The Rheic Ocean: Origin, Evolution, and Significance

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ABSTRACT

The Rheic Ocean, which separated Laurussia from Gondwana after the closure of Iapetus, was one of the principal oceans of the Paleozoic. Its suture extends over 10,000 km from Middle America to Eastern Europe, and its closure assembled the greater part of Pangea with the formation of the Ouachita-Alleghanian-Variscan orogen.

The Rheic Ocean opened in the Early Ordovician, following protracted Cambrian rifting that represented a continuum of Neoproterozoic orogenic processes, with the separation of several Neoproterozoic arc terranes from the continental margin of northern Gondwana. Separation likely occurred along a former Neoproterozoic suture in response to slab pull in the outboard Iapetus Ocean. The Rheic 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 largely complete by the Mississippian as Gondwana and Laurussia sutured to build Pangea. In this process, North Africa collided with southern Europe to create the Variscan orogen in the Devonian-Carboniferous, and West Africa and South America sutured to North America to form the Alleghanian and Ouachita orogens, respectively, during the Permo-Carboniferous.

The Rheic Ocean has long been recognized as the major Paleozoic ocean in southern Europe, where its history dominates the basement geology. In North America, however, the Rheic has historically received less attention than Iapetus because its suture is not exposed. Yet, it was the Rheic Ocean that played the dominant role in creating the Appalachian-Ouachita orogen, and an important record of its history may be preserved in Mexico.

INTRODUCTION

The Rheic Ocean—named for the Titan, Rhea, sister to Iapetus in Greek mythology—is arguably the most important ocean of the Paleozoic. Following the Silurian closure of the Iapetus Ocean, the Rheic Ocean separated the major paleocontinents

Figure 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 is purely schematic. Heavy black lines trace Tornquist suture zone.

Figure 2. 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., 2006). A—Avalonia; ARM—Armorica; BM—Bohemian Massif; C—Carolina; Ch—Chortis; Fl—Florida; NW—I—northwestern Iberia; Oax—Oaxaquia; OM—Ossa Morena; Y—Yucatán; question marks—areas where continuity of suture uncertain.
of Laurussia (Laurentia-Baltica-Avalonia) from Gondwana (Fig. 1). Subsequent closure of the Rheic Ocean produced the Ouachita-Alleghanian-Variscan orogeny and assembled the supercontinent of Pangea.

The Rheic Ocean’s importance has long been recognized in Europe, where its suture is well constrained and separate 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. In North America, however, the two sutures follow a similar path, and the importance of the Rheic Ocean is often overlooked. Instead, the history of the Appalachian-Ouachita orogen is traditionally described in terms of the evolution of Iapetus, the opening of which is recorded in the late Neoproterozoic–Early Cambrian rifted margin of eastern and southern Laurussia and whose closure is documented in the accretion of a variety of peri-Gondwanan arc terranes in the Silurian (e.g., van Staal et al., 1998). The Rheic Ocean, in contrast, opened in the Early Ordovician with the separation of these peri-Gondwanan arc terranes from the margin of northern Gondwana and closed with the collision of this margin with Laurussia during the Permo-Carboniferous assembly of Pangea (e.g., Murphy et al., 2006).

The lack of attention to the Rheic Ocean’s role in the development of the Appalachian-Ouachita orogen is largely a function of geography. The orogen contains both the rifted margin and final suture of the Iapetus Ocean, and so preserves a complete record of its opening and closure. But it preserves no such margin of the Rheic Ocean, the suture of which lies buried beneath the sediments of the Coastal Plain outboard of the accreted peri-Gondwanan terranes or was removed with the opening of the Atlantic Ocean and the Gulf of Mexico. Nevertheless, the continent-continent collision that produced the Appalachian-Ouachita orogen in the late Paleozoic was the result of the closure, not of Iapetus, but of the younger Rheic Ocean, important vestiges of which may be preserved in Mexico.

This paper aims to correct this oversight by providing a review of the origin and evolution of the Rheic Ocean that demonstrates its significance to the geological history of both Europe and North America. The time scale used is that of Gradstein et al. (2004).

**EVOLUTION OF THE RHEIC OCEAN**

The 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, by which time Iapetus 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 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., 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., Nance et al., 2002).

