et al., 2003), suggest that any separation between the two was minimal.

The Rheic Ocean reached its greatest width (ca. 4000 km) with the elimination of the Tornquist Sea between Avalonia and Baltica in the Late Ordovician and the closure of Iapetus in the Silurian (e.g., Pickering, 2008). With this closure, Laurentia collided, on the one hand, with a combined Avalonia–Baltica to form the Caledonide orogen of Western Europe and, on the other, with the northward-drifting peri-Gondwanan terranes to form the ancestral Appalachian Mountains (Fig. 7).

4. Ocean closure

Closure of the Rheic Ocean took place during the Devonian and is likely to have been largely accommodated by intra-oceanic

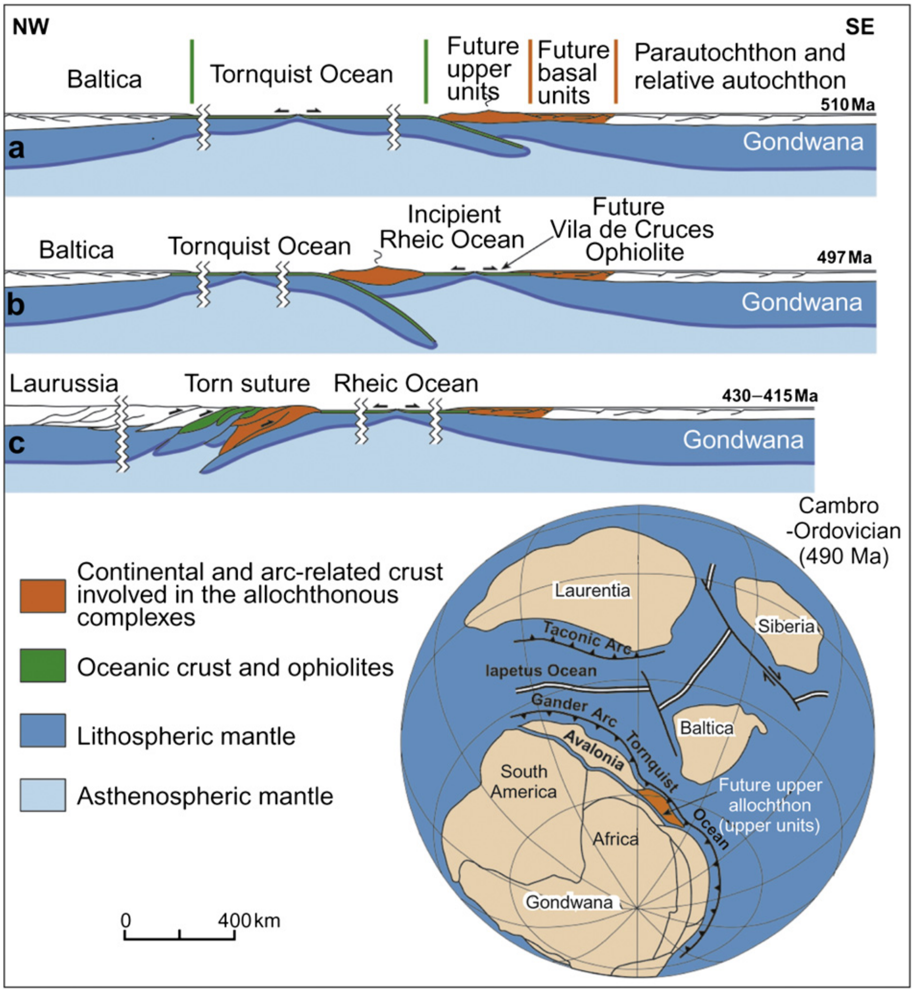

Figure 5 Plate tectonic model for the opening of the Rheic Ocean in NW Iberia (from Arenas et al., 2007). a: Subduction of the Tornquist Ocean at the northern periphery of Gondwana; b: formation of a peri-Gondwanan terrane by slab roll-back of Tornquist lithosphere; and c: closure of the Tornquist Ocean and accretion of the peri-Gondwanan terrane to Laurussia as the Rheic Ocean reaches its maximum width.

