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GR Focus

Evolution of the Rheic Ocean

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ABSTRACT

The Rheic Ocean, which separated Laurussia from Gondwana following the closure of Iapetus, is arguably the most important ocean of the Palaeozoic. Its suture extends from Mexico to Turkey and its closure produced the climactic Variscan–Alleghanian–Ouachita orogeny that assembled the supercontinent, Pangaea.

Following protracted Cambrian rifting that represented a continuum from Neoproterozoic orogenic processes, the Rheic Ocean opened in the Early Ordovician with the separation of several Neoproterozoic arc terranes from the continental margin of northern Gondwana. Separation occurred along the line of a former Neoproterozoic suture following the onset of subduction in the outboard Iapetus Ocean. The timing of rift–drift transition and drive for subsequent spreading was likely governed by slab pull, accounting for the rapid rate (8–10 cm/yr) at which the Rheic Ocean widened.

During the Ordovician, the ocean broadened at the expense of Iapetus and attained its greatest width (~4000 km) in the Silurian, by which time Baltica had sutured to Laurentia and the Neoproterozoic arc terranes had accreted to Laurussia, closing Iapetus in the process. Closure of the Rheic Ocean began in the Devonian and was facilitated by northward subduction beneath southern Baltica and southward subduction beneath northwest Gondwana. Closure was largely complete by the Mississippian as Gondwana and Laurussia sutured to build Pangaea, North Africa colliding with southern Europe to create the Variscan orogen in the Devonian–Carboniferous, and West Africa and South America suturing to North America to form the Alleghanian and Ouachita orogens, respectively, during the Carboniferous–Permian.

The Rheic Ocean consequently plays a dominant role in the basement geology of southern Europe, in the Appalachian–Ouachita orogeny of North America, and in the Palaeozoic sedimentary, structural and tectonothermal record from Middle America to the Middle East. With its closure, the ocean brought about the assembly of Pangaea and brought the Palaeozoic Era to an end.

Contents

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1. Introduction

The Rheic Ocean, which separated the major palaeocontinents of Gondwana and Laurussia (Laurentia–Baltica–Avalonia) following the closure of Iapetus (Fig. 1), was one of the principal oceans of the Palaeozoic (e.g., Nance and Linnemann, 2008). Its suture extends over 10,000 km from Mexico to Turkey, and its closure assembled the greater part of Pangaea with the formation of the vast Variscan–Alleghanian–Ouachita orogen. The evolution of the Rheic Ocean is consequently central not only to the history of the Palaeozoic, but also to the broader issue of supercontinent assembly (e.g., Murphy et al., 2009; Santosh et al., 2009).

Named for the Titan, Rhea, sister to Iapetus in Greek mythology, the importance of the Rheic Ocean has long been recognized in Europe, where its suture is well constrained and well separated from that of the Iapetus Ocean to the north. Hence, in Europe, the Caledonide orogen, created by the closure of Iapetus, is a geographically distinct orogenic belt from the Variscan orogen, created by the closure of the Rheic Ocean (Fig. 2). In North America, however, the Rheic Ocean has historically received less attention than Iapetus because its suture follows a similar path, but unlike that of Iapetus, lies buried beneath the sediments of the Coastal Plain or was removed with the opening of the Atlantic Ocean and Gulf of Mexico. As a result, the history of the Appalachian–Ouachita orogen is traditionally

Fig. 1. Early Silurian reconstruction of the Rheic Ocean immediately prior to the closure of Iapetus by way of subduction beneath Laurentia (toothed red line). 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.

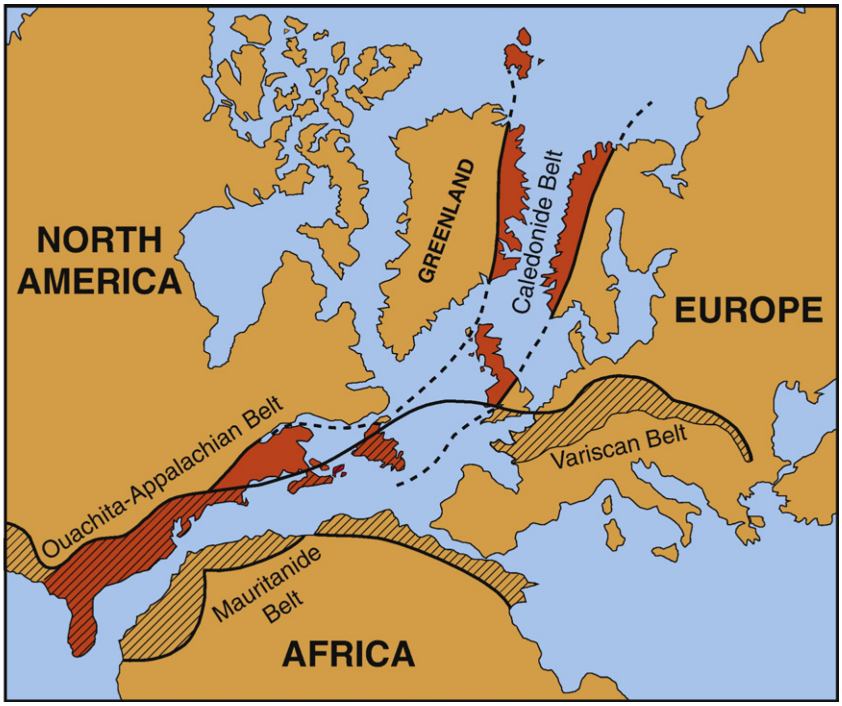

Fig. 2. Continuity of the Ouachita–Appalachian belt of North America with the Caledonian and Variscan belts of Europe and the reactivated Mauritanide belt of West Africa in a Pangaea fit of the North Atlantic. Cross hatching identifies areas of Late Palaeozoic (Variscan–Alleghanian–Ouachita) deformation associated with closure of the Rheic Ocean.

described in terms of the evolution of Iapetus. But in bringing together the two largest continents of the Palaeozoic, it was the closure of the Rheic Ocean that produced North America's Appalachian–Ouachita orogen in the Late Palaeozoic, assembling Pangaea in the process (cf., Murphy et al., 2010-this issue).

In this paper, we demonstrate the significance of the Rheic Ocean to the geological history of both Europe and North America by reviewing the record of its origin and evolution in the Bohemian Massif, southern Britain, northwestern and southern Iberia, eastern and southern North America and southern Mexico. The time scale used is that of Gradstein et al. (2004).

2. Evolution of the Rheic Ocean

Initial rifting of the Rheic Ocean forms a continuum with the Neoproterozoic–Early Cambrian accretionary orogenic processes that preceded it. Rifting took place along the northern (African–South American) margin of Gondwana in the mid- to Late Cambrian (e.g., Sánchez-García et al., 2003, 2008, 2010-this issue), by which time Iapetus, which lay to the north (Fig. 1) and had opened in the Late Neoproterozoic–Early Cambrian (e.g., Cawood et al., 2001), was already a wide ocean. Prior to this, in the Late Neoproterozoic, the northern Gondwanan margin had witnessed a prolonged history of subduction and accretion that was followed, in the Late Ediacaran–Early Cambrian, by the diachronous cessation of arc magmatism and the development of a transform continental margin (e.g., Nance et al., 1991; 2008). This pre-rift history is analogous to that of the Pacific margin of North America in the Cenozoic and the transition in tectonic regime along the Gondwanan margin has been similarly attributed to ridge–trench collision (e.g., Murphy et al., 1999a, 2006a; Nance et al., 2002; Keppie et al., 2003).

Following a protracted period of rifting, the Rheic Ocean finally opened in the Early Ordovician with the separation of several Neoproterozoic arc terranes from the margin of northern Gondwana. The microcontinental terranes that separated (e.g., Avalonia, Ganderia, Carolinia, Meguma) were, in large part, the same terranes that had accreted to this margin in the Late Neoproterozoic, leading Murphy et al. (2006a) to suggest that separation occurred along the line of a former Neoproterozoic suture (Fig. 3). The timing of separation closely followed the onset of subduction in the Iapetus Ocean between Gondwana and Laurentia at ca. 510 Ma (van Staal et al., 1998). This may not be coincidental if the earlier termination of arc magmatism on the Gondwanan margin was a consequence of ridge–trench collision since, with elimination of the intervening ridge, the subducting Iapetan slab may have been directly coupled to the Gondwanan margin. Hence, the likelihood exists that the change in

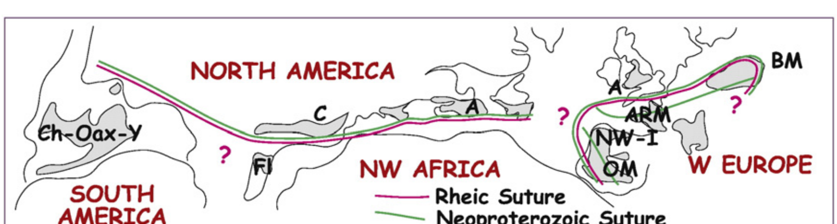

Fig. 3. Location of Rheic suture on Early Mesozoic reconstruction of the North Atlantic and its close correspondence with sutures associated with the accretion of arc terranes to the northern Gondwanan margin in the Late Neoproterozoic (from Murphy et al., 2006a). Abbreviations: A = Avalonia, Arm = Armorica, BM = Bohemian Massif, C = Carolinia, CAD = Cadomia, Ch = Chortis, Fl = Florida, NW-I = northwest Iberia, Oax = Oaxaquia, OM = Ossa Morena, Y = Yucatan.

tectonic regime from rift to drift, and the subsequent opening of the Rheic Ocean in the wake of the separating terranes, was provided by slab pull within Iapetus to the north (Fig. 4).

In western Europe, separation of Avalonia by the Arenig is supported by palaeomagnetic data (e.g., Cocks and Torsvik, 2002) and Sm/Nd isotopic studies of the sedimentary record in southern Britain (Thorogood, 1990), and is recorded in the widespread deposition of the Armorican Quartzite and its equivalents, the depositional age of which, in northwestern Iberia, is ca. 475 Ma (Gutiérrez-Alonso et al., 2007). In Mexico, however, the onset of passive margin sedimentation occurs in the latest Cambrian (Landing et al., 2007), whereas backstripped subsidence curves in the Anglo-Welsh segment of eastern Avalonia suggest that drifting may not have been achieved until the mid-Arenig to Llanvirn (Prigmore et al., 1997). At the same time, the Early Ordovician Gondwanan fauna of Avalonia were gradually replaced by endemic forms (Fortey and Cocks, 2003). It is therefore likely that, as with the previous transition from magmatic arc to continental transform, the rifting and separation of terranes from northern Gondwana was a protracted process that took place diachronously.

Throughout the Ordovician, the Rheic Ocean widened at the expense of Iapetus as Avalonia–Carolinia drifted northward towards Baltica and Laurentia (Fig. 4). The endemic fauna of Avalonia is progressively replaced by those of Baltic and Laurentian affinities in the Llandeilo–Ashgillian (Fortey and Cocks, 2003), suggesting increasing proximity to these continents and a widening gap with Gondwana by the mid-Ordovician (ca. 465 Ma). Similarly, palaeomagnetic data indicate that, by 460 Ma, Avalonia lay at 41°S (Hamilton and Murphy, 2004), some 2000 km south of Laurentia (at ~20°S; Mac Niocaill and Smethurst 1994) and about 2100 km north of the northern Gondwanan margin (at ~60°S; Cocks and Torsvik, 2002). This requires Avalonia to have drifted north at the relatively rapid rate of 8–10 cm/yr. This is well in excess of modern ridge–push spreading rates, like those of the Mid-Atlantic Ridge (1–2 cm/yr; e.g., DeMets et al., 1990), supporting the involvement of slab pull (Murphy et al., 2006a) or slab roll back (Martínez-Catalán et al., 2009) in the opening of the Rheic Ocean. Even faster rates may have been attained by Carolinia, which was likely attached to, but ~2000 km north of Avalonia, and minimally separated from Laurentia latitudinally by ca. 455 Ma (e.g., Noel et al., 1988; Vick et al., 1987). On the other hand, European Cadomia, which also formed part of the active Neoproterozoic margin of Gondwana, likely remained on the northern Gondwanan margin (Linnemann et al., 2004), forming the southern margin of the Rheic Ocean from the Early Ordovician until at least the latest Devonian (Fig. 1). This is supported by palaeomagnetic data (Köβler et al., 1996) and the southerly palaeolatitude of Cadomia in the Late Ordovician indicated by the presence of glacial tillites, which are characteristic of Gondwana (e.g., Oggiano and Mameli, 2006) but absent in Avalonia.

The Rheic Ocean reached its greatest width (~4000 km) in the Silurian (Fig. 1), by which time Laurentia had collided with Baltica to the north and with Avalonia–Carolinia to the south (e.g., Trench and Torsvik, 1992), closing the Iapetus Ocean and creating the Appalachian (Salinic)–Caledonide orogen in the process (Fig. 2). Closure of the Rheic Ocean began in the Early Devonian and was facilitated by northward subduction beneath the southern margin of Baltica in the Variscan belt, where arc magmatism developed on the previously accreted Avalonian terranes (e.g., Kroner et al., 2007), and by

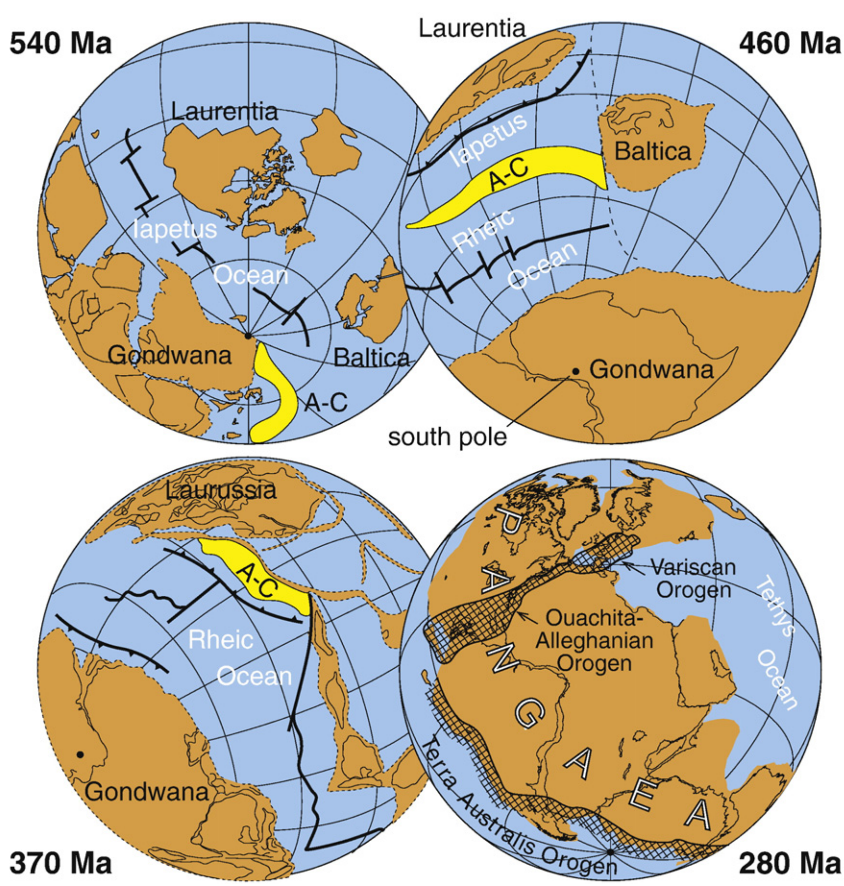

Fig. 4. Palaeozoic reconstructions (modified from Scotese, 1997; Cocks and Torsvik, 2002; Stampfli and Borel, 2002; Murphy et al., 2006a; Cawood and Buchan, 2007). By 540 Ma, the Iapetus Ocean had formed between Laurentia and Gondwana. By 460 Ma, Avalonia–Carolinia (A–C) had separated from Gondwana, creating the Rheic Ocean. By 370 Ma, Laurentia, Baltica and Avalonia–Carolinia had collided to form Laurussia, and the Rheic Ocean began to contract, closing by 280 Ma, to form Pangaea. The Terra Australis orogen at 280 Ma was located along the periphery of Pangaea, representing the vestige of tectonic activity within the Palaeo-Pacific Ocean (from Murphy and Nance, 2008).

southward subduction beneath the northwestern margin of Gondwana in the Appalachian–Ouachita belt (Fig. 4), where Laurentia forms the lower plate (Hatcher, 1989; Viele and Thomas, 1989). Closure was accompanied at ca. 395–370 Ma (mid- to Late Devonian) by the emplacement of ophiolites onto the southern margin of eastern Avalonia in southern Britain (e.g., Nutman et al., 2001), northwest Iberia (e.g., Martínez et al., 2007), and southern Iberia (e.g., Quesada et al., 1994; Ribeiro et al., 2010-this issue), and may have accelerated as a result of ridge subduction along the ocean's northern margin (Woodcock et al., 2007; Gutiérrez-Alonso et al., 2008a). Closure was essentially complete by the Mississippian as Gondwana and Laurussia collided, a process that continued into the Early Permian. The sequential collision of Gondwana's West African margin with southern Baltica and eastern Laurentia created the Variscan and Alleghanian orogens, respectively, and reactivated the Neoproterozoic Mauritanide orogen of West Africa (e.g., Piqué and Skehan, 1992; Fig. 2), whereas the Amazonian margin of Gondwana collided with southern Laurentia to produce the Ouachita orogen (e.g., Sacks and Secor, 1990). The resulting Variscan–Alleghanian–Ouachita belt was the largest collisional orogen of the Palaeozoic and sutured Gondwana and Laurussia to form Pangaea.