Following protracted rifting, the Rheic Ocean opened in the Early Ordovician with the separation of several Neoproterozoic arc terranes from the margin of northern Gondwana. The micro-continental terranes that separated (e.g., Avalonia and Carolina) were the same terranes that had accreted to this margin in the late Neoproterozoic, leading Murphy et al. (2006) to suggest that separation occurred along the line of a former Neoproterozoic suture (Fig. 2).

In Europe, separation of Avalonia by Arenig time is supported by paleomagnetic data (e.g., Cocks and Torsvik, 2002) and Sm/Nd isotopic studies of the sedimentary record (Thorogood, 1990), and is also recorded in the widespread deposition of the Armorican Quartzite. In Mexico, the onset of passive margin sedimentation occurred in the latest Cambrian (Landing and Sm/Nd, 2007), whereas backstripped subsidence curves in eastern Avalonia suggest that drifting may not have been achieved until the mid-Arenig to Llanvirn (Prigmore et al., 1997). It is therefore likely that the rifting and separation of terranes from northern Gondwana took place diachronously. Also during this time, the Early Ordovician Gondwanan fauna of Avalonia were gradually replaced by endemic forms (Fortey and Cocks, 2003).

Throughout the Ordovician, the Rheic Ocean widened at the expense of Iapetus as Avalonia-Carolina drifted northward toward Baltica and Laurentia (Fig. 3). The endemic fauna of Avalonia were 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, paleomagnetic data indicate that
by 460 Ma Avalonia lay at 41°S (Hamilton and Murphy, 2004), some 1700–2000 km south of Laurentia (at ~20°S; Mac Niocaill and Smethurst, 1994) and ~2100 km north of Gondwana (at ~60°S; Cocks and Torsvik, 2002). This requires Avalonia to have drifted northward at the relatively rapid rate of 8–10 cm/yr. This is well in excess of modern ridge-push spreading rates (1–2 cm/yr), which suggests that the opening of the Rheic Ocean was likely driven by slab pull within the closing Iapetus Ocean to the north. Even faster rates may have been attained by Carolina, which was likely attached to, but ~2000 km north of Avalonia and minimally separated from Laurentia latitudinally by ca. 455 Ma (e.g., Hibbard et al., 2002). European Cadomia (Fig. 1), also part of the active Neo-proterozoic margin of Gondwana, likely remained on the northern Gondwanan margin, forming the southern margin of the Rheic Ocean from Lower Ordovician until at least uppermost Devonian times. This is supported by paleomagnetic data and the southerly paleolatitude of Cadomia in the Late Ordovician, indicated by widespread evidence for glaciation, which is characteristic of Gondwana but absent in Avalonia (e.g., Linnemann et al., 2004).

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-Carolina to the south, closing the Iapetus Ocean and creating the Appalachian-Caledonide orogen. Closure of the Rheic 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 southward subduction beneath the northwestern margin of Gondwana in the Appalachian-Ouachita belt, where Laurentia forms the lower plate (Hatcher, 1989; Viele and Thomas, 1989). Closure was accompanied ca. 395–370 Ma by the emplacement of ophiolites in southern Britain and northwestern and southern Iberia, and may have accelerated as a result of ridge-trench collision along the ocean’s southern margin (Woodcock et al., 2007). 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 Mauritanides of West Africa (e.g., Piqué and Skehan, 1992), whereas Gondwana’s Amazonian margin collided with southern Laurentia to produce the Ouachita orogen. The resulting Ouachita-Alleghanian-Variscan belt was the largest collisional orogen of the Paleozoic and sutured Gondwana and Laurussia to form Pangea (Fig. 3).
Figure 5. Model for the plate-tectonic transition from Cadomian arc to Rheic Ocean in central Europe based on data derived from the Saxo-Thuringian zone of the Bohemian Massif (from Linnemann et al., 2007). (A) Cadomian back-arc basin development ca. 590–545 Ma. (B) Cadomian retro-arc foreland basin development ca. 545–540 Ma. (C) Early to Middle Cambrian asymmetric rifting ca. 530–500 Ma. (D) Upper Cambrian oceanic ridge incision ca. 500–490 Ma (MOR—mid-ocean ridge). (E) Early Ordovician Rheic rift-drift transition ca. 490–480 Ma. Insets 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).