subduction because preserved arcs are rare. Subduction was predominantly NW-directed beneath Laurentia–Baltica in the Canadian Appalachians (e.g., van Staal et al., 2009) and in the Variscan belt of Europe, where arc magmatism developed on the previously accreted peri-Gondwanan terranes (e.g., Mid-German Crystalline High; Kroner et al., 2007). However, the polarity of subduction was SE-directed beneath Gondwana in the U.S. Appalachian-Ouachita belt, where Laurentia forms the lower plate (e.g., Cook and Vasudevan, 2006). This would have required a major transform boundary in the southwestern Rheic Ocean, which Pe-Piper et al. (2010) have suggested was located in the eastern Gulf of Maine based on plutonism linked to the slab tear.

In Mexico and Europe, closure of the Rheic Ocean was accompanied in the Late Devonian and Early Carboniferous by the emplacement of rare ophiolites and associated high-pressure rocks (e.g., Murphy et al., 2009b). Emplacement ages range from ca. 385–380 Ma in the Bohemian Massif (Ślęża ophiolite and Mariánské Lázně Complex; e.g., Kryza and Pin, 2010) and southern Britain (Lizard ophiolite; e.g., Nutman et al., 2001), to ca. 365 Ma in NW Iberia (Upper and Lower Ophiolites; e.g., Martínez-Catalán et al., 1997), and ca. 350–340 Ma in southern Iberia (Beja-Acebuches ophiolite; e.g., Pin and Paquette, 1997; Azor et al., 2008) and southern Mexico (Piaxtla Suite; e.g., Middleton et al., 2007). The ophiolites themselves are either Ordovician in age, as is the case for the Mariánské Lázně Complex, Piaxtla Suite and Lower Ophiolite of NW Iberia, or they are Devonian, as is the case for the Upper Ophiolite of NW Iberia and the Ślęża, Lizard and Beja-Acebuches ophiolites, the latter probably extending into the Early Carboniferous (Azor et al., 2008). Hence, they developed either very early or very late in the evolution of the Rheic Ocean. Some of the early mafic complexes, such as the Piaxtla Suite in Mexico, are rift-related (e.g., Keppie et al., in press) and, hence, not strictly ophiolites. However, those that are ophiolites are probably true vestiges of the Rheic Ocean (e.g., Ribeiro et al., 2010). The origin of the Devonian ophiolites, on the other hand, is more controversial and most are interpreted to have formed in a variety of marginal basins during Rheic Ocean closure (e.g., Davies, 1984; Quesada et al., 1994; Sánchez Martínez et al., 2007; Azor et al., 2008).

Nd-isotopic data for many of these ophiolites (e.g., Murphy et al., 2009b) show unusually high ε_{Nd} values that are at or above the model depleted mantle curve. According to Murphy et al. (2011), this indicates their derivation from an anomalous