3. The Rheic Ocean in Central Europe

The origin of the Rheic Ocean in Europe is closely linked to the termination of the Late Neoproterozoic Cadomian orogeny (ca. 700–540 Ma), and its closure caused the Variscan orogeny (e.g., Linnemann et al., 2007). Closure occurred at ca. 370–330 Ma and produced a suture (Fig. 5) that runs westward from the Mid-German Crystalline zone in Germany (Zeh et al., 2001, Zeh and Gerdes, 2010-this issue) and the Lizard ophiolite in southern Britain (e.g., Nutman et al., 2001), around the Iberian–Armorican arc to the Beja-Acebuches ophiolite and Pulo do Lobo suture (e.g., Quesada et al., 1994; Braid et al., 2010-this issue) of southern Iberia. To the east, in the Bohemian Massif, the Rheic suture is documented by the Sleza ophiolite (e.g., Floyd et al., 2002; Kryza and Pin, 2010-this issue) of the northern Sudetes, and may extend to the Moravo-Silesian zone on the massif's eastern margin (considered part of Avalonia [Finger et al., 2000] or Baltica [Nowrocki et al., 2004]) and on into Eastern Europe (Bulgaria, Romania, Turkey; e.g., Winchester et al., 2002; Balintoni et al., 2009, 2010-this issue; Boncheva et al., 2010-this issue; Wehrmann et al., 2010-this issue).

In central and western Europe, the suture separates Cadomia and its Palaeozoic passive margin from the southern margin of Laurussia as represented by the eastern part of Avalonia and its overlying Palaeozoic strata. Important vestiges of the Rheic Ocean exist (1) in the Cornubian basins and Lizard ophiolite of southern Britain (e.g. Nutman et al., 2001), (2) in the development at ca. 500 Ma of a passive margin sequence and emplacement at ca. 340 Ma of ophiolitic allochthons in northwestern Iberia (e.g. Arenas et al., 2007a), (3) in the well-documented rift succession of the Ossa-Morena zone (e.g., Sánchez-García et al., 2003, 2008, 2010-this issue), the Pulo do Lobo accretionary prism and the Beja-Acebuches ophiolite in southern Iberia (Quesada et al., 1994; Braid et al., 2010-this issue), (4) in the ca. 500 Ma old Vesser Complex in the Saxo-Thuringian zone at the northern periphery of the Bohemian Massif (Linnemann et al., 2007), (5) in different slices within the Mid-Germany Crystalline zone (Zeh et al., 2001; Zeh and Gerdes, 2010-this issue), and (6) in the evidence of an Early Ordovician breakup unconformity and widespread subsidence indicated by the distribution of the Armorican Quartzite and its equivalents across Iberia, northwestern France and Bohemia (e.g., Noblet and Lefort, 1990). In this section, however, we focus on the northern Bohemian Massif where a record of the evolution of the Rheic Ocean is well preserved. In this region (Fig. 6), the northern (Avalonian) margin of the Rheic Ocean is represented by the Rhenohercynian zone (Brabant and Rhenish massifs), the suture by the Mid-German Crystalline zone (e.g., Zeh et al., 2001; Zeh and Gerdes, 2010-this issue), and the southern (Gondwanan) margin by

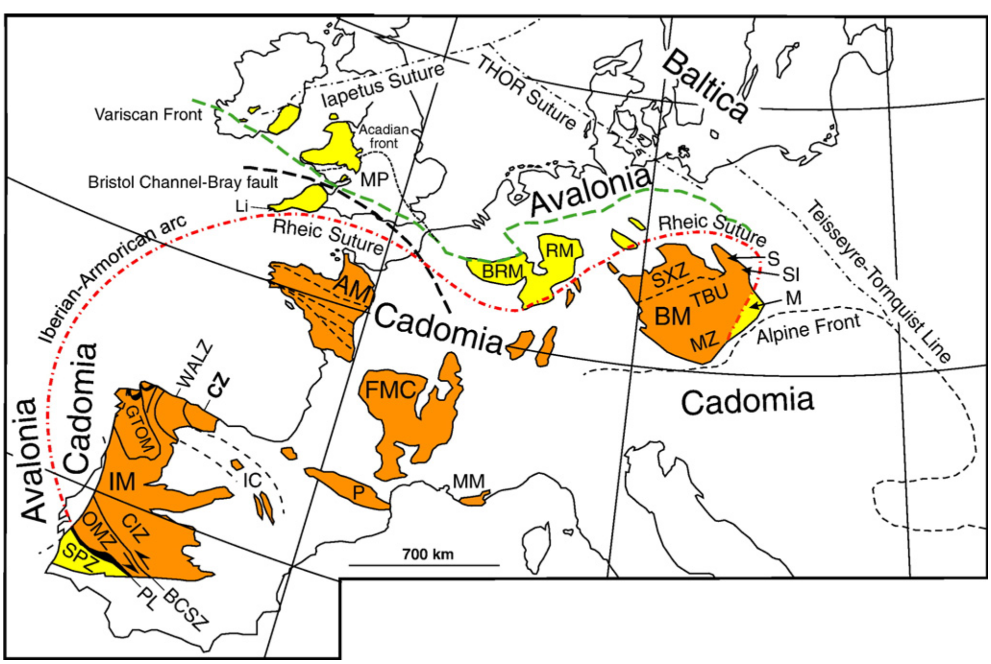

Fig. 5. Location of the Rheic suture with respect to Cadomian and Variscan Massifs in southeastern and central Europe (after Linnemann et al., 2007). Abbreviations: (1) Iberia—BCSZ = Badajoz-Cordoba Shear zone, CIZ = Central Iberian zone, CZ = Cantabrian zone, IC = Iberian Chains, IM = Iberian Massif, GTOM = Galicia Trás-os-Montes zone, MM = Maures Massif, OMZ = Ossa-Morena zone, P = Pyrénées, PL = Pulo de Lobo oceanic units, SPZ = South Portuguese zone, WALZ = West Asturian Leonese zone, (2) Western Europe—AM = Armorican Massif, FMC = French Massif Central, Li = Lizard Ophiolite, (3) Central and Eastern Europe—BM = Bohemian Massif, BRM = Brabant Massif, M = Moravo-Silesian zone, MP = Midland Platform, MZ = Moldanubian zone, RM = Rhenish Massif, S = Sudetes, SI = Sleza ophiolite, SXZ = Saxo-Thuringian zone, TBU = Teplá-Barrandian Unit. Black = oceanic rocks of the Pulo de Lobo suture (Beja-Acebuches ophiolite) in southern Iberia and ophiolitic units of allochthonous complexes in NW Spain (Galicia).

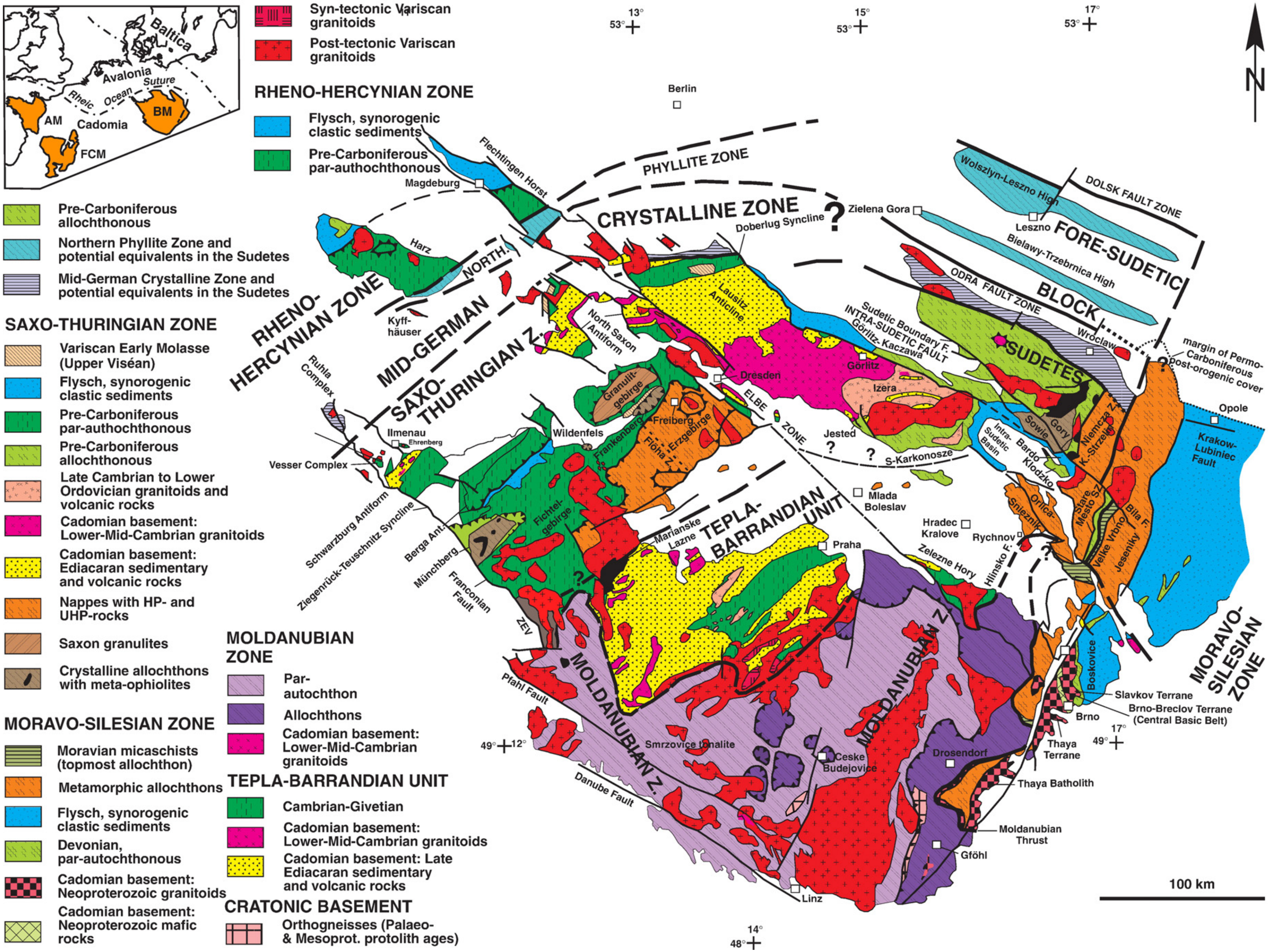

Fig. 6. Geology of the Bohemian Massif (modified after Linnemann et al., 2008).

the northern Bohemian Massif (Saxo-Thuringian and Moldanubian zones, including the Teplá-Barrandian Unit).

As part of Cadomia, the Bohemian massif is thought by some to have separated from the northern margin of Gondwana as part of the Armorican Terrane Assemblage (e.g., Franke, 2000). However, recent U–Pb detrital zircon and Hf and Nd isotopic data (e.g., Linnemann et al., 2007; Bahlburg et al., 2010-this issue) suggest Cadomia likely remained attached to Gondwana until the formation of Pangaea and so provides a record of the Palaeozoic processes at the Gondwanan margin during the Palaeozoic, consistent with the apparent polar wander curve of Scotese and Barret (1990).

3.1. Rifting and opening: aftermath of the Cadomian orogeny

In western and central Europe there is no sharp break between the Cadomian orogeny of the Late Neoproterozoic–Early Cambrian and the Cambro-Ordovician rifting that led to the opening of the Rheic Ocean. The transition from subduction to rifting occurs by way of transform activity mirroring the Cenozoic evolution of the North American Cordillera (e.g., Nance et al., 2002; Keppie et al., 2003). Hence, Cadomian orogenic processes form an important precursor to the opening of the Rheic Ocean (Fig. 7; Linnemann et al., 2007). In the Saxo-Thuringian zone, the oldest (ca. 570–565 Ma) rocks date from this orogenic event and are thought to record Cadomian back-arc basin development on thinned continental crust flanked by a magmatic arc to the north (present coordinates) and by a cratonic (West African) source to the south (Fig. 7A). Subduction during basin development is assumed to have been oblique (inset Fig. 7A).

During the interval ca. 545–540 Ma, sedimentation was dominated by monotonous sequences of turbidites and conglomerates that were derived, in large part, from the back-arc basin (flat arrows, Fig. 7B) and have been interpreted as parts of a short-lived Cadomian retro-arc or foreland basin (Linnemann et al., 2007). Inversion of the back-arc basin is attributed to the collision of the Cadomian arc with the West African craton, which deformed the inner basin closest to the colliding arc prior to the intrusion of voluminous granitoids at ca. 540 Ma. As a result, an angular Cadomian unconformity separates the Late Neoproterozoic rocks from younger Cambro-Ordovician deposits. But in the outer basin nearer the cratonic hinterland, the deposits are concordant and sedimentation was more-or-less continuous. The ca. 540 Ma granitoids were likely derived from melting of the Late Neoproterozoic turbidites and are thought to record a short-lived regime of high heat-flow attributed to slab break-off as a result of ridge–trench collision.

Following this event, the margin switched from active to transform, leading to the development of asymmetric rifts (Fig. 7C). This change in plate-tectonic regime is reflected in the deposition of Lower and Middle Cambrian carbonates, siliciclastic sediments and redbeds that contain detritus predominantly derived from the Cadomian orogen. The plate-tectonic setting is interpreted to have been similar to that of the present-day Basin and Range Province of the North American Cordillera (inset Fig. 7C).

By the Middle to Late Cambrian, mid-ocean ridge igneous rocks and associated metasediments preserved on the outer margin of the now-eroded and recycled Cadomian orogen, record propagation of an oceanic ridge into the periphery of the orogen (Fig. 7D) in a manner analogous to the present-day Gulf of California (inset Fig. 7D). Lithospheric thinning and mantle upwelling is thought to have been focused between the outer and inner zone of the asymmetric rift basin such that the former Cadomian arc of the upper plate (destined to separate as part of Avalonia) was characterized by ongoing subsidence and Upper Cambrian sedimentation, whereas the cratonic margin of the lower plate (destined to remain part of Cadomia) experienced uplift and erosion (Linnemann et al., 2007). This is consistent with the scarcity of Upper Cambrian sediments in the Saxo-Thuringian zone and the high maturity of its Lower Ordovician deposits following intense chemical weathering during the Late Cambrian.

Lower Ordovician deposits in the Cadomian part of Central and Western Europe are characterized by widespread sandstones exemplified by the ≤700 m thick Armorican quartzite of the Armorican and Iberian massifs (e.g., Noblet and Lefort, 1990). Equivalent quartzites in the Saxo-Thuringian zone (Frauenbach and Phycodes groups) are ca. 3000 m thick. In all areas, these deposits overstep Early to Middle Cambrian strata or lie directly on Cadomian basement (Linnemann and Romer, 2002). It is therefore likely that rifting culminated in the Late Cambrian with the formation of rift shoulders and tilted fault blocks, such that Lower to Middle Cambrian strata were preserved in some areas, whereas in others the underlying Cadomian basement was exposed (Fig. 7E). Blanketing of this palaeo-landscape by vast thicknesses of post-rift Lower Ordovician siliciclastics points to significant thermal subsidence and the formation of large-scale detachment fault systems (Linnemann et al., 2007). The development of this Early Ordovician sedimentary regime coincides with the final rift-related magmatism at ca. 485 Ma and is taken to record the opening of the Rheic Ocean and the separation of Avalonia from the Gondwanan margin.

From the mid-Late Ordovician to mid-Devonian, the Saxo-Thuringian zone is characterized by relative tectonic and magmatic quiescence and shelf sedimentation, consistent with its position on the southern passive margin of the Rheic Ocean. In places sedimentation continued into the Early Carboniferous, but by the Late Devonian, closure of the Rheic Ocean had led to the subduction of Gondwanan continental crust and the incorporation of the Gondwanan shelf into the developing Variscan orogen.

3.2. Closure and collision

In the European record, the Rheic Ocean continued to expand until Avalonia collided with Baltica at ca. 450 Ma with the closure of the Tornquist Sea along the Teisseyre–Tornquist Line (Fig. 5). The collision appears to have been a soft one, but produced Andean-type magmatism in Avalonia, a gigantic ash fall in Baltica (at ca. 455 Ma), and low-grade metamorphism in northeast Germany (North Sea basement) (Torsvik and Rehnström, 2002; Winchester et al., 2002). The collision is also responsible for a number of gaps in sedimentation during mid-Late Ordovician time in the Brabant and northeastern Rhenish massifs (Herbosch and Verniers, 2002). Additional gaps in the Siluran sedimentary record of these massifs record the closure of Iapetus and the collision of Baltica and Avalonia with Laurentia to form Laurussia. There is a broad agreement that closure of Iapetus was complete by the latest Silurian (e.g., Pickering, 2008), following which the Brabant and Rhenish massifs become Central European representatives of the Old Red Continent and are blanketed by Lower Devonian redbeds.