Figure 6. Simplified tectonic map of Gondwanan Middle America showing location of Mexico’s Oaxacan Complex and Novillo Gneiss (Oaxaquia terrane), Acatlán Complex (Mixteca terrane), and Granjeno Schist (Sierra Madre terrane). Modified after Keppie (2004).
The Rheic Ocean in Central Europe

The formation 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. This closure, ca. 370–330 Ma, produced a suture (Fig. 4) that runs westward from the Mid-German Crystalline zone in Germany and the Lizard ophiolite in southern Britain to the Pulo do Lobo unit 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) in the Sudetes and may extend to the Moravo-Silesian zone on the massif’s eastern margin (considered part of Avalonia; Finger et al., 2000) and on into Eastern Europe (Bulgaria, Romania, Turkey; e.g., Winchester et al., 2002).

In central and western Europe, the suture separates Cadomia and its Paleozoic passive margin from the southern margin of Laurussia as represented by the eastern part of Avalonia and its overlying Paleozoic 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 ca. 500 Ma of a passive margin sequence and emplacement ca. 340 Ma of ophiolitic allochthons in northwestern Iberia (e.g., Sánchez-Martínez et al., 2007); (3) in the well-documented rift succession of the Ossa-Morena Zone (e.g., Sánchez-García et al., 2003) as well as the Pulo do Lobo accretionary prism and Beja-Acebuches ophiolite in southern Iberia (Quésada et al., 1994); and (4) in the evidence of an Early Ordovician breakup unconformity and widespread sub-
The Rheic Ocean in North America

Although the Rheic suture is not exposed in North America, closure of the Rheic Ocean in the late Paleozoic dictated the sedimentary and deformational history of the entire Ouachita-Appalachian orogen. Furthermore, important vestiges of the ocean's southern (Gondwanan) rifted continental margin and a possible record of its Late Devonian-Mississippian subduction are preserved in the Mixteca, Sierra Madre, and Oaxacan terranes of southern and western Mexico (e.g., Nance et al., 2007).

Rifting and Opening

Within the Appalachians, evidence of the opening of the Rheic Ocean occurs only in those peri-Gondwanan terranes that defined the ocean's northern margin and that were accreted to Laurentia with the closure of Iapetus. In Avalonia, for example, minor bimodal rift volcanism, predominantly of Middle to Late Cambrian age but locally spanning the entire Cambrian (e.g., Greenough and Papezik, 1986), may record initial rifting.

Faunal data suggest 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 because the separation is not detectable paleomagnetically (e.g., Van der Voo, 1988). By the Middle Cambrian, the faunal barrier had broken down and, in the Early Or dovician, the fauna of Avalonia are of Gondwanan affinity. Faunal provinciality and paleomagnetic data following the Early Ordovician document the
increasing separation of Avalonia from Gondwana (e.g., Cocks and Torsvik, 2002).

In Mexico, vestiges of the Gondwanan continental margin of the Rheic Ocean are preserved in the Oaxaquia terrane, and voluminous bimodal magmatism that is interpreted to record rifting along this margin is present in the adjacent Mixteca terrane (Fig. 6). The Oaxaquia terrane, the largest exposed portions of which are the Oaxacan Complex and Novillo Gneiss, exposes Mesoproterozoic (ca. 1.0–1.2 Ga) basement (e.g., Keppe, 2004) unconformably overlain by latest Cambrian–Early Ordovician (Tremadocian) and mid-Silurian (early to mid-Wenlock) continental margin siliciclastics containing fauna of Gondwanan affinity (e.g., Boucot et al., 1997; Landing et al., 2007).

To the west, the Mixteca and Sierra Madre terranes are interpreted to contain vestiges of the Rheic Ocean juxtaposed against the Oaxaquia terrane along major north-south dextral faults of Early Permian age (Nance et al., 2007, and references therein). These vestiges form a major component of the Acatlan Complex, which constitutes the basement of the Mixteca terrane, as well as the Granjo Schist of the Sierra Madre terrane to the north. In the Acatlan Complex, megacrystic granitoids and amphibolites of Ordovician age (ca. 440–480 Ma) intrude siliciclastic metasedimentary rocks (Piaxtla Suite) with detrital zircon signatures that closely match those of the early Paleozoic platform overlying the Oaxacan Complex (Gillis et al., 2005). The association is interpreted as a part of a protracted rift–passive margin sequence (e.g., Miller et al., 2007) analogous to the present-day Gulf of California, in which rifting continued well beyond terrane separation. Predominantly low-grade siliciclastic rocks of pre-Carboniferous age are thought to represent either continental rise deposits laid down within the Rheic Ocean or trench deposits associated with its subsequent closure.