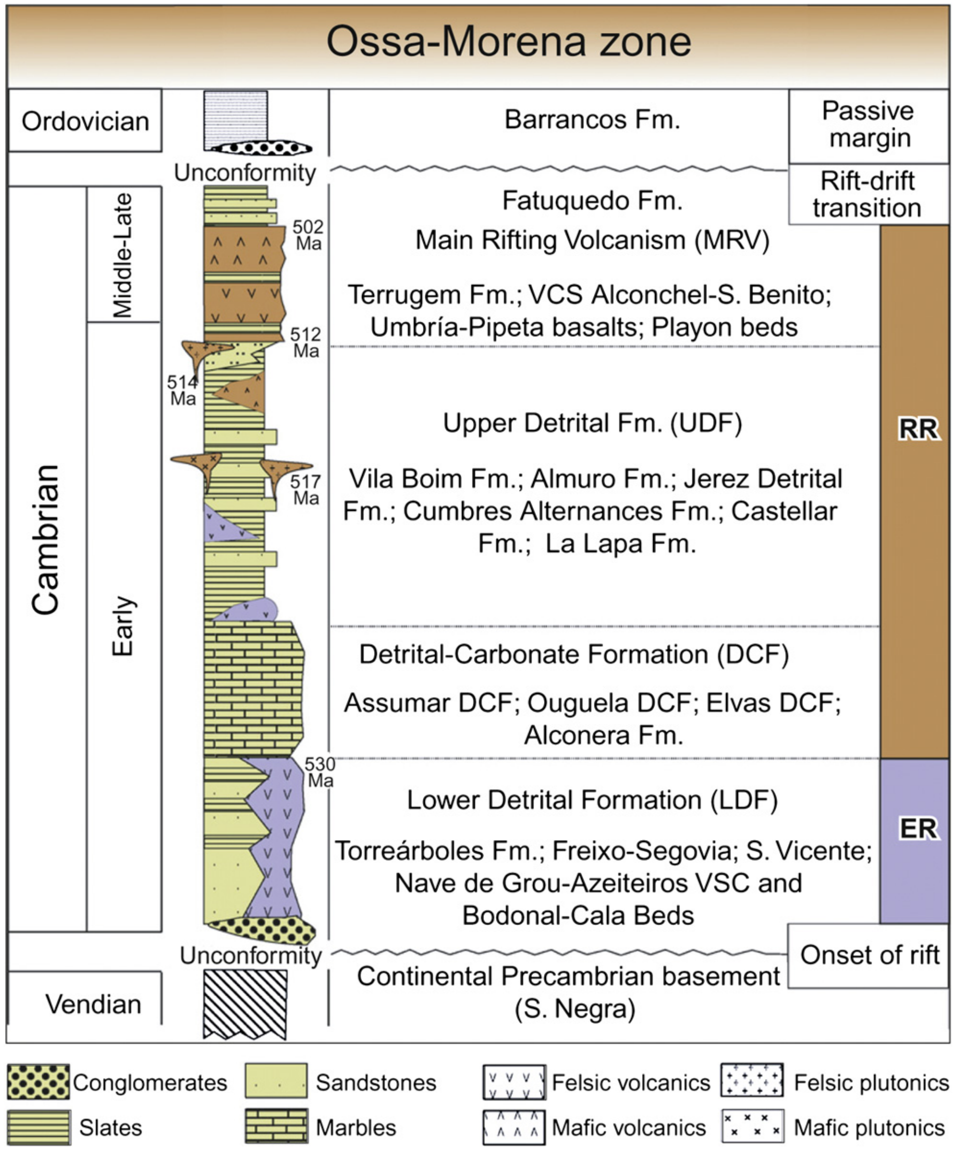

Figure 6 Generalized stratigraphic column of the Rheic rift sequence in the Ossa-Morena zone of southern Iberia (from Sánchez-García et al., 2010). ER = early rift-related stage, RR = main rift-related stage.

mantle that was highly depleted as the result of a melting event that occurred prior to the opening of the Rheic Ocean. Hence, these authors suggest that the preserved ophiolites could not have been generated during the opening phase of the Rheic Ocean, but rather represent mantle lithosphere captured from an adjacent, older ocean in a manner analogous to the Mesozoic–Cenozoic transfer of the Caribbean and Scotia plates from the Pacific Ocean to the Atlantic realm. If so, closure of the Rheic Ocean may have involved a similar process to that proposed for the Iapetus Ocean (Waldron et al., 2011).

5. Terminal collision

As with its initial opening, final closure of the Rheic Ocean took place diachronously. It was essentially complete in Europe by the Early Carboniferous as Gondwana collided with southern Baltica to create the Variscan orogen (e.g., Kroner et al., 2007). But further west, closure took place in the Late Carboniferous and continued into the Permian as the West African margin of Gondwana collided with eastern Laurentia to produce the climactic Alleghanian phase of Appalachian orogenesis (and reactivate the Mauritanides), while the Amazonian margin of Gondwana collided with southern Laurentia to produce the Ouachita orogen of the southern United States (e.g., Sacks and Secor, 1990). The resulting Ouachita-Alleghanian-Variscan belt was the largest collisional orogen of the Paleozoic and sutured Gondwana and Laurussia to form Pangea.