In the Mid-German Crystalline zone, this continent–continent collision is recorded in magmatic episodes of Early Llandovery (ca. 444–434 Ma) and Wenlock (ca. 426–423 Ma) age (e.g., Anthes and Reischmann, 2001). A Late Silurian (Pridoli) to Early Devonian (ca. 418–400 Ma) magmatic event may record the onset of Rheic Ocean closure by way of north-directed subduction beneath Laurussia following the closure of Iapetus (e.g., Kroner et al., 2007).

Final closure of the Rheic Ocean in Europe is marked by the Variscan orogeny, which, in the Saxo-Thuringian zone and other parts of Central and Western Europe (e.g., Kroner et al., 2007) juxtaposed widespread Late Devonian to Early Carboniferous high-pressure metamorphic units (allochthonous domains) against low-grade Cadomian and Palaeozoic successions (autochthonous domains). Following destruction of the Rheic Ocean, oblique, north-directed diachronous subduction of thinned Gondwanan continental crust started in the Early Devonian and persisted until the Early Carboniferous, with early exhumation of Gondwanan high-pressure rocks at ca. 370 Ma. These rocks were locally subducted to depths at which metamorphic diamond is stable (>150 km; e.g., Dobrzhinetskaya et al., 2007). Southeast-directed exhumation was initially accommodated in the subduction channel, after which regional dextral transpression accompanied rapid exhumation of the rocks of the allochthonous domain, and the filling and folding of flysch basins

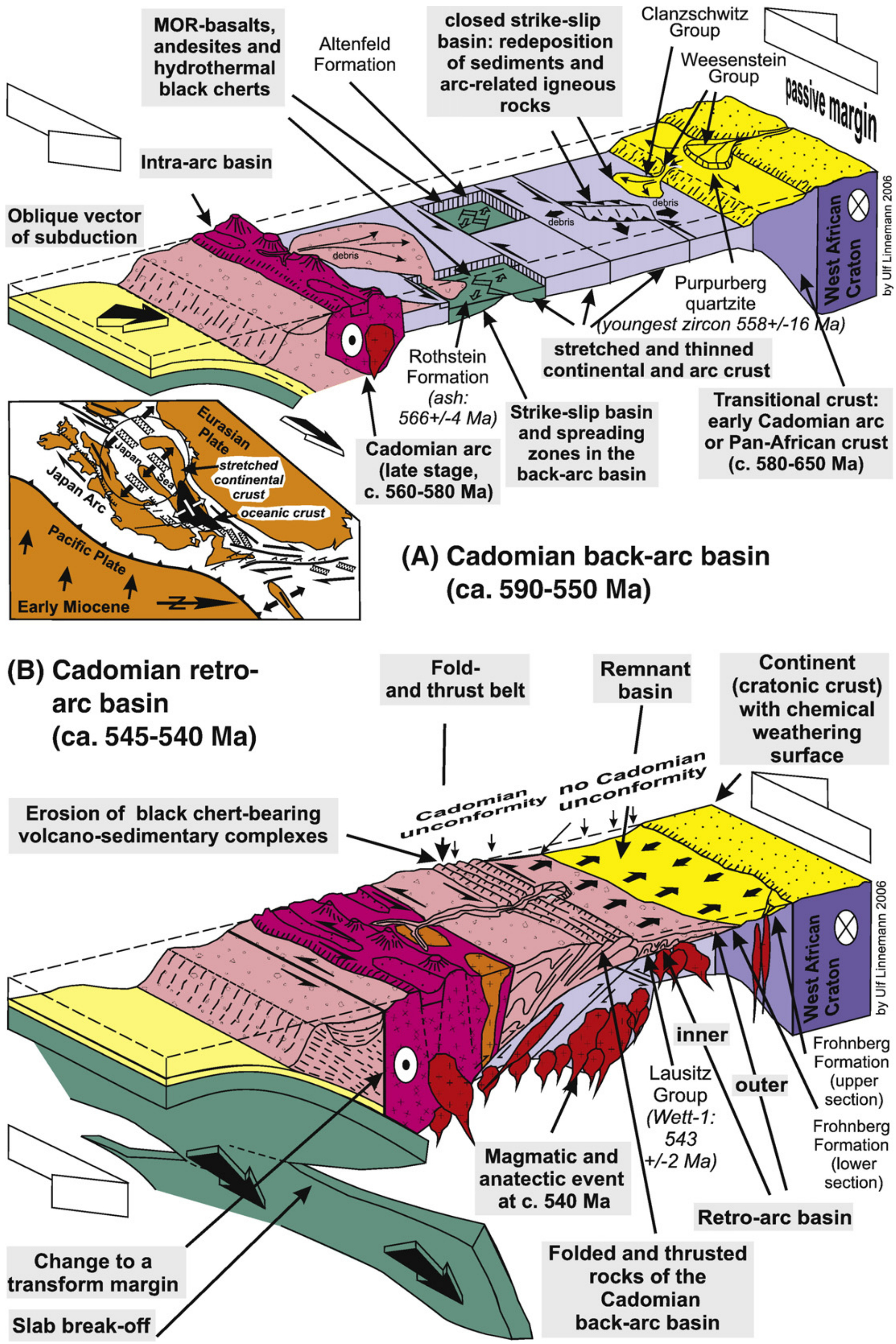

Fig. 7. Model for the plate-tectonic transition from Cadomian arc to Rheic Ocean based on data derived from the Saxo-Thuringian zone of the Bohemian Massif (from Linnemann et al., 2007): (A) Cadomian back-arc basin development at ca. 590–550 Ma, (B) Cadomian retro-arc basin development at 545–540 Ma, (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 (after Jolivet et al., 1992). Insets in (C)–(E) show analogous settings (circled) illustrated by the Miocene–Pliocene evolution of the Pacific margin of North America (from Nance et al., 2002, modified after Atwater, 1970; Dickinson, 1981).

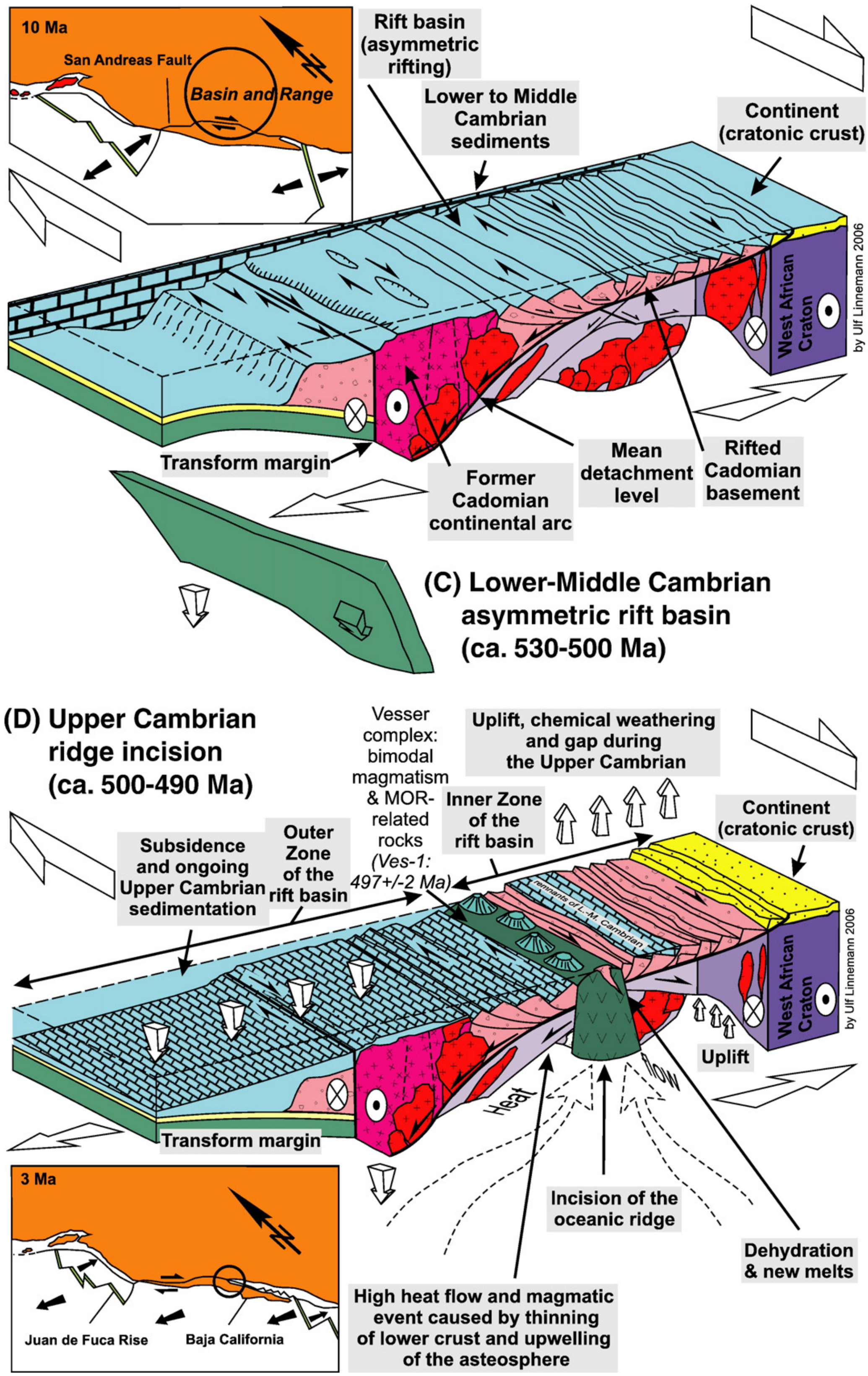

Fig. 7 (*continued*).

(at ca. 340–330 Ma). Related widespread Variscan plutonism occurred in the Bohemian Massif at ca. 335–320 Ma. Consistent with this evolution, the Mid-German Crystalline zone, which defines the Rheic suture, records a history of oblique subduction, collision, exhumation and strike-slip tectonics during the Late Devonian–Early Carboniferous (e.g., Kroner et al., 2007).

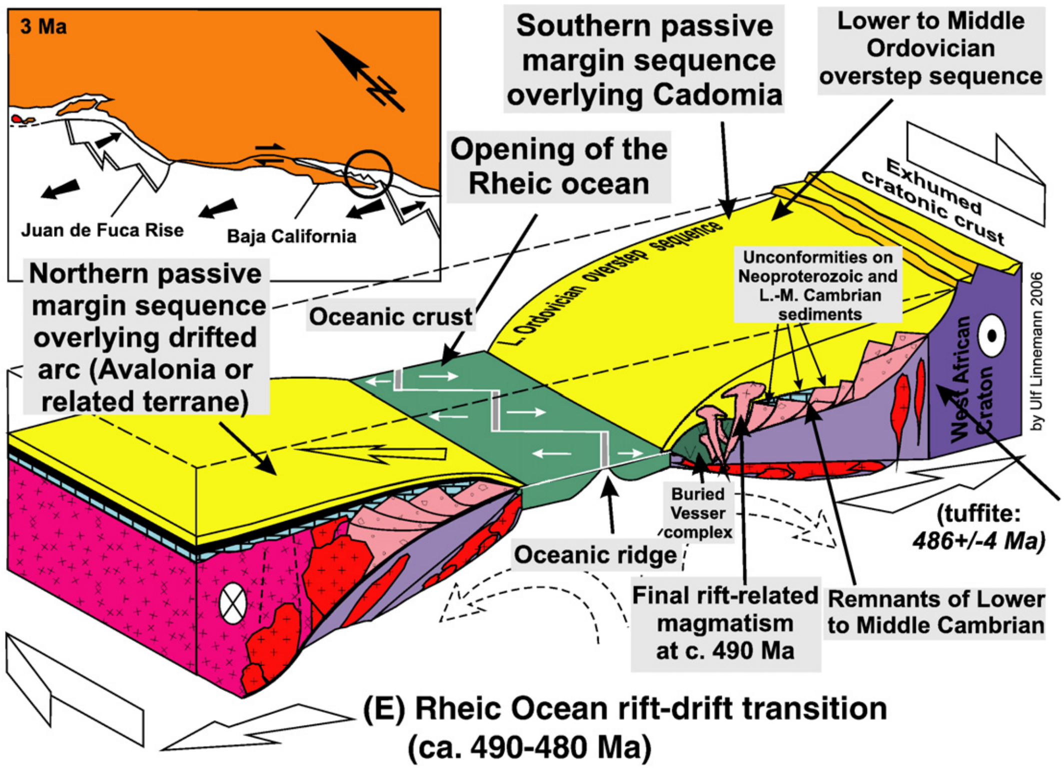

Fig. 7 (*continued*).

4. The Rheic Ocean in Southern Britain

A record of the northern margin of the Rheic Ocean, north of the Rheic suture, is preserved in the southern part of the British Isles, which formed the trailing edge of the Avalonian microplate as it separated from Gondwana (Fig. 5). Although indirect evidence for this separation is present in the Lower Ordovician strata of Wales and the Welsh Borderlands (Thorogood, 1990; Prigmore et al., 1997), no record of the rifting and opening stages of the Rheic Ocean cycle is preserved south of the Variscan Front where the bedrock geology is dominated by Upper Palaeozoic volcano-sedimentary successions that are correlated with the Rhenohercynian and South Portuguese zones of mainland Europe (Holder and Leveridge, 1986; Franke, 2000). Extensional rifting in the Early Devonian, interpreted as being driven by slab roll back (see below), corresponds to the initial stages of closure of the Rheic Ocean, rather than being related to its Ordovician opening. In the Early Devonian, southwest England was probably located several hundred kilometres further to the southeast (Woodcock et al., 2007). Here, it escaped the Acadian (mid-Devonian) deformation seen in the rest of England, Wales and southern Ireland, which was caused either by flat-slab subduction or by the collision of a Gondwana-derived continental fragment (see Fig. 4 in Woodcock et al., 2007). The subsequent collision of Iberia/Cadomia with Avalonia during the Late Devonian and Carboniferous resulted in the obduction of the ophiolitic Lizard Complex, dextral translation of southwest England along the Bristol Channel–Bray Fault to its present location, and widespread Variscan deformation in southern England, South Wales and southern Ireland.

4.1. Rifting in southwest England: result of slab roll back along the Rheic Ocean's northern margin?

Although Avalonia is thought to have rifted from Gondwana in the Early Ordovician, the sedimentary record exposed in southwest England does not commence until the Devonian. Devonian–Carboniferous successions are preserved within six, east–west trending sedimentary basins (Leveridge and Hartley, 2006 and references therein, Fig. 8). The oldest sequences comprise Early Devonian fluvial to shallow-marine sediments and bimodal, rift-related igneous rocks (Merriman et al., 2000). A major period of extensional rifting was initiated in the Middle Devonian, probably corresponding to the initiation of subduction along the northern margin of the Rheic Ocean. A long-lived lineament, the Start–Perranporth Line (Holdsworth, 1989), developed as a basin-bounding fault that separated quite different sedimentary successions during the Middle to Late Devonian. To the north, Devonian sediments are mainly of marine shelf and fluvial facies, in contrast to the deep-water marine facies to the south (Bluck et al., 1988, 1992, and references therein). The lineament also broadly corresponds to a change in the chemistry of the Devonian basaltic lavas that are interlayered with some of the sedimentary sequences. To the north, basaltic pillow lavas are alkaline, whereas to the south the volcanic rocks are tholeiitic (Floyd, 1982).

The Devonian basins are thought to have been located to the south of a zone of shallow, occasionally emergent, Precambrian basement. To the south lay the Exmoor or North Devon basin, containing marine and marginal marine deposits that interfinger with tongues of northerly derived fluvial sediments. These facies probably passed southwards into marine shelf deposits, although the transition is now obscured by the overlying Culm basin of Carboniferous age (Fig. 8). When Devonian rocks re-emerge along the southern edge of the Culm basin, they contain slumps, debris flows and basaltic volcanics marking the northern fault-controlled margin of the deeper marine Tavy and South Devon basins. These basins were separated and bordered to the south by the Landulph and Plymouth highs, fringed by shallow-marine carbonate reefs. To the south of the Plymouth high is the Looe basin, hosting the oldest exposed remnant of the rift basins (Fig. 8). The Looe basin is overthrust at the Start–Perranporth Line by the Middle to Upper Devonian Gramscatho Group, comprising mainly deep-water turbiditic sandstones and mudstones.