**Closure and Collision**

Subduction of the Rheic Ocean in the Late Devonian–Mississippian is thought to be documented in the Piaxtla Suite of the Acatlan Complex by eclogites and decompression metamorphites with ages of ca. 345–550 Ma (Middleton et al., 2007) and by high-pressure rocks (including blueschists) with ages spanning the interval 320–345 Ma (Vega-Granillo et al., 2007). Associated arc rocks are not preserved, nor are they present in the Ouachita orogen, where the arc is most likely to have accreted and where pyroclastic detritus and tuffs indicating the approach of an arc occur in rocks of Middle Mississippian age (e.g., Morris, 1989). Boulders of Devonian igneous and metamorphic rocks in strata of Pennsylvanian age (Dennison et al., 1977) may also attest to subduction in the outboard Rheic Ocean. The absence of an arc in Mexico has led Keppie et al. (2008) to suggest that, in this segment of the Rheic, the arc may have been removed by subduction erosion beneath the Oaxacan (Gondwanan) margin. Evidence of arc-related igneous rocks of Devonian-Mississippian age is likewise absent in the Appalachian orogen (e.g., Hermes and Murray, 1988), indicating that Laurentia, in contrast to Baltica, formed the lower plate during Rheic Ocean closure.

Closure of the Rheic Ocean resulted in the formation of the Ouachita belt and gave rise to the 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). The onset of this clastic deposition took place in the Middle Mississippian, which, in the southern Appalachians, broadly coincides with the earliest dextral thrusting in the orogenic interior (ca. 335 Ma; Wortman et al., 1998).

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. 7). 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-by-east-trending faults. In Canada, deformation is largely of Late Pennsylvanian age, and deposition was mainly confined to small wrench-related basins (e.g., Marillier, 1993). In New England, 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 décollement 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. 8). In this way, the foreland fold-thrust belts that are the hallmark of Ouachita-Alleghanian orogenesis and that 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.

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, as in New England, is associated with significant metamorphism and anatectic magmatism (e.g., Horton et al., 1987). 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 subgreenschist facies of poorly constrained Pennsylvanian to
mid-Permian age (e.g., Viele and Thomas, 1989). Hence, the exposed portion of the orogen presumably lay well to the north of the Riche suture. Following cessation of orogenic activity, this suture likely separated Laurentia from the Maya terrane (Fig. 6), which, prior to the opening of the Gulf of Mexico, is thought to have been contiguous with the Florida basinement (e.g., Dickinson and Lawton, 2001).

CONCLUSIONS

As the ocean whose closure was responsible for the creation of the >10,000 km Ouachita-Alleghanian-Variscan orogen and the assembly of the supercontinent of Pangaea, the Riche Ocean is arguably the most important ocean of the Paleozoic. Following the onset of subduction within the older Iapetus Ocean, the Riche opened in the Early Ordovician as the result of the separation of Avalonia-Carolina from the northern margin of Gondwana along the line of a Neoproterozoic suture, likely in response to Iapetus slab pull. Records of this rifting and subsequent passive-margin development are preserved on the Gondwanan margin in the Oaxaquia and Mixteca terranes of southern Mexico, the Ossa-Morena zone of southern Spain, and the northern Bohemian Massif of central Europe. They are also preserved in Avalonia, the faunal and paleomagnetic records of which document the terrane’s rapid northward drift toward Laurentia during the mid- to Late Ordovician.

The Riche Ocean reached its maximum width (>4000 km) in the Silurian, following the accretion of Avalonia-Carolina to Laurentia and Baltica with the closure of Iapetus and the Tornquist Sea. Riche Ocean closure began in the Early Devonian with subduction beneath both 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 facies metamorphism in Mexico and Europe.

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 paleocontinents were sutured to form Pangaea by the largest collisional orogenic belt of the Paleozoic. Closure of the Riche Ocean played an unparalleled role in the sedimentary, structural, and tectonothermal record of the late Paleozoic from Central America to the Middle East and, with its completion, brought the Paleozoic era to an end.

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