In Europe, final closure of the Rheic Ocean in the Devono-Carboniferous involved oblique, north-directed subduction of thinned Gondwanan continental crust, followed by SE-directed exhumation, regional dextral transpression, and widespread Variscan plutonism (e.g., Kroner et al., 2007). The irregularities of the colliding continental margins are exemplified by the excision of large crustal blocks from regions well inboard of Laurentia into the collision zone (Braid et al., 2011). In North America, on the

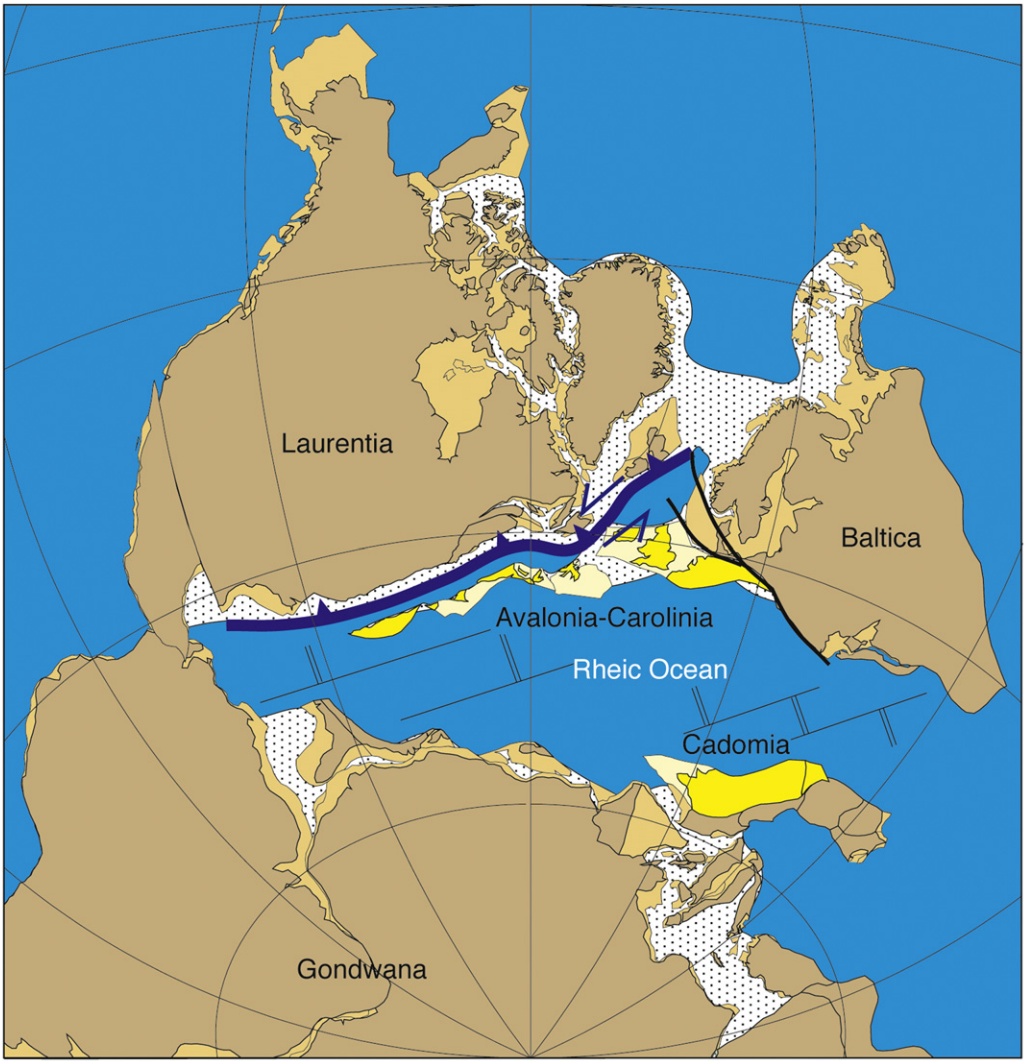

Figure 7 Early Silurian reconstruction of the Rheic Ocean immediately prior to the closure of Iapetus by way of subduction (toothed purple line) beneath Laurentia (from Nance and Linnemann, 2008). Stippled areas denote inferred regions of thinned and/or anomalous thickness of continental and arc crust (simplified after Pickering and Smith, 1995, with Cadomia placed adjacent to Gondwana). Rheic ridge-transform system purely schematic. Heavy black lines trace Tornquist suture zone.