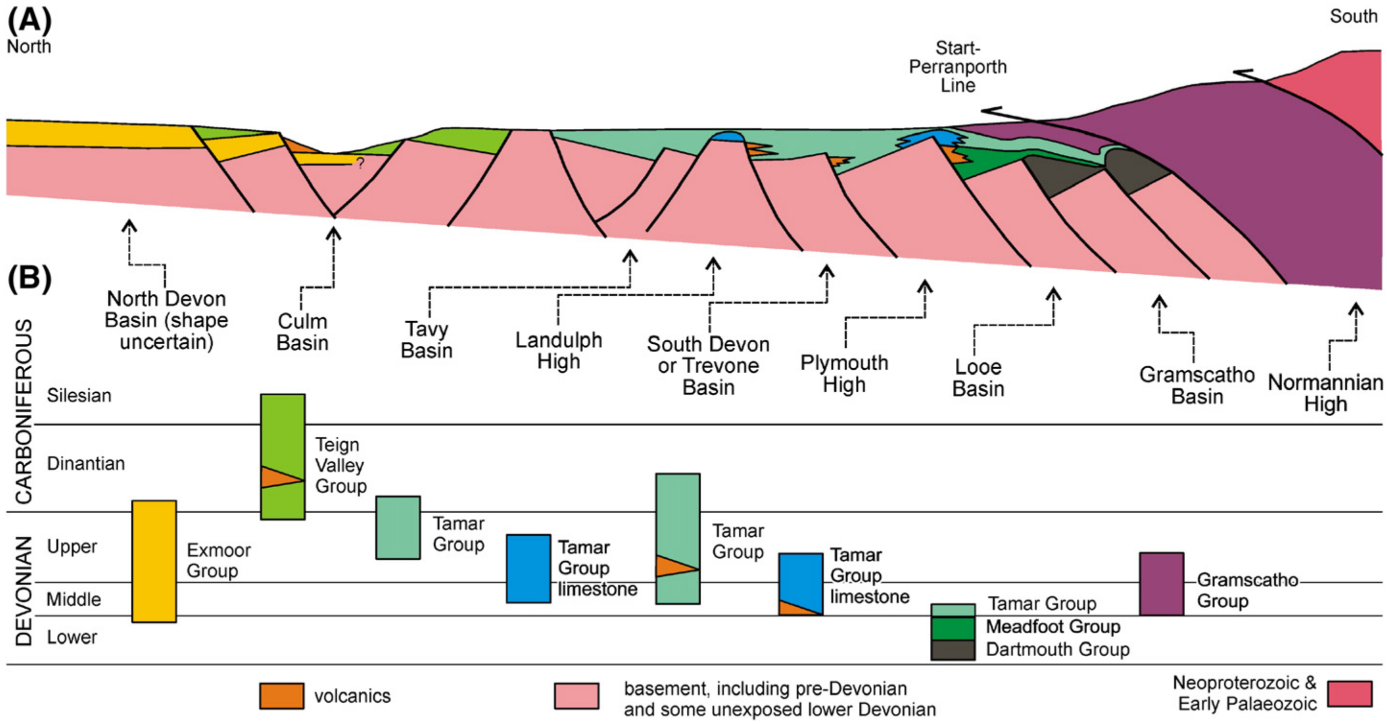

Fig. 8. (A) Schematic N–S cross section and (B) stratigraphic key of SW England during earliest Carboniferous (Tournaisian) time, as the Gramscatho Basin begins to thrust over the earlier rifted margin basins to the north. Section modified from Shail and Leveridge (2009).

The trailing edge of the extended Avalonian margin is likely represented by the allochthonous rocks of the Lizard Complex. This complex structurally overlies continental basement rocks of the Man O'War Gneiss, which has yielded a U–Pb zircon igneous protolith age of 499 + 8/−3 Ma (Sandeman et al., 1997). The Lizard Complex is dominated by mantle peridotites thought to represent sub-continental lithosphere that was exhumed during Devonian rifting (Cook et al., 2000, 2002). The peridotites overlie and are intruded by gabbros, dolerites and basalts that have MORB-type chemistry (e.g., Gibbons and Thompson, 1991; Floyd et al., 1993; Roberts et al., 1993). In places these form sheeted dykes and pillow lavas consistent with emplacement during the early stages of sea-floor spreading (Roberts et al., 1993). Many of these rock types were intruded into the peridotite at the same time as it was being exhumed by displacement along km-scale, steep shear zones (Cook et al., 2000, 2002). The main constraint on the timing of exhumation and associated mafic magmatism is provided by a U–Pb zircon age of 397 ± 2 Ma (earliest Middle Devonian) obtained from a plagiogranite within the Traboe Cumulate Complex (Clark et al., 1998). The presence of inherited zircons of Cambrian–Ordovician age within this cumulate complex and rare metasedimentary inclusions (Nutman et al., 2001; Clark et al., 2003) indicate that the ophiolite formed in proximity to older continental basement, although whether in a back-arc or supra-subduction zone setting is uncertain.

4.2. Closure and collision: Acadian and Variscan orogenic events

The history of Devonian extension that characterized southwest England while it occupied its former mainland Europe location contrasts markedly with events of the same age along strike in the former Early Palaeozoic basin areas of northwest England, Wales and southern Ireland. These areas underwent widespread Acadian (400–390 Ma, mid-Devonian) deformation that has traditionally been linked to the final closure of the Iapetus Ocean. This deformation resulted in regional upright folding and cleavage development at anchizone to epizone metamorphic conditions (Woodcock and Soper, 2006 and references therein). However, it is now known that the Acadian deformation occurred at least 20 my after Iapetus closure, and is more plausibly related to early closure of the Rheic Ocean (Woodcock et al., 2007). There is indirect evidence to support the existence of a now-missing Devonian arc in the vicinity of the Pretannia landmass, south of the Bristol Channel Fault Zone, that was moved laterally westward during the main Variscan collision. The preferred model for Acadian deformation involves northward-directed, flat-slab subduction along this sector of the Rheic Ocean margin. This may have involved the attempted subduction of the Rheic ridge, an oceanic plateau or a microcontinent, but probably not the involvement of a mantle plume or a major continent. Evidence for Acadian-aged deformation in the northwest Iberian allochthons is consistent with these representing a fragment of Avalonia that was accreted during the later Variscan collision (Woodcock et al., 2007).

In southwest England, the onset of the collision of Cadomia during the Late Devonian is marked by the appearance within the Gramscatho basin of southerly sourced turbidites and melanges derived from the erosion of advancing Variscan thrust nappes mainly composed of acidic continental arc materials together with MORB-type volcanic rocks (Floyd and Leveridge, 1987). The source of the acidic material is thought to be the “Normannian High”, a largely submerged and, as yet, undated area of orthogneisses within the English Channel area (Holder and Leveridge, 1986, Fig. 8). Whether this is a fragment of a Devonian magmatic arc or Cadomian basement is unknown. Northerly directed obduction of the Lizard Complex onto the Avalonian margin commenced during the Late Devonian. A U–Pb zircon age of 376 ± 2 Ma obtained from the syn-kinematic Kennack Gneiss (Sandeman et al., 2000) constrains the timing of early obduction, while $^{40}Ar/^{39}Ar$ ages of 370–350 Ma reflect continued Late Devonian to earliest Carboniferous metamorphism and recrystallization events as obduction progressed (Sandeman et al., 1995). The complex was finally obducted as a cold sheet at the top of a series of northward-directed thrust nappes (Holder and Leveridge, 1986). Emplacement into its present structural position must have occurred at the end of the Devonian or later since the complex overlies sedimentary rocks from which Late Fammenian palynomorphs have been recovered (Wilkinson and Knight, 1989).

Variscan deformation propagated northwards through the Late Devonian and Carboniferous to form a major fold and thrust belt in southwest England, South Wales and southern Ireland (Fig. 9, e.g.. Sanderson, 1984; Coward and McClay, 1983; Hobson and Sanderson, 1983; Leveridge et al., 1984; Whalley and Lloyd, 1986; Lloyd and Whalley, 1986; Seago and Chapman, 1988). Regional metamorphism ranged from deep diagenetic to the greenschist facies, and locally reached amphibolite facies in the Lizard Complex (Warr et al., 1991; Robinson et al., 1994). As deformation propagated northwards, rift basins were successively inverted and the style of deformation was probably controlled, in part, by the position of pre-existing faults and the geometry of the basin-fill (Warr, 1993, 2000). The Start–Perranporth Line was activated as a major ductile structure during the development of the fold and thrust belt. A major 'D_2' backfold may indicate buttressing along this basement fault zone and structures compatible with dextral transpression are developed on its steep limb (Holdsworth, 1989). In another example of basement fault control on the location of younger orogenic structures, the faulted northern margin of the South Devon or Trevone basin appears to have acted as a buttress to the northward-migrating compression. This is thought to have initiated a zone of back-thrusting that propagated southward into the central part of the basin, and interacted with forethrusts to form a zone of structural confrontation that can be found in the Padstow and Plymouth areas (Selwood and Thomas, 1988, Fig. 9).

The recognition of shallow seismic reflectors has been used to propose thin-skinned models for Variscan deformation, with a single regional décollement horizon at ~10–12 km depth (Brooks et al., 1984). Alternatively, displacements at depth may have occurred along a series of shallow and deep detachment horizons that were linked to steeper faults in the basement (Warr, 2000; Fig. 9). The latter view is compatible with the pre-collision rift geometry, the presence of strike-slip structures, and the steepness of some structures.

As Carboniferous deformation spread northwards, the thickening orogenic wedge loaded the lithosphere and flexed the foreland downward. The 3–4 km thick clastic successions preserved in each of the Culm, South Wales Coalfield and Clare basins thus provide an indirect record of the developing orogenic belt (Hartley, 1993a,b). The onset of foreland basin sedimentation occurred progressively later towards the north with rapid subsidence commencing in the southern part of the Culm Basin by the Early Namurian (Late Mississippian), in south Wales by the Early Westphalian (Early Pennsylvanian), and perhaps in the Staffordshire Coalfield by the end Westphalian (Late Pennsylvanian).

The Cornubian Batholith (Fig. 9) comprises peraluminous S-type granites that were emplaced over a 20 my interval spanning the Late Carboniferous to Early Permian (Chen et al., 1993; Chesley et al., 1993). Anatexis is estimated to have occurred at about 800 °C and 7–8 kbar by partial melting of pelitic rocks in the lower or intermediate crust (Charoy, 1986), although Nd and Sm isotope systematics also indicates a mantle contribution (Darbyshire and Shepherd, 1994). The latter authors favour a model of magma generation as a consequence of crustal underplating during collision. Emplacement of the batholith was accompanied by late-orogenic collapse and the extensional reactivation of older thrusts, as well as the development of high-angle normal faults (Shail and Wilkinson, 1994). Horizontal to south-dipping seismic reflectors at crustal depths of 10–15 km suggest that the batholith formed as a shallow, flat-bottomed body that was emplaced along a regional décollement surface towards the base of the Variscan thrust wedge (Brooks et al., 1984).

5. The Rheic Ocean in Northwestern Iberia

Although heterogeneously deformed by Late Palaeozoic Variscan orogenesis, one of the most complete sections of the Rheic passive margin of northern Gondwanan is exposed in northwestern Iberia (Fig. 10) where Palaeozoic rocks lie within the tightly curved core of the Iberian–Armorican Arc (Fig. 5). If this arc is restored to a pre-Variscan geometry (Weil et al., 2001), the Iberian continental platform of Gondwana is shown to be extremely extensive with a stratigraphic record classically represented by a thick, mostly siliciclastic Ordovician sequence that is overlain, sometimes unconformably, by widespread Silurian black shales (Gutiérrez-Marco et al., 1998). These relationships, together with sedimentological studies, are consistent with palaeogeographic reconstructions that place northwest Iberia adjacent to West Africa along the southern flank of the Rheic Ocean throughout the Palaeozoic (e.g. Martínez-Catalán et al., 2007; Robardet, 2002, 2003).

The Palaeozoic rocks of the Iberian Massif are traditionally divided into zones based on differences in their Lower Palaeozoic sedimentary successions, which are interpreted to reflect their relative proximity to the Gondwanan margin (Fig. 10). From the coastline seaward towards the Gondwanan outer platform, five such zones are identified. The Cantabrian zone preserves a coastal environment, whereas the West Asturian Leonese, Central Iberian and Galicia Tras-os-Montes (Schistose Domain) zones, together with the Ossa-Morena zone of southern Iberia, preserve the more outboard tectonostratigraphy (Julivert et al., 1972; Quesada, 1990a; Ribeiro et al., 1990; Pérez-Estaún et al., 1990; Quesada et al., 1991; Martínez-Catalán et al., 1997, 1999; Marcos and Farias, 1999; Gutiérrez-Marco et al., 1999; Aramburu et al., 2002; Robardet, 2002, 2003; Robardet and Gutiérrez-Marco, 2004). Boundaries between these zones are major Variscan thrusts and reverse faults that were, in some cases, reactivated by extension in the aftermath of the Variscan orogeny (Martínez-Catalán et al., 1997, 2003). The alleged basement of the northern Gondwana margin is preserved in the so-called Basal Units, the lowermost units within the allochthonous complexes of the Galicia Tras-os-Montes zone.

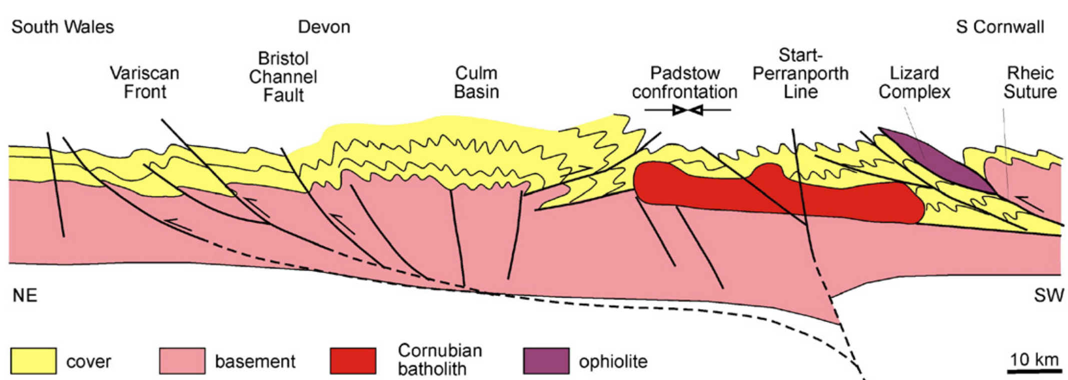

Fig. 9. Cross section from South Wales to south Cornwall, showing the main structures from the Variscan deformation. Modified from Warr (2000).

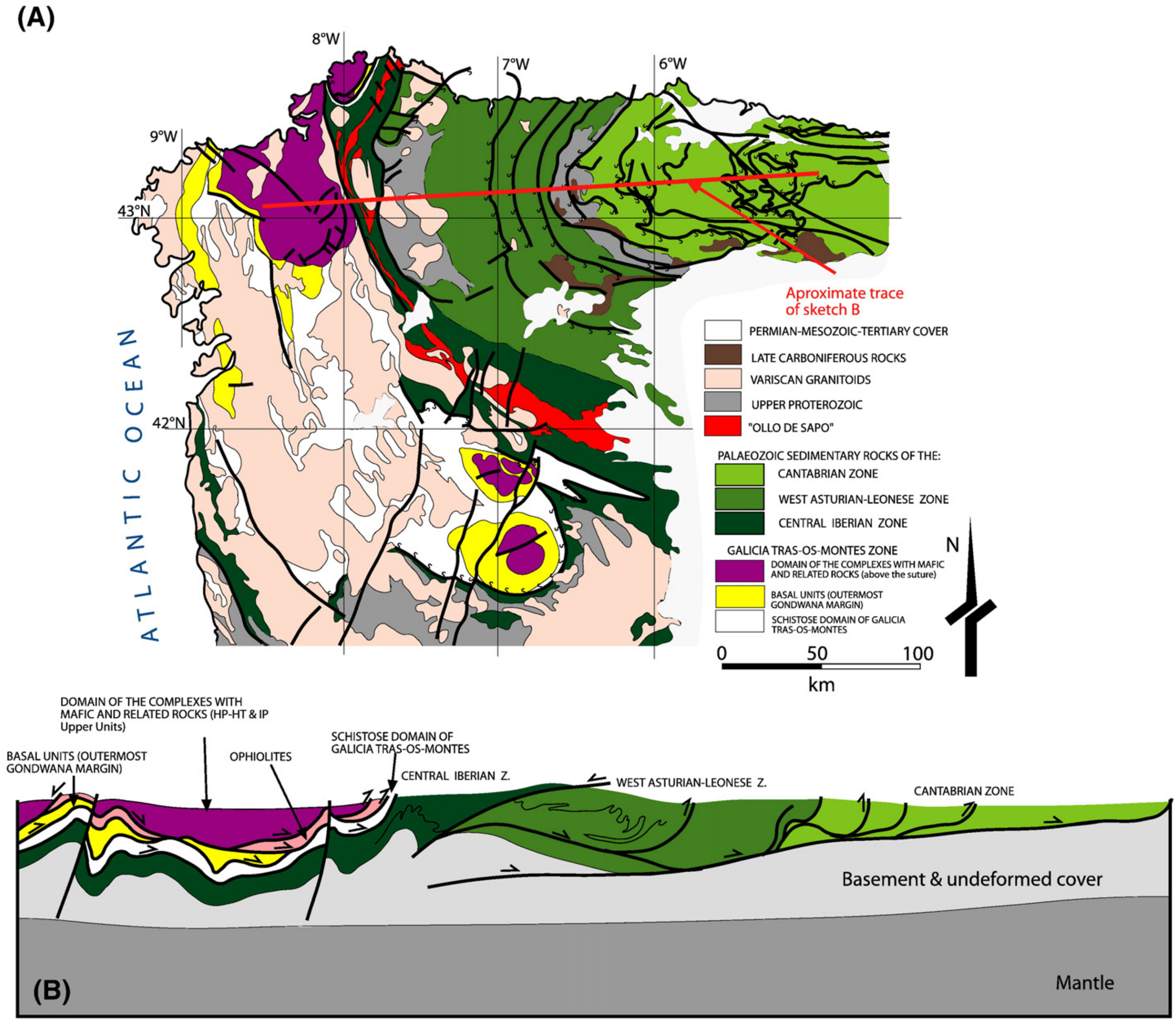

Fig. 10. Schematic map and cross section of major structural and stratigraphic units in northwest Iberia (after Martínez-Catalán et al., 1997, 2007). See Fig. 5 for location.

5.1. Rifting and opening

In northwestern Iberia, opening of the Rheic Ocean is recorded mainly by intense rift-related igneous activity (e.g., Murphy et al., 2008). Widespread Early Ordovician (Tremadoc–Arenigian) volcanism is represented in all of the tectonostratigraphic zones (Valverde-Vaquero et al., 2005; Díez Montes 2006; Gutiérrez-Alonso et al., 2007; Fernández et al., 2008), and the coeval accumulation of ~4500 m of strata in sub-basins or troughs parallel to the northern Gondwanan margin has been interpreted to reflect a sharp increase in subsidence due to tectonic extension during the rift–drift transition stage of Rheic Ocean development (Pérez-Estaún et al., 1990; Martínez-Catalán et al., 1992, 2009; Aramburu et al., 2002; Marcos et al., 2004). This extensional event is also coeval with the genesis of widespread Early Ordovician granitoid and felsic volcanic rocks that are interpreted to be intra-crustal melts generated in response to the steep geothermal gradients associated with the rifting event (Ribeiro and Floor, 1987; Gallastegui et al., 1987; Pin et al., 1992; Valverde-Vaquero et al., 2005; Díez Montes, 2006). Although volcanic activity continued until the Late Ordovician, post-Arenig activity is relatively minor and developed only locally (Heinz et al., 1985, Corretgé and Suárez, 1990, Gallastegui et al., 1992).

Volcanism in the Cantabrian zone (Fig. 11) is particularly voluminous and mostly of Early Ordovician age (Loeschke and Zeidler, 1982; Heinz et al., 1985; Gallastegui et al., 1992; Barrero and Corretgé, 2002). Smaller volumes of volcanic rocks are also widespread in the West Asturian Leonese zone where their emplacement is thought to have accompanied increased basin subsidence. However, the most volumetrically significant Early Ordovician volcanic event in northwestern Iberia is preserved in the northern portion of the Central Iberian zone where voluminous felsic volcanic rocks, including the "Ollo de Sapo" belt (e.g., Díez Montes et al., 2010-this issue), crop out along a continuous northwest- to north-trending belt (Fig. 11). Detailed studies of the age (ca. 495–480 Ma), origin and geochemistry of these volcanic rocks can be found in Valverde-Vaquero and Dunning (2000), Castro et al. (1999, 2003), Díez Montes (2006) and Montero et al. (2007). The felsic intrusive bodies in the northern part of the zone have Late Cambrian–Early Ordovician U–Pb (zircon) ages ranging from 496 ± 3 (Zeck et al., 2007) or 483 ± 3 Ma (Bea et al., 2006) for the Miranda de Douro body to 465 ± 10 Ma for

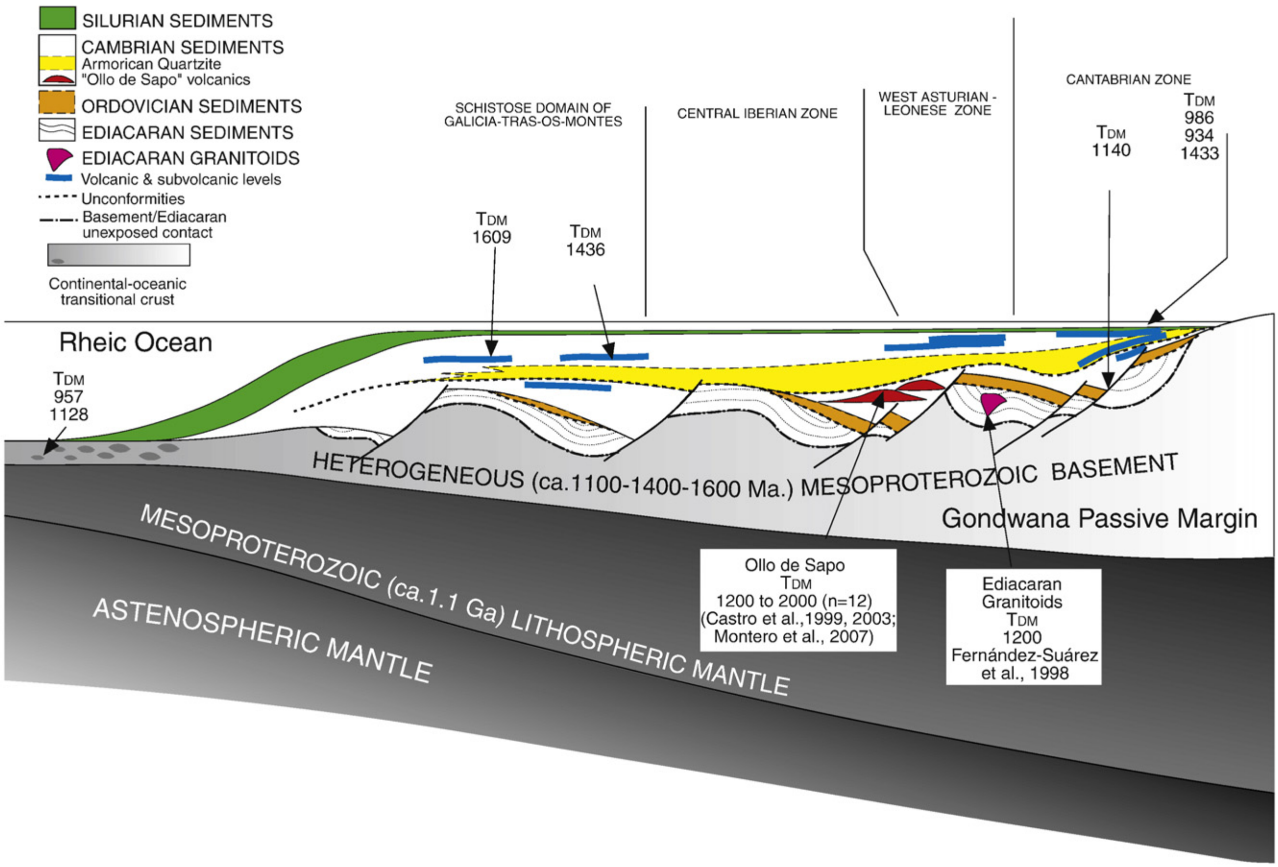

Fig. 11. Schematic reconstruction of Gondwanan passive continental margin in northwest Iberia showing location of units from which depleted mantle model ages (T_{DM}) have been determined (after Murphy et al., 2008).

the Covelo and San Sebastián bodies (Lancelot et al., 1985). The southern portion of the Central Iberian zone additionally contains tholeiitic mafic sills that have yielded a Sm/Nd isochron age of 436 ± 17 Ma (López-Moro et al., 2007). The Galicia Tras-os-Montes zone (Farias et al., 1987; Martínez-Catalán et al., 1996; Marcos et al., 2002) rests tectonically on the Central Iberian zone and consists of a thick siliciclastic sequence with interbedded volcanic rocks, some of which have yielded Early Ordovician (475 ± 2 Ma; Valverde-Vaquero et al., 2005) ages. The succession has been interpreted to represent the most outboard part of the Gondwanan passive margin sedimentary wedge.

Resting tectonically on the most external parts of this sedimentary wedge is a set of allochthonous complexes consisting (from bottom to top) of Gondwana basement (Basal Units, Fig. 10) structurally overlain by two ophiolitic units, respectively of Early Ordovician and Devonian age, that are interpreted to be remnants of the Rheic Ocean or subsidiary ocean basins that closed during the Variscan orogeny (Martínez-Catalán et al., 1997, 2009; Arenas et al., 2007b, c). The Upper Units, which structurally overlie the ophiolites, have been interpreted to be part of the northern (Laurussian) margin of the Rheic Ocean (Martínez-Catalán et al., 1997, 2009; Arenas et al., 2007b, c; Fuenlabrada et al., 2010-this issue). The Basal Units beneath the ophiolites are of continental affinity and are thought to represent the most external part of the Gondwanan margin (Martínez-Catalán et al., 1996). The igneous protoliths of the Basal Units are of Early Ordovician age (ca. 480 Ma; Santos Zalduegui et al., 1995 and references therein).

5.2. Closure and collision

Closure of the Rheic Ocean is recorded in northwest Iberia by the deformation associated with Laurussia–Gondwana collision and in the oceanic remnants preserved as ophiolites in the suture between these continents (Fig. 10). The earliest evidence of oceanic closure is recorded by northward subduction of the Rheic Ocean along the Laurussian margin, the onset of which occurred before ca. 400 Ma based on the age of the earliest metamorphism (Dallmeyer and Gil Ibarguchi, 1990; Mendía Aranguren, 2000; Fernández-Suárez et al., 2007; Gómez Barreiro et al., 2006; Martínez-Catalán et al., 2009). Subduction of the Rheic mid-ocean ridge by 395 Ma (Woodcock et al., 2007; Gutiérrez-Alonso et al., 2008a) is thought to have caused an increase in the convergence rate and the coupling of both oceanic margins.

The onset of continental collision began at ca. 365 Ma (Dallmeyer et al., 1997) with initial subduction of the Gondwana margin (Basal Units) below Laurussia. Deformation of the Gondwanan passive margin succession caused by the subsequent overriding of Gondwana by Laurussia migrated eastward in both space and time.

Convergence initially produced recumbent folds (D_1) that verge and migrate from the suture towards the present-day core of the Iberian–Armorican Arc. Continued shortening is then thought to have led to the extensional collapse (D_2) of the thickened orogenic hinterland (Escuder et al., 1994; Arenas and Martínez-Catalán, 2003) at ca. 320 Ma (Martínez-Catalán et al., 2009), an event that was coeval with the development of a non-metamorphic foreland fold-thrust belt within the Cantabrian zone (Pérez-Estaún et al., 1994). Final deformation associated with the closure of the Rheic Ocean (D_3) produced large-wavelength upright folds and strike-slip ductile shear zones (Martínez-Catalán et al., 2009). Immediately following ocean closure, an abrupt change in the stress-strain field associated with Pangaea amalgamation caused a dramatic 180° rotation of the entire Variscan orogen to produce the Iberian–Armorican Arc, the development of which was accompanied by a major thermal event that has been interpreted to record Late Carboniferous–Early Permian lithospheric delamination (Fernández-Suárez et al., 2000; Weil et al., 2001, Gutiérrez-Alonso et al., 2004, 2008b).

6. The Rheic Ocean in Southern Iberia

Like its counterpart to the north, southern Iberia preserves a remarkably complete record of the evolution of the Rheic Ocean starting with its initial rifting stages in the Cambrian, and continuing through the drifting stage to culminate in its final closure during the Variscan orogeny in the Late Palaeozoic. In addition to the suture, delineated by the Pulo do Lobo accretionary prism and the Beja-Acebuches ophiolite (Munhá et al., 1986; Quesada et al., 1994; Braid et al., 2010-this issue), the main units in southern Iberia include (from north to south; Fig. 5): the Central Iberian and Ossa-Morena zones of Gondwanan affinity and, south of the suture, the South Portuguese zone of Laurussian (?Avalonian) affinity. The Ossa-Morena zone (Fig. 12) exposes an exceptional record of the rifting event that culminated in opening the Rheic Ocean in the Early Ordovician (Sánchez-García et al., 2003, 2008, 2010-this issue), and preserves an outer shelf assemblage that, together with the inner shelf succession of the Central Iberian zone, document the complete Ordovician through Devonian history of the northern passive margin of Gondwana as the Rheic Ocean opened. The southern Iberian segment of the Variscan orogen is additionally unique in regard to its highly transpressional nature, which is largely the consequence of sinistral escape tectonics during oblique collision between Laurussia and Gondwana (Ribeiro et al., 1990; Quesada, 1991, 1998; Pereira and Quesada, 2006).

6.1. Rifting and opening

As in the Bohemian Massif, the onset of rifting in southern Iberia closely followed, and was intimately linked to, the abrupt termination of subduction processes taking place along the northern margin of Gondwana during the Ediacaran (Quesada, 1990a, b, 1997, 2006), and a similar mechanism of oblique ridge–trench collision (following back-arc basin closure and the accretion of a Neoproterozoic arc), leading to the opening of a slab window and eventual rifting (Fig. 13), has been proposed to account for the evolution of this margin at this time (Sánchez-García et al., 2008).

The record of rifting is best preserved in the Ossa-Morena zone where a short (<5 Ma) period of uplift and erosion of the subduction-related arc sequences, the youngest of which are dated at ca. 535 Ma, was rapidly succeeded by magmatic activity assigned to an Early Igneous Event by Sánchez-García et al. (2003, 2008). The initial uplift may reflect thermal expansion in response to slab window development, while the subsequent magmatism was accompanied by partial melting, migmatite formation and core complex development at mid- to upper crustal levels. The age of this Early Igneous Event is constrained by U–Pb zircon dates of ca. 530 ± 3 Ma from both volcanic and plutonic rocks (Ochsner, 1993; Romeo et al., 2006).

The Early Igneous Event was followed by a general marine transgression, probably related to thermal contraction, which culminated in the development of a shallow-marine carbonate platform during the remaining part of the Early Cambrian, essentially in the absence of igneous activity (Liñán and Quesada, 1990). Collapse of this platform and the formation of horst and graben structures occurred at the end of the Early Cambrian, most likely in response to a period of

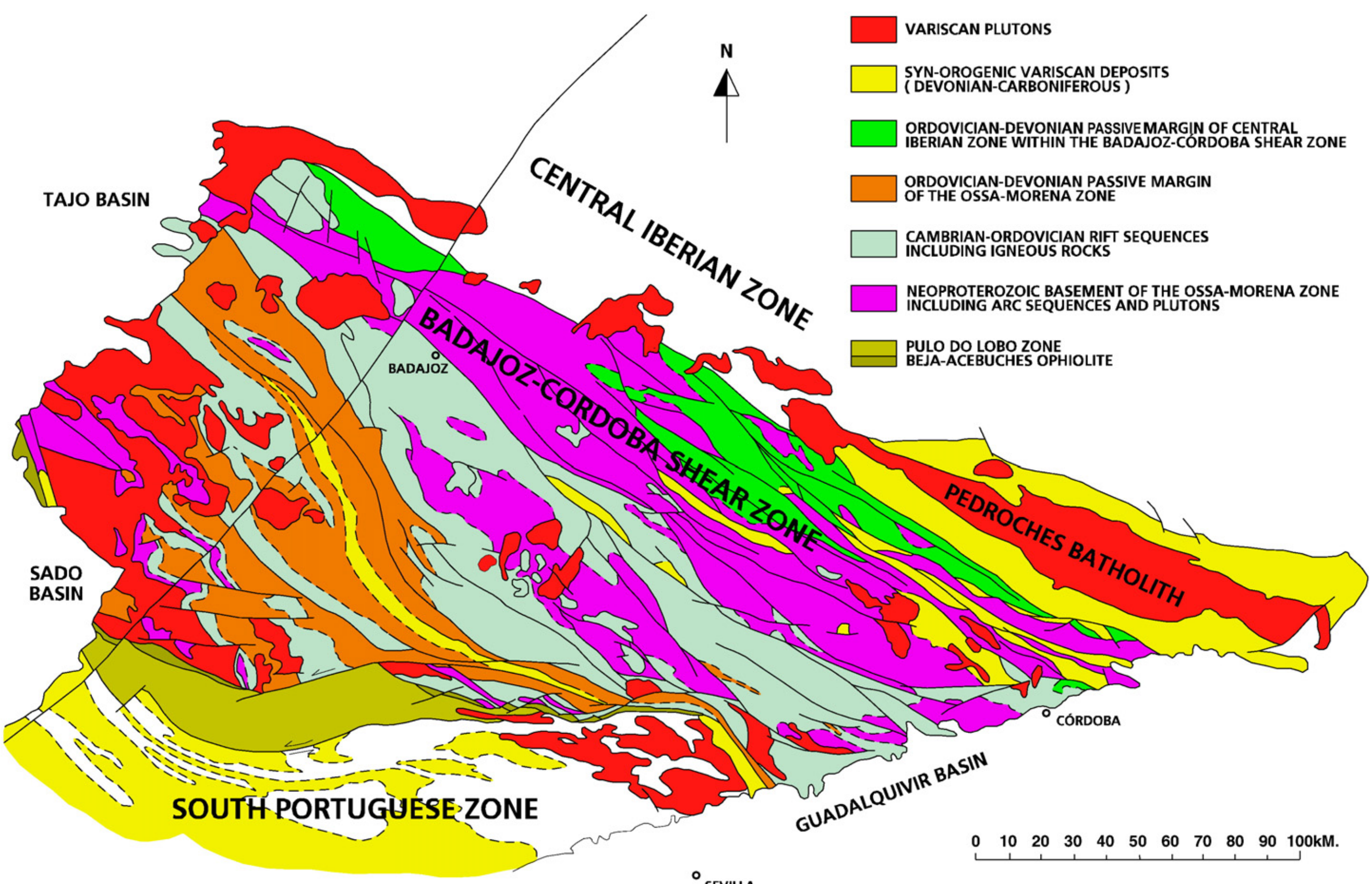

Fig. 12. Schematic map showing major structural and stratigraphic units in the Ossa-Morena zone (Quesada, 2006) See Fig. 5 for location.