other hand, the nature of the collision varies significantly from north to south (Fig. 8). In the northern Appalachians, collision between Laurentia and Gondwana was markedly oblique and Alleghanian orogenesis is largely of Pennsylvanian age and dominated by dextral strike-slip motion on major NW-trending faults. High-grade metamorphism and associated magmatism occurred in the Late Pennsylvanian–Early Permian, but is limited in its extent and attributed to local crustal thickening (e.g., Snoke and Mosher, 1989). Conversely, in the southern Appalachian orogen and Ouachita belt, collision began in the late Mississippian and was essentially head-on, leading to the development of crustal-scale decollement structures and north- and west-vergent fold-thrust belts as thinned Laurentian continental crust was subducted beneath Gondwana (e.g., Cook and Vasudevan, 2006). In the orogenic hinterland exposed in the southern Appalachians, deformation was accompanied by dextral strike-slip tectonics, significant metamorphism and widespread latest Mississippian–Pennsylvanian magmatism attributed to crustal thickening (e.g., Hatcher, 2002).

Further south in the Acatlán Complex southern Mexico (e.g., Nance et al., 2007), closure of the Rheic Ocean did not result in continental collision, but rather brought Gondwana into contact with the paleo-Pacific (Keppie et al., 2008). As a result, Rheic closure, which is marked by the Early Mississippian exhumation of high-pressure rocks representing the Ordovician rift-shelf sequence of the Gondwana continental margin (e.g., Keppie et al., 2010), was followed by dextral transpression and the coeval development of a Permian magmatic arc, which is thought to record the onset of oblique subduction of the paleo-Pacific brought about by Pangea assembly (Keppie et al., in press).

6. Discussion

As the largest interior ocean of the Paleozoic, the closure of which assembled the greater part of Pangea with the formation of the Ouachita-Appalachian-Variscan orogenic belt, the Rheic Ocean was clearly one of the most important of the Paleozoic Era. It was