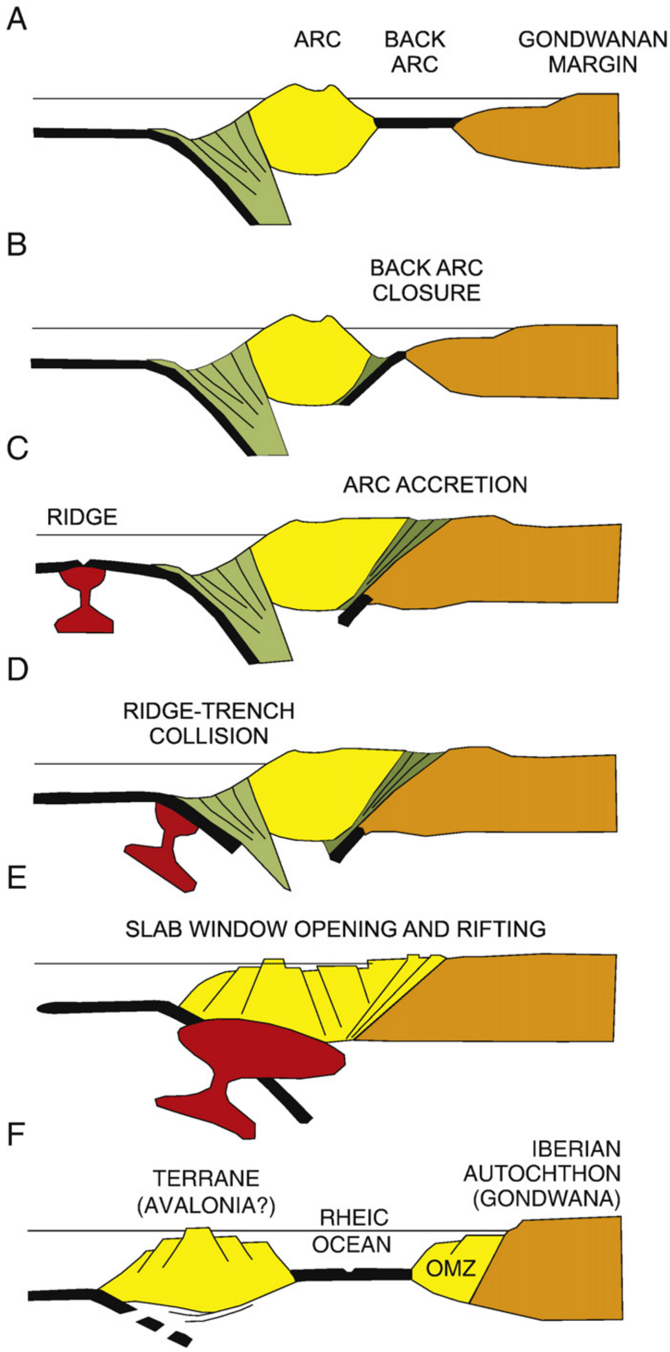

Fig. 13. Schematic plate tectonic model for the northern margin of Gondwana in the Neoproterozoic–Early Palaeozoic based on the evolution of the Ossa-Morena zone: (A) Arc growth, (B) back-arc closure, (C) arc accretion, (D) ridge–trench collision, (E) rifting following opening of a slab window, and (F) ocean opening (modified from Sánchez García et al., 2008).

enhanced extension. Subsequent sedimentation was mainly terrigenous and was accompanied by bimodal magmatic activity (the Main Igneous Event of Sánchez-García et al., 2003, 2008) that became voluminous during the Middle Cambrian. As in the Bohemian Massif, Late Cambrian rocks are absent in the Ossa-Morena zone, probably as a consequence of renewed thermal expansion and rift shoulder uplift during the preceding period of voluminous magmatism. Following an angular and erosional unconformity, Early Ordovician strata represent a transgressive sequence, leading to the development of outer platform sedimentation that persists in this zone until the onset of the Variscan orogeny in the Middle Devonian.

A similar history is recorded in the Central Iberian zone, although rift-related magmatism is volumetrically minor and somewhat younger than that of the Ossa-Morena zone and, following Ordovician transgression, the zone occupied inner shelf positions on the passive margin of northern Gondwana. Quesada (1991) interpreted the transgression as a breakup unconformity recording the opening of this part of the Rheic Ocean and the progressive thermal relaxation and floundering of the continental margin.

A common element of the transgressive sequence in both zones is the presence, near the basal unconformity, of a major quartzarenite correlative with the Armorican Quartzite of France, the Bohemian Massif, northwestern Iberia and the northern West African craton (e.g., Noblet and Lefort, 1990). This unit is somewhat older in the Ossa-Morena zone (Tremadoc: Gutiérrez Marco et al., 2002; 489.3 ± 1.3 Ma: U–Pb zircon age of interbedded K-bentonites, López Guijarro et al., 2007) than it is in the Central Iberian zone (Arenig: Gutiérrez Marco et al., 2002; 477.47 ± 0.93 Ma: U–Pb zircon age of interbedded K-bentonites, Gutiérrez-Alonso et al., 2007), suggesting that ocean opening propagated from present-day south to north. A potentially important indication of palaeogeography is provided by the presence of Late Ordovician glaciomarine diamictites in both zones, as well as in northern Iberia, parts of France and the Bohemian Massif (Robardet and Doré, 1988). This is taken as evidence that these areas remained attached to mainland Gondwana for most, if not all, of the Palaeozoic, bringing into question the existence of the Armorican microplate (Robardet, 2003; Linnemann et al., 2007).

Highly dismembered relics of the Rheic Ocean itself are interpreted to occur within the Pulo do Lobo accretionary prism that, together with the Beja-Acebuches ophiolite (attributed to a Rheic marginal basin by Quesada et al., 1994), delineate the Variscan suture in southern Iberia. Their presence immediately south of the Ossa-Morena zone, in close proximity to the Cambrian rift axis, supports the interpretation of these oceanic sequences as the successful culmination of the rifting process (Quesada et al., 1994; Sánchez-García et al., 2003, 2008).

6.2. Closure and collision

The earliest evidence for the onset of collisional deformation in the Gondwanan units in southern Iberia dates to the latest Early Devonian (Terena flysch; Pereira et al., 1998), and deformation was widespread by the Late Devonian. However, the persistence of platformal (passive margin) sedimentation throughout the Lower and Middle Palaeozoic requires closure of the Rheic Ocean to have been accommodated outboard, either by intraoceanic subduction, subduction beneath the Laurussian margin, strike-slip activity, or a combination of these processes. No evidence exists to constrain the onset of Rheic Ocean closure, although the Iberian margin of Gondwana clearly belonged to the lower plate.

Northwestern Iberia always remained part of the lower plate (Martínez-Catalán et al., 1996, 1997, 1999, 2003, 2007; Arenas et al., 2007a, b, c), but in southern Iberia, irregularities in the shape of the continental margin are thought to have led to the lateral escape of the Ossa-Morena zone, starting in the Middle Devonian. According to Quesada (1991, 1998, 2006), this escape was accommodated by highly oblique north-directed subduction of the remaining ocean beneath the Ossa-Morena zone. As a result, southern Iberian Gondwana became part of the upper plate, and remained so until the end of the Variscan convergence, as demonstrated by punctuated mid-Devonian through Early Viséan arc magmatism in the southern Ossa-Morena zone (Santos et al., 1987; Andrade et al., 1991).

Growth of the Pulo do Lobo accretionary prism is thought to have taken place during this period of oblique subduction, incorporating dismembered sheets of what is believed to be Rheic ocean floor into syn-orogenic flysch and mafic (ophiolitic) mélange formations of Late Devonian age (Oliveira et al, 1986; Giese et al., 1988; Eden, 1992).

Mafic lithologies incorporated into the Pulo do Lobo accretionary prism are typically N-MORBs (Quesada et al., 1994). On the other hand, the Beja Acebuches Ophiolite, which lies between this accretionary unit and the Ossa-Morena zone, includes mainly E-MORB amphibolites and metagabbro with the characteristics of supra-subduction zone ophiolites. The ophiolite is therefore attributed to an intrarc or forearc basin marginal to the main Rheic Ocean (Quesada et al, 1994; Castro et al., 1996; Pereira and Quesada, 2006). Recently published U–Pb SHRIMP ages from Beja-Acebuches amphibolites as young as 332 ± 3 (Azor et al., 2008) provide an upper limit to the duration of this marginal basin.

The southern Iberian segment of the Variscan orogen is also unique in its transpressional response to a highly oblique regime of continental collision (Brun and Burg, 1982; Burg et al., 1987). The entire region, including the South Portuguese zone, exhibits a prominent sinistral transpressional geometry that is best developed in the Ossa-Morena zone, which defines a dramatic, large-scale left-lateral strike-slip duplex (Fig. 12).

The South Portuguese zone is thought to represent an exotic non-Gondwanan element largely because of its position on the south side of the suture (Ribeiro et al., 1990; Quesada, 1991). Its correlation with Avalonia (Quesada, 1998) is based on similarities with the southern British Isles and the Rhenohercynian zone of the Bohemian Massif (Oliveira et al., 1979; Oliveira and Quesada, 1998). However, the zone's short stratigraphic record (the oldest rocks are Late Devonian) precludes unambiguous correlation and, in the absence of reliable provenance, inheritance and palaeomagnetic data, its palaeogeography remains uncertain.

7. The Rheic Ocean in North America

The evolution of the Rheic Ocean in North America is recorded by several terranes, collectively referred to as peri-Gondwanan, which occupy much of the southeastern flank of the Appalachian orogen (Fig. 14). These terranes include Ganderia, Avalonia and Meguma in the northern Appalachians, and Carolinia and the Suwanee terrane in the southern Appalachians (Hibbard et al., 2007). Ganderia and Avalonia are regionally extensive and have correlatives in Western Europe (e.g., van Staal et al., 1998). Carolinia has been correlated with both Ganderia (e.g. Hibbard et al., 2007) and Avalonia (Nance and Murphy, 1994, 1996; Murphy and Nance, 2002). The Meguma terrane is exposed only in southern mainland Nova Scotia, although geophysical data indicates that it underlies much of the continental shelf off New England and Maritime Canada. The Suwannee terrane is found only in the sub-surface of Florida, Alabama and Georgia.

A wealth of palaeontological, palaeomagnetic and isotopic data indicate that these terranes (A–C, Fig. 4) lay along the northern (Amazonian–West African) margin of Gondwana in the Neoproterozoic and Early Palaeozoic at considerable latitudinal distance from Laurentia (e.g., Cocks and Torsvik, 2002; Landing, 2005). Their tectonothermal histories show that they continuously faced an open ocean during this time (e.g., Murphy et al., 2004a). The Suwannee terrane probably remained along the Amazonian margin of Gondwana during the entire Palaeozoic (e.g. Heatherington and Mueller, 2003). The separation of the other peri-Gondwanan terranes from the Gondwanan margin in the Late Cambrian–Early Ordovician resulted in the birth of the Rheic Ocean (e.g., van Staal et al., 1998, 2009; Murphy et al., 2002, 2006a; Nance et al., 2002; Keppie et al., 2003; Nance and Linnemann, 2008; Pollock et al., 2009). These terranes were later accreted to Laurentia during the closure of the Iapetus Ocean, although their relative palaeogeography and the timing of their accretion remain controversial. The Rheic Ocean suture produced by the Carboniferous–Permian collision between Laurentia and Gondwana is not exposed in North America. But this collisional event dictated the Late Palaeozoic sedimentary and deformational history of the entire Ouachita–Appalachian orogen (e.g. Hatcher, 1989, 2002).

7.1. Rifting and opening

Although palaeontological data indicate that Avalonia was isolated from Gondwana during the Early Cambrian, final separation from Gondwana did not occur until the Late Cambrian–Early Ordovician, and it is this separation that is taken to mark the birth of the Rheic Ocean. In Avalonia (Fig. 14), Cambrian–Lower Ordovician continental to shallow-marine platformal sequences can be traced with remarkable lithostratigraphic homogeneity from New England, through Atlantic Canada to correlative rocks in the Anglo-Welsh segment of southern Britain (Landing, 1996, 2005). Minor bimodal rift volcanism within local pull-apart basins, the development of which collectively spans the entire Cambrian (e.g., Greenough and Papezik, 1986; White et al., 1994; Murphy and Dostal, 2007), may record rifting that ultimately led to Rheic Ocean development. However, faunal data suggests that rifting was a protracted process. Distinct faunal provinciality in the Early Cambrian suggests that Avalonia and Gondwana were separate (e.g., Landing, 1996), although the seaway between the two was narrow since the separation is not detectable palaeomagnetically (e.g., Van der Voo, 1988). By the Middle Cambrian, however, the faunal barrier had broken down (Landing, 2005) and, in the Early Ordovician, the fauna of Avalonia is of Gondwanan affinity. Detrital zircon data from Newfoundland suggest that final separation of Avalonia from Amazonia occurred during the Early Ordovician (Pollock et al., 2009), whereas faunal provinciality and palaeomagnetic data document the increasing separation of Avalonia from Gondwana during the Ordovician (e.g., Cocks, 2000; Cocks and Torsvik 2002). By

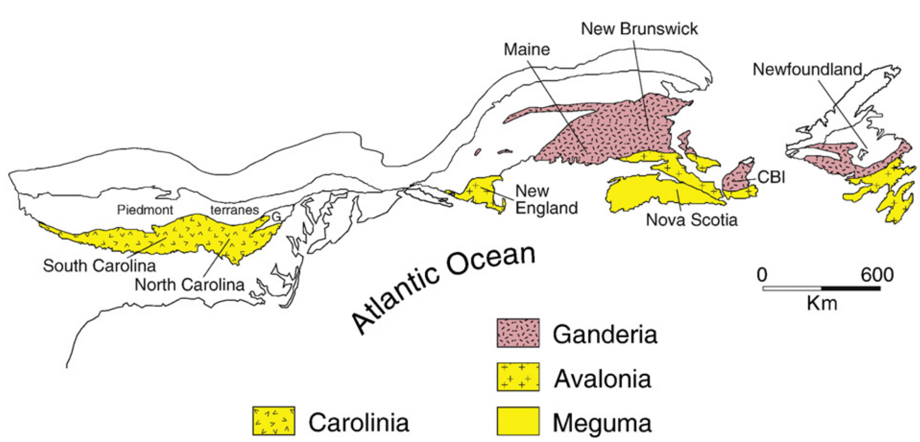

Fig. 14. Peri-Gondwanan terranes within the Appalachian orogen of eastern North America (modified from Hibbard et al., 2007). CBI = Cape Breton Island, G = Goochland terrane.

460 Ma, palaeomagnetic data show Avalonia lay about 2000 km north of the Gondwanan margin (Hamilton and Murphy, 2004).

Ganderia is predominantly exposed in Atlantic Canada and northern Maine (Fig. 14) and consists of Neoproterozoic platformal sequences followed by Late Neoproterozoic and Early Cambrian arc sequences (van Staal et al., 1998, 2009; Barr et al., 1998; White and Barr, 1996; Barr et al., 2002). The arc sequences are overlain by Middle Cambrian–Lower Ordovician metasedimentary rocks, the depositional age of which is constrained by scarce fossils, detrital zircon data and field relationships. Facies indicate an outer shelf or continental slope environment (van Staal et al., 1996). In Carolinia, Neoproterozoic activity continued into the Early Cambrian (Hibbard et al., 2007) and was succeeded by a 1–2 km thick Middle Cambrian platformal assemblage (Dennis and Wright, 1997). However, strata that document the opening of the Rheic Ocean are sparse (Hibbard et al., 2007).

Shared evidence of Early Cambrian arc activity and similarities in Cambrian–Ordovician lithotectonic histories has led Hibbard et al. (2007) to propose that Ganderia and Carolinia are correlatives. However, the Sm–Nd isotopic signature for crustally derived igneous rocks in Carolinia is indistinguishable from that of Avalonia, and indicate derivation from a relatively juvenile (ca. 0.8–1.0 Ga) basement (Murphy and Nance, 2002). In contrast, the Sm–Nd isotopic signature of Ganderia indicates the presence of a much older basement (e.g. Kerr, 1997).

The Meguma terrane (Fig. 14) is dominated by a ca. 13 km thick Late Neoproterozoic–Early Ordovician conformable sequence of siliciclastics rocks (Meguma Supergroup; Schenk, 1997; Waldron et al., 2009). The lower part of this succession (Goldenville Group) is a sparsely fossiliferous, turbiditic (outer shelf/continental rise) deposit, and is conformably overlain by the predominantly pelitic Halifax Group (Schenk, 1971, 1997; Waldron and Jensen, 1985; Waldron, 1992; White et al., 2005). Schenk (1971, 1997) drew attention to similarities between the Meguma Supergroup and coeval successions deposited on the West African craton (Supergroup II of Morocco, Mauritania and Mali). Recent detrital zircon and Sm–Nd isotopic studies have shown that a West African affinity is most prominent near the base of the Goldenville Group, whereas Mesoproterozoic zircons attributed to derivation from Amazonia, occur at higher stratigraphic levels (Waldron et al., 2009).

7.2. Accretion of peri-Gondwanan terranes to Laurentia

Following their separation from Gondwana, the peri-Gondwanan terranes (Avalonia–Carolinia, Figs. 1 and 4) defined the northern flank of a widening Rheic Ocean, and were separated from Laurentia by a narrowing Iapetus Ocean (e.g. van Staal et al., 1998; Cocks and Torsvik, 2002; Murphy et al., 2006a). The relative palaeogeography and timing of accretion of the peri-Gondwanan terranes to Laurentia remain one of the most enduring controversies in Appalachian tectonics. Two rival hypotheses have emerged. In one, the peri-Gondwanan terranes of Ganderia, Avalonia and Meguma are viewed as separate crustal blocks that accreted at different times during the Palaeozoic, each accretionary event producing a separate orogeny respectively assigned to the Salinic in the Late Ordovician–Early Silurian, the Acadian in the Early Devonian, and the Neoacadian in the Middle to Late Devonian (van Staal, 2007; van Staal et al., 1998, 2009). The advocates of this view also favour the correlation of Ganderia with Carolinia (Hibbard et al., 2007), the implication of which is that Carolinia also accreted during the Salinic orogeny (Hibbard, 2000). In this scenario, most of the tectonic evolution of the Appalachian orogen is related to accretionary tectonics. In the rival hypothesis, Ganderia–Carolinia is viewed as the leading edge, and Meguma as the trailing edge (Murphy and Keppie, 2005), of a large composite terrane (Avalonia) that separated from Gondwana in the Late Cambrian to form the Rheic Ocean, and accreted to Baltica by the Early Silurian (Murphy et al., 1996, 2004b; Cocks and Torsvik, 2002) and Laurussia by the middle Silurian. According to this model, the collision of Avalonia with Laurussia resulted in a single, protracted orogenic event (the Salinic orogeny). Subsequent Late Silurian–Late Devonian tectonothermal events (assigned to the Acadian orogeny) are viewed to reflect northward subduction beneath an amalgamated Avalonia–Laurussia during the closure of the Rheic Ocean as a precursor to terminal Carboniferous continent–continent collision (Murphy et al., 1999b, 2004c; Murphy and Keppie, 2005).

Within the Ouachita orogen, boulders of Devonian igneous and metamorphic rocks in strata of Pennsylvanian age (Dennison et al., 1977) may attest to subduction in the outboard Rheic Ocean. However, no phase of terrane accretion appears to precede ocean closure. Instead, pyroclastic detritus and tuffs indicating the approach of an arc first occur in rocks of Middle Mississippian age (e.g., Houseknecht, 1986; Morris, 1989).

7.3. Closure and collision

Final closure of the Rheic Ocean resulted in the formation of the Ouachita belt and gave rise to the final climactic phase in Appalachian orogenesis with the development of the Alleghanian orogen. Ocean closure was also responsible for the burial of the Laurentian platform, which was carbonate-dominated in the Mississippian, by thick, Pennsylvanian clastic wedges that were shed westward (in the Appalachians) and northward (in the Ouachitas) into developing foreland basins from the rising orogenic front (e.g., Hatcher, 1989; Viele and Thomas, 1989; Thomas, 2004). In both the central Appalachians (Whisonant and Schultz, 1986) and the Ouachita belt (e.g., Morris, 1989), the onset of this clastic deposition took place in the Middle Mississippian, which, in the southern Appalachians, broadly coincides with the earliest ductile thrusting in the orogenic interior (ca. 335 Ma; Wortman et al., 1998). Burial of the Laurentian margin by foreland basin deposits, together with the absence of evidence for Devonian–Mississippian arc-related igneous rocks in the Appalachian–Ouachita orogen (e.g., Hermes and Murray, 1988; Speer and Hoff, 1997), indicates that Laurentia, in contrast to Baltica, formed the lower plate during closure of the Rheic Ocean.

Alleghanian deformation brought about by the collision of Gondwana and Laurentia likely involved oblique, rotational and orthogonal components and spanned the Pennsylvanian into the Early Permian (Fig. 15). In the northern Appalachians, Alleghanian orogenesis occurred as the result of oblique convergence between Laurentia and Gondwana and is dominated by dextral strike-slip tectonics on major northeast- and east-trending faults. In Canada, deformation is largely of Late Pennsylvanian age and deposition was mainly confined to small wrench-related basins (e.g., Nance, 1987; Marillier, 1993; Waldron, 2004; Murphy and Hamilton, 2000). In New England (e.g., Snoke and Mosher, 1989), deformation was accompanied by Barrovian-style metamorphism that locally reached the sillimanite zone and has yielded cooling ages that span the Permian (e.g., Wintsch et al., 2003). Associated anatectic magmatism took place in the Late Carboniferous (ca. 325–305 Ma) and, more locally, in the Early Permian (ca. 275 Ma), presumably as the result of crustal thickening.

In contrast, in the Ouachitas and the central and southern Appalachians, the deformational architecture takes the form of crustal-scale decollement structures that verge north and west, respectively. Seismic profiling across the southern Appalachians (e.g., Cook and Vasudevan, 2006) shows these structures to be orogen-wide with the Laurentian platform on the lower plate extending almost 100 km beneath the crystalline thrust sheets of the orogenic interior (Fig. 16). In this way, the foreland fold-thrust belts that are the hallmark of Ouachita–Alleghanian orogenesis and which first developed within the exposed Laurentian platform in the Early Pennsylvanian (e.g., Hatcher, 1989; Viele and Thomas, 1989), represent only the supracrustal toes of low-angle structures that originated in the mid-crust and rose in stair-step fashion to progressively higher crustal levels.

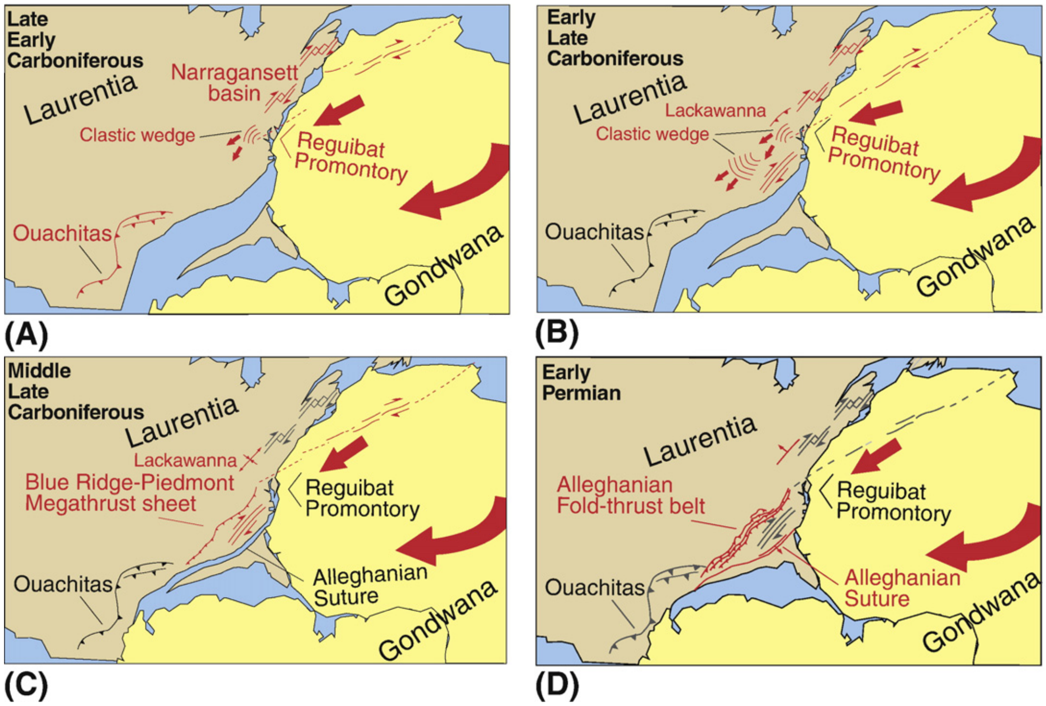

Fig. 15. Oblique rotational collision between Laurentia and Gondwana according to Hatcher (2002). Symbols in red identify features active during time interval represented. (A) Initial contact between Laurentia and Gondwana during Late Mississippian, (B) southward motion and clockwise rotation of Gondwana during Early Pennsylvanian, (C) continued rotation and southward movement of Gondwana in Late Pennsylvanian, and (D) head-on Laurentia–Gondwana collision in Early Permian.

Post-Mississippian deformation in the orogenic hinterland of the southern Appalachians is accompanied by dextral strike-slip tectonics on northeast-trending ductile shear zones, and, like New England, is associated with significant metamorphism and anatectic magmatism (e.g., Horton et al., 1987; Hatcher, 2002). Metamorphism locally reached the kyanite zone and records hornblende cooling ages of 320–295 Ma (Dallmeyer et al., 1986). Widespread granitoid magmatism of latest Mississippian–Pennsylvanian age (ca. 321–304 Ma; e.g., Samson, 2001) either accompanied or followed the metamorphism and, again, is probably the result of tectonic thickening of the crust in response to transpressive convergence between Laurentia and Gondwana (e.g., Hatcher, 2002).

In contrast, the Ouachita orogen is distinctive in that metamorphism is essentially absent and there is no associated magmatic activity. Where present, metamorphism is mostly of sub-greenschist facies and of poorly constrained Pennsylvanian to mid-Permian age (e.g., Viele and Thomas, 1989). Hence, the exposed portion of the orogen, which is interpreted to include leading parts of an accretionary prism (Thomas, 2004), presumably lay north of the Rheic suture. Following cessation of orogenic activity, this suture likely separated Laurentia from the Maya terrane (Fig. 17), which, prior to the opening of the Gulf of Mexico, is thought to have been contiguous with the Florida basement (e.g., Pindell et al., 1990; Dickinson and Lawton, 2001).

8. The Rheic Ocean in Mexico

Important vestiges of the Rheic Ocean's southern (Gondwanan) rifted continental margin and evidence of its Late Devonian–Mississippian subduction are thought to be preserved in the Mixteca, Sierra Madre and Oaxaquia terranes of southern and eastern Mexico (Fig. 17). Together, these terranes appear to record: (1) Ordovician rifting on the

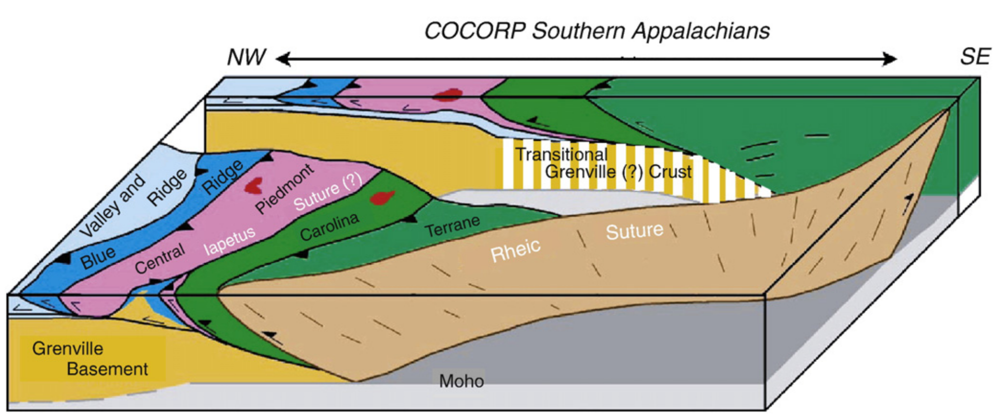

Fig. 16. Schematic block diagram of the crustal structure of the southeastern Appalachians based on reprocessed data from the COCORP reflection survey (modified from Cook and Vasudevan, 2006).

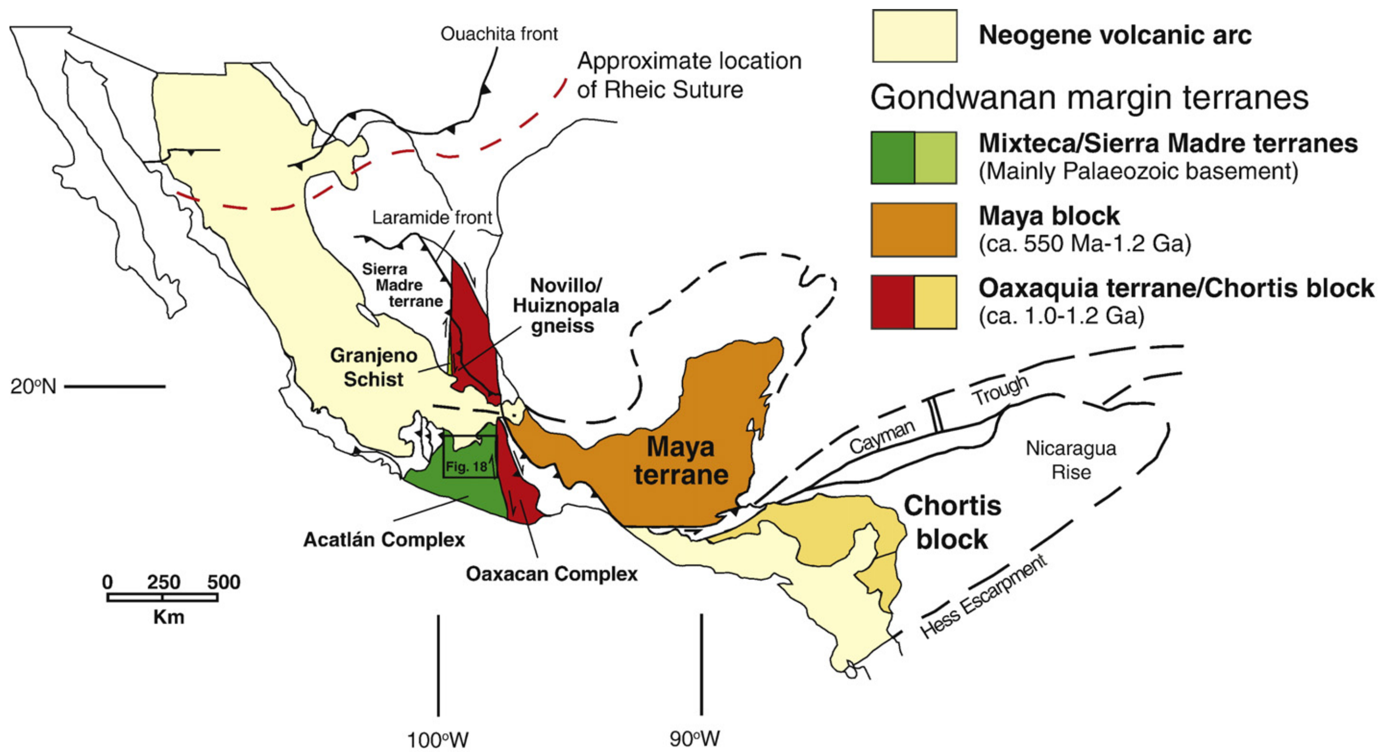

Fig. 17. Simplified tectonic map of Gondwanan Mexico showing location of Oaxacan Complex and Novillo Gneiss (Oaxaquia terrane), Acatlán Complex (Mixteca terrane) and Granjeno Schist (Sierra Madre terrrane). Figure modified after Keppie (2004).

southern margin of the Rheic Ocean, (2) passive drifting with Amazonia during the Silurian, (3) Devonian–Mississippian subduction, high-pressure metamorphism and exhumation, followed by (4) re-establishment of a Permian arc (e.g. Nance et al., 2007a; Keppie et al., 2008a). Although the rift–drift history is similar to that recorded elsewhere, the record of ocean closure lacks evidence of terminal collision because this part of Mexico lay west of the Ouachita orogen and, with ocean closure, came to lie on the active margin of the Pacific.