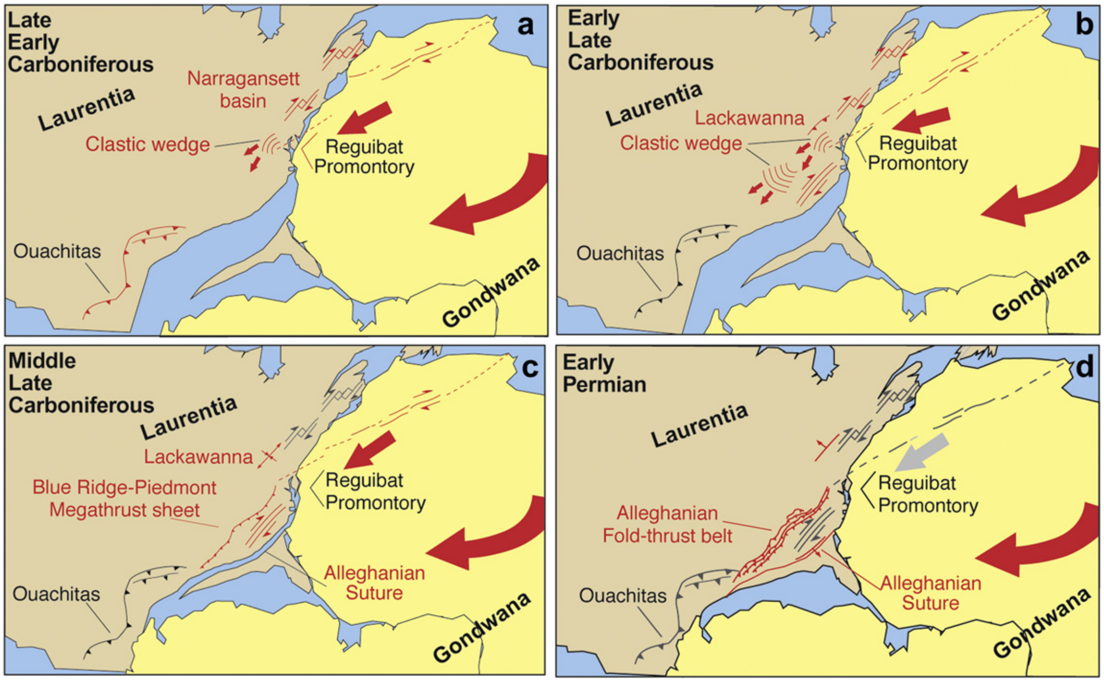

Figure 8 Oblique rotational collision between Laurentia and Gondwana according to Hatcher (2002). Symbols in red identify features active during the time interval represented. a: Initial contact between Laurentia and Gondwana during the Late Mississippian; b: southward motion and clockwise rotation of Gondwana during the Early Pennsylvanian; c: continued rotation and southward movement of Gondwana in the Late Pennsylvanian; and d: head-on Laurentia Gondwana collision in the Early Permian.

formed with the separation of several ribbon terranes from the northern margin of Gondwana in the Early Ordovician, and widened at the expense of the Iapetus Ocean as the ribbon terranes, which separated the two oceans, drifted northward. Accretion of these terranes to, and the suturing of, Laurentia and Baltica by the Late Silurian effectively closed the Iapetus Ocean. Following this the Rheic Ocean lay between the paleocontinents of Laurussia and Gondwana, which were then separated by at least 4000 km. Rheic Ocean closure during the Devonian was achieved by predominantly NW-directed subduction beneath Baltica to the north and SE-directed subduction beneath Gondwana to the west, and was accompanied in Europe and Mexico by the Late Devonian emplacement of ophiolites and high-pressure rocks. Ocean closure was essentially complete by the Mississippian, but continued into the Early Permian as the irregular West African margin of Gondwana collided obliquely with southern Baltica and eastern Laurentia while the Amazonian margin of Gondwana sutured to southern Laurentia. The history of the Rheic Ocean consequently plays a pivotal role in the Paleozoic tectonosedimentary record from Mexico to the Middle East and its completion brought an end the Paleozoic Era.

Despite the importance of the Rheic Ocean, major uncertainties still exist with regard to its evolution. Opinions differ on the mechanism by which the peri-Gondwanan ribbon terranes that formed its northern flank separated from northern Gondwana, and whether they did so en masse as a single crustal block or piecemeal as independent crustal units. Consequently, it is unclear whether the Rheic Ocean was a single entity or a collage of smaller oceanic tracts. The importance of these uncertainties is highlighted as the Rheic suture is traced eastwards into the realm of the younger Paleo-Tethys and Tethys oceans. These oceans were likewise opened by the removal of ribbon terranes from the northern margin of Gondwana (e.g., von Raumer and Stampfli, 2008), suggesting that the mechanism responsible for the opening of the Rheic Ocean was repeated along the same Gondwanan margin on several occasions.

An additional issue, given the estimated 4000 km width of the Rheic Ocean, is the apparent scarcity (beyond the Mid-German Crystalline Rise) of Devono-Carboniferous continental arcs associated with its closure. This has led to the general assumption that closure of the Rheic Ocean was accommodated mainly by intra-oceanic subduction. However, preserved island arcs are likewise scarce. It is therefore possible that arc removal by subduction erosion, like that proposed for the Rheic arc in Mexico (Keppie et al., 2008), was an important process during Rheic Ocean closure.

Finally, on a larger scale, it remains unclear why Pangea amalgamated as the result of the closure of Iapetus and Rheic Oceans rather than the paleo-Pacific (Murphy and Nance, 2008). This bears upon the process of supercontinent assembly as most forward geodynamic models favor the continued closure of the present-day Pacific and the ultimate assembly of the supercontinent Amasia (Hoffman, 1992) with the suturing of the Americas to Asia. Yet the only supercontinent for which we have a reliable record did not form in this way but, instead, assembled through the closure of today's equivalent of the Atlantic. Modeled forward, this would reunite Pangea to form the supercontinent Pangea Proxima (Scotese, 2000).

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