8.1. Rifting and opening

In the Oaxaquia terrane of southern Mexico, the Mesoproterozoic (ca. 975–1350 Ma; Solari et al., 2003) basement (Oaxacan Complex) is unconformably overlain by a ~200 m uppermost Cambrian–lowest Ordovician shelf sequence (Tiñu Formation, Fig. 19A) containing Gondwanan fauna (Landing et al., 2007). The detrital zircon signature and geochemistry of this sequence indicate derivation from the underlying basement (Gillis et al., 2005; Murphy et al., 2005). Farther north, Mesoproterozoic (ca. 980–1235 Ma; Cameron et al., 2004) basement rocks (Novillo Gneiss) are unconformably overlain by platformal strata containing Gondwanan fauna of mid-Silurian age (Boucot et al., 1997; Stewart et al., 1999).

To the west (Fig. 17), the Mixteca and Sierra Madre terranes are juxtaposed against the Oaxaquia terrane along major north–south dextral faults of Early Permian age (Elías-Herrera and Ortega-Gutiérrez, 2002; Dowe et al., 2005; Elías-Herrera et al., 2007). Juxtaposed against the Oaxacan Complex in southern Mexico, Palaeozoic rocks of the Mixteca terrane (Acatlán Complex) consist of two metamorphic sequences (Fig. 18), one high grade and the other low grade (Keppie et al., 2008a). The low-grade sequence (Fig. 19A, B) consists of ?Cambrian–Ordovician siliciclastic strata (Las Minas, Otate, Calaveras, Epazote, Amate and Huerta units: Keppie et al., 2006; Ramos-Arias et al., 2008; Hinojosa-Prieto et al., 2008; Morales-Gámez et al., 2008) intruded by bimodal, rift-related igneous rocks that include ca. 480–440 Ma megacrystic granitoids (Ortega-Gutiérrez et al., 1999; Talavera-Mendoza et al., 2005; Keppie et al., 2008b). The protracted rifting is inferred to be analogous to the present-day Gulf of California, with rifting continuing well beyond terrane separation (e.g., Nance et al., 2002; Keppie et al., 2003).

The high-grade sequence of the Mixteca terrane is interpreted to comprise: (1) Cambrian–Ordovician rift-shelf rocks intruded by bimodal rift-related igneous rocks that are similar to those of the low-grade sequence and include Ordovician megacrystic granitoids (Murphy et al., 2006b; Middleton et al., 2007; Ortega-Obregon et al., 2009); (2) peri-arc ultramafic rocks (Proenza et al., 2004), and (3) arc and MORB rocks (Meza-Figueroa et al., 2003). The Ordovician granitoids contain concordant inherited zircons that range in age from ca. 900 to 1300 Ma (Talavera-Mendoza et al., 2005; Miller et al., 2007), indicating a source in the Oaxacan Complex. Concordant ages of detrital zircons in both the low- and high-grade Cambrian–Ordovician metasedimentary rocks indicate a provenance in local Ordovician plutons and/or the ca. 1 Ga Oaxacan basement, and distal northwestern Gondwana sources, including an unique source in the 900–750 Ma Goiás magmatic arc within the Brasiliano orogen (Keppie et al., 2008a). These data, together with the rift-related nature of the Cambrian–Ordovician rocks, are most consistent with an origin along the southern margin of the Rheic Ocean (Nance et al., 2009) (Fig. 19C).

Juxtaposed against the Novillo Gneiss farther north (Fig. 17), Palaeozoic rocks of the Sierra Madre terrane comprise low-grade pelitic and psammitic units of the Granjeno Schist and contain tectonic slivers of serpentinite–metagabbro (e.g., Dowe et al., 2005). Detrital zircon populations in the Granjeno Schist are similar to those in the Ordovician units of the Acatlán Complex (Nance et al., 2007b) and, along with lithological similarities, suggest that they are correlative.

8.2. Convergence

The Precambrian and Lower Palaeozoic rocks of Oaxaquia are unconformably overlain by Carboniferous clastic and shallow-marine

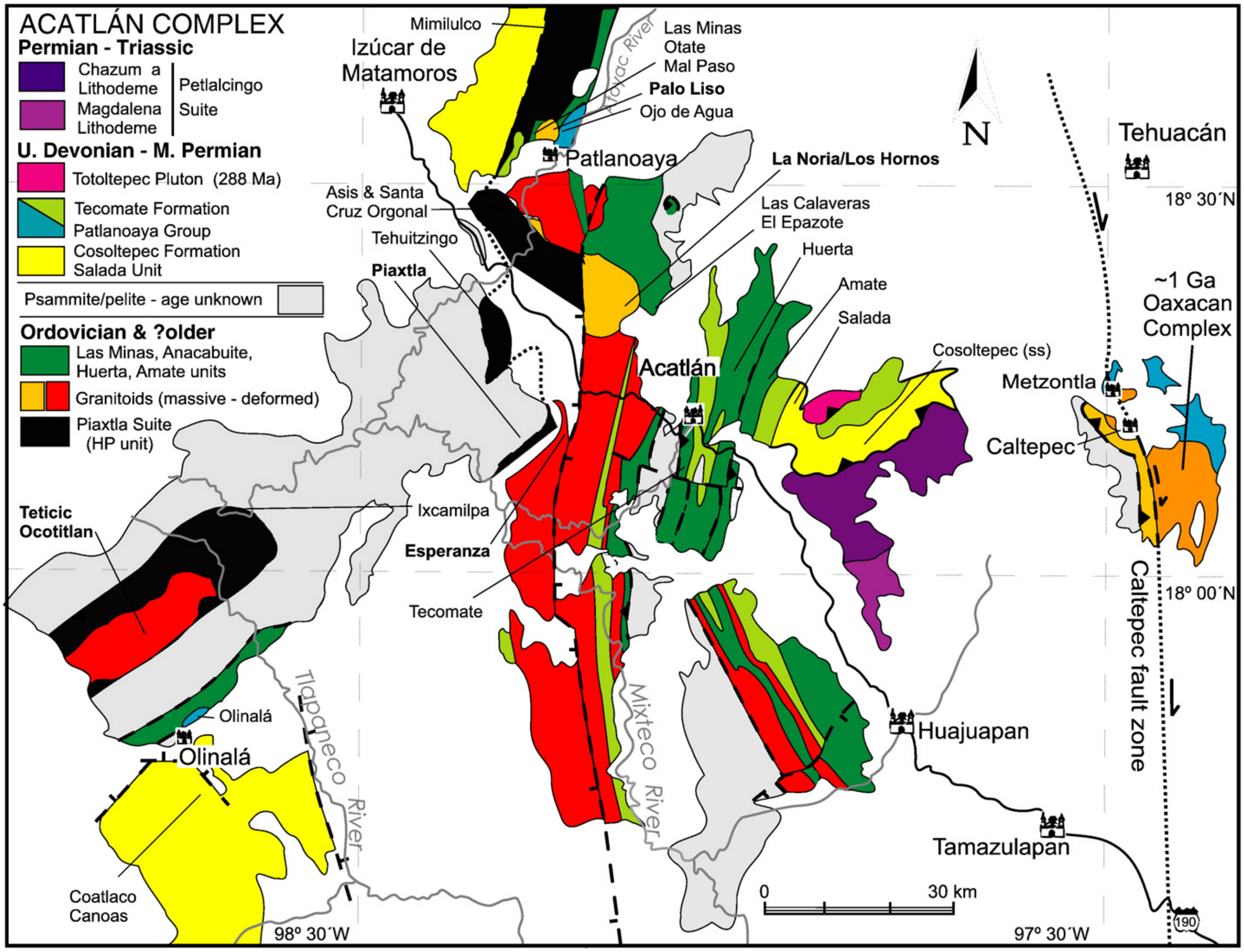

Fig. 18. Geological map of the Acatlán Complex (Mixteca terrane) of southern Mexico (modified after Keppie et al., 2008a). See Fig. 17 for location.

strata that contain a Midcontinental (USA) fauna (Boucot et al., 1997; Navarro-Santillán et al., 2002), indicating proximity to Laurentia during the initial stages of Pangaea amalgamation. Most of the detrital zircon ages from these rocks indicate derivation from the underlying basement, but several grains record Ordovician (ca. 447 Ma, 470–475 Ma) and Devonian–Carboniferous (ca. 340 and 358 Ma) ages (Gillis et al., 2005).

Upper Palaeozoic rocks in southern Mexico comprise a sequence of sandstones, shales, conglomerates and limestones that range in age from uppermost Devonian to Middle Permian (Patlanoaya Group: Vachard et al., 2000; Vachard and Flores de Dios, 2002; Ramos-Arias et al., 2008). Deformed equivalents of these rocks include low-grade psammites, pelites and marbles (Morales-Gámez et al., 2008). The early part of this deposition was synchronous with high-grade and high-pressure (blueschist and eclogite facies) metamorphism and polyphase deformation dated at ca. 350–320 Ma (Middleton et al., 2007; Vega-Granillo et al., 2007; Keppie et al., 2009), whereas the latter part was accompanied by arc magmatism (Torres et al., 1999; Malone et al., 2002).

The high-pressure rocks have been inferred to mark an oceanic suture between Laurentia and Gondwana (Ortega-Gutiérrez, 1981; Talavera-Mendoza et al., 2005; Vega-Granillo et al., 2007, 2009). However, the similarity of the geologic record on either side of the high-grade belt led Keppie et al. (2008a) to suggest that they represent rocks extruded into the upper plate (Ortega-Obregon et al., 2009). Exhumation of the high-pressure rocks was accompanied by deformation that ranged from intense and polyphase adjacent to the extruded mass to undeformed farther away (Ramos-Arias et al., 2008). The high-pressure Cambrian–Ordovician rift-shelf rocks are inferred to have originated in the forearc region of the upper plate that was removed by subduction erosion, carried down the subduction channel, and then extruded into the upper plate in the middle of the Mixteca terrane (Fig. 19D). The presence of arc-related rocks in the high-pressure assemblage suggests that the arc complex was also removed, whereas the MORB rocks may have been derived from the subducting slab. Detrital zircons in the Carboniferous rocks of both the Mixteca and Oaxaquia terranes contain Devonian detrital zircons and volcanic clasts (Gillis et al., 2005; Keppie et al., 2008b) that are inferred to have come from the removed Devonian arc on the western margin of the Mixteca terrane and/or from the exhumed high-pressure rocks (Keppie et al., 2008a).

During the Permian (Fig. 19E), arc-related intrusions in both the Mixteca and Oaxaquia terranes were accompanied by dextral transtensional deformation (Malone et al., 2002) that produced the dextral Caltepec fault zone between the Mixteca and Oaxaquia terranes (Elías-Herrera and Ortega-Gutiérrez, 2002; Elías-Herrera et al., 2007). This activity was synchronous with the deposition of carbonates and clastic rocks containing Permian detrital zircons in peri-arc, pull-apart basins (Morales-Gámez et al., 2008). Empirical relationships between the dip of a Benioff zone and the width of the

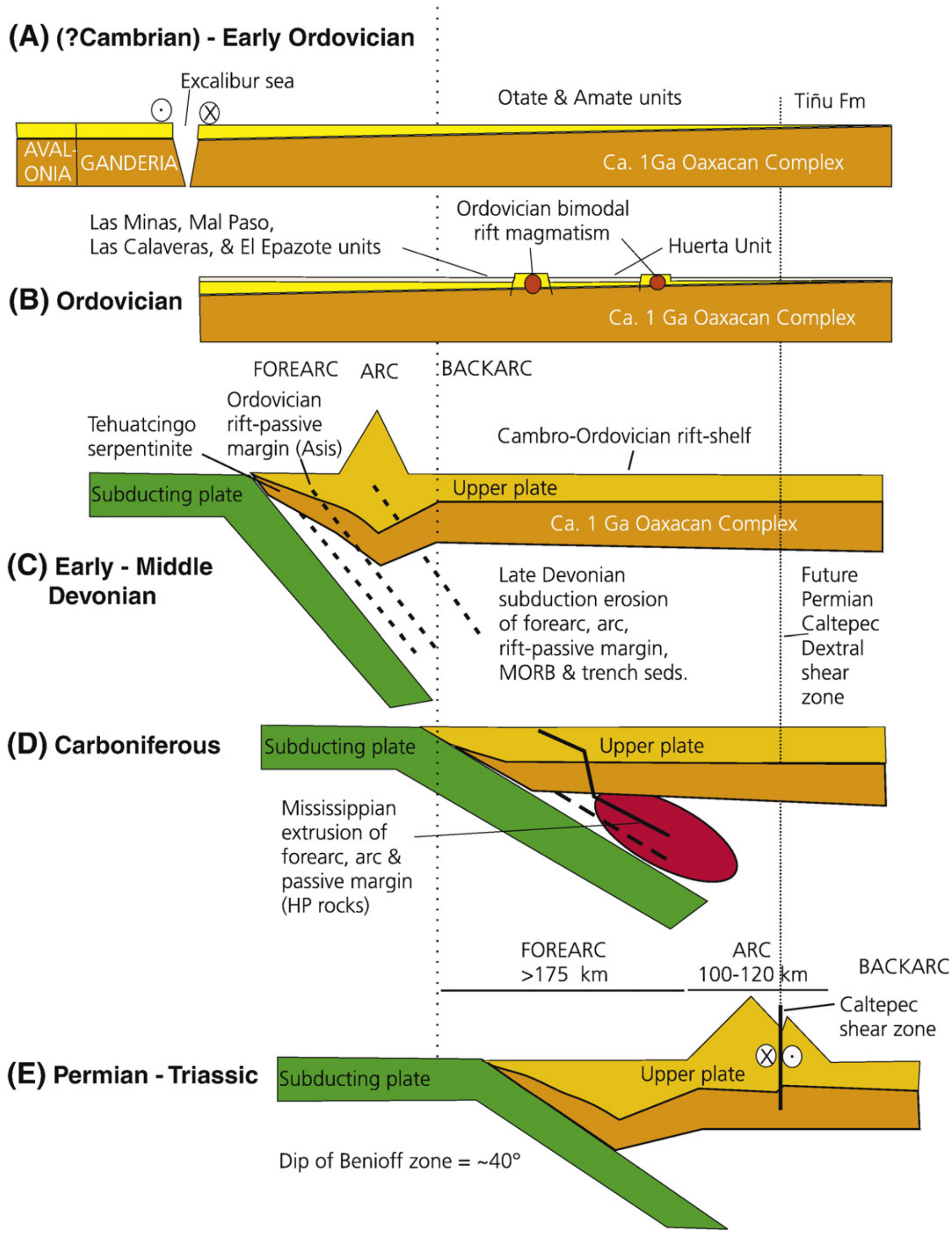

Fig. 19. Schematic cross-sections illustrating the Palaeozoic evolution of southern Mexico (modified after Keppie et al., 2008a).

associated arc–forearc (e.g., von Huene and Scholl, 1991) suggest that the Permian trench lay beneath the eastern edge of the Mesozoic Guerrero terrane, which borders the Pacific to the west, while the association of arc activity with strike-slip deformation suggests that subduction was oblique (Keppie et al., 2008a). The development of this Permian arc, which extends along the backbone of Mexico, is attributed to the onset of subduction in the Palaeo-Pacific following closure of the Rheic Ocean and the assembly of Pangaea (e.g., Nance et al., 2006).

9. Conclusions

As the ocean whose closure was responsible for the creation of the >10,000 km Variscan–Alleghanian–Ouachita orogen and the assembly of the supercontinent, Pangaea, the Rheic Ocean is arguably the most important ocean of the Palaeozoic. Following the onset of subduction within the older Iapetus Ocean, the Rheic Ocean opened in the Early Ordovician as the result of the separation of several Neoproterozoic arc terranes (Avalonia, Ganderia, Carolinia, Meguma) from the northern margin of Gondwana largely along the line of a pre-existing Neoproterozoic suture, likely in response to Iapetus slab pull. Records of this rifting and subsequent passive margin development are well preserved on the Gondwanan margin in the northern Bohemian Massif, in northwestern and southern Iberia, and in the Oaxaquia and Mixteca terranes of southern Mexico. They are also preserved in Avalonia, the faunal and palaeomagnetic record of which documents the terrane's rapid northward drift towards Laurentia during the mid- to Late Ordovician.

The Rheic Ocean reached its maximum width (~4000 km) in the Silurian, following the accretion of the Neoproterozoic arc terranes previously separated from Gondwana to Laurentia and Baltica with the closure of Iapetus and the Tornquist Sea. Ocean closure began in the Early Devonian with subduction beneath Baltica and northwestern Gondwana, and is recorded in the mid- to Late Devonian by ophiolite emplacement in southern Britain, and northwestern and southern Iberia, and in the Late Devonian–Mississippian by eclogite and blueschist facies metamorphism in southern Mexico.

By the Mississippian, closure was essentially complete, but it continued into the Early Permian as Gondwana's irregular West African margin collided with, and then moved westward and southward relative to, southern Baltica and eastern Laurentia, while its Amazonian margin converged with southern Laurentia. As a result, all three palaeocontinents were sutured to form Pangaea by the largest collisional orogenic belt of the Palaeozoic. Closure of the Rheic Ocean played an unparalleled role in the sedimentary, structural and tectonothermal record of the Late Palaeozoic from Middle America to the Middle East and, with its completion, brought the Palaeozoic Era to an end.

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