How the closure of paleo-Tethys and Tethys oceans controlled the early breakup of Pangaea

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ABSTRACT

Two end-member models have been invoked to accommodate the Mesozoic dispersal of the supercontinent Pangaea. In one end-member, the opening of the Atlantic Ocean is inferred to have been balanced by the closure of the Panthalassan Ocean related to subduction off the western margins of the Americas. In the other end-member model, the opening of the Atlantic Ocean is accommodated by the closure of the paleo-Tethys and Tethys oceans linked to subduction off the southern margins of Eurasia. Here, I re-evaluate global plate circulation data compiled for the middle Mesozoic Era. The present evaluation confirms that closure of the paleo-Tethys and Tethys oceans compensated for the early opening of the central Atlantic and proto-Caribbean oceans. This result implies that the tectonic evolution of the North American Cordillera was independent from the processes governing Pangaea breakup in the Jurassic and Early Cretaceous Periods. As well, the opening Atlantic and closing Tethys realm must have been tectonically connected through the Mediterranean region in terms of a transform fault or point yet to be factored into geological interpretations. Tight geometric and kinematic correlations evident between the opening Atlantic and closing Tethyan domains can be demonstrated, which are most readily explained if the forces causing Pangaea breakup were transmitted from the Tethyan domain into the Atlantic domain, and not vice versa. Thus, slab sinking–based forces produced during the evolution of the Tethyan subduction zones are hypothesized to have controlled the early Atlantic breakup of Pangaea.

INTRODUCTION

Why Pangaea broke up where and when it did remains an open question in modern tectonics (Nance et al., 2014). Yet, resolution of these questions are central to understanding the driving mechanisms of supercontinent breakup and plate tectonic processes (Morra et al., 2013; Buiter and Torsvik, 2014). Recent studies appear to favor models in which a superplume in the sublithospheric mantle beneath the central Atlantic provides the key drive (Nance et al., 2014). An alternative possibility is that tectonic forces imparted at subduction zones peripheral to Pangaea provided the motivation for supercontinent failure (Hamilton, 2007). A number of geometric and kinematic properties of Pangaea breakup continue to be enigmatic. It is unclear why re-activation of the late Paleozoic sutures preserved in Pangaea following the collision of Laurentia and Gondwana were preferred over the re-activation of other structural lineaments preserved within Pangaea (Buiter and Torsvik, 2014). And, it is also unclear why reactivations of the late Paleozoic sutures were mostly confined to segments south of Newfoundland during the Jurassic and early Cretaceous and did not extend further to the north until the late Cretaceous (Buiter and Torsvik, 2014).

In this study, I investigate the processes responsible for the failure and dispersal of Pangaea by re-evaluating the global plate circuit data compiled for the Mesozoic era (Seton et al., 2012) and identifying the compensation system(s) that accommodated the early stages of central Atlantic and proto-Caribbean rifting (Fig. 1). By identifying explicitly the oceanic domains that closed to accommodate the opening of the Atlantic domain, it is possible to consider the fundamental links that existed between rifting and sea-floor spreading within the Pangaean interior and the subduction and seafloor consumption at its peripheral margins.

Two competing models of compensation for the Mesozoic opening of the central Atlantic exist. In the Atlantic-Panthalassan model, the opening of the central Atlantic and proto-Caribbean oceans is inferred to have been balanced by subduction under the Cordilleran margin of North America and partial closure of the Panthalassan oceanic domain (e.g., Pindell and Dewey, 1982; Johnston and Borel, 2007; Miall and Blakey, 2008; Sigloch and Mihalynuk, 2013). In the alternative Atlantic-Tethyan model, the opening of the central Atlantic and proto-Caribbean oceans is inferred to have been balanced by the closure of the paleo-Tethys and Tethys oceans located south of Eurasia (e.g.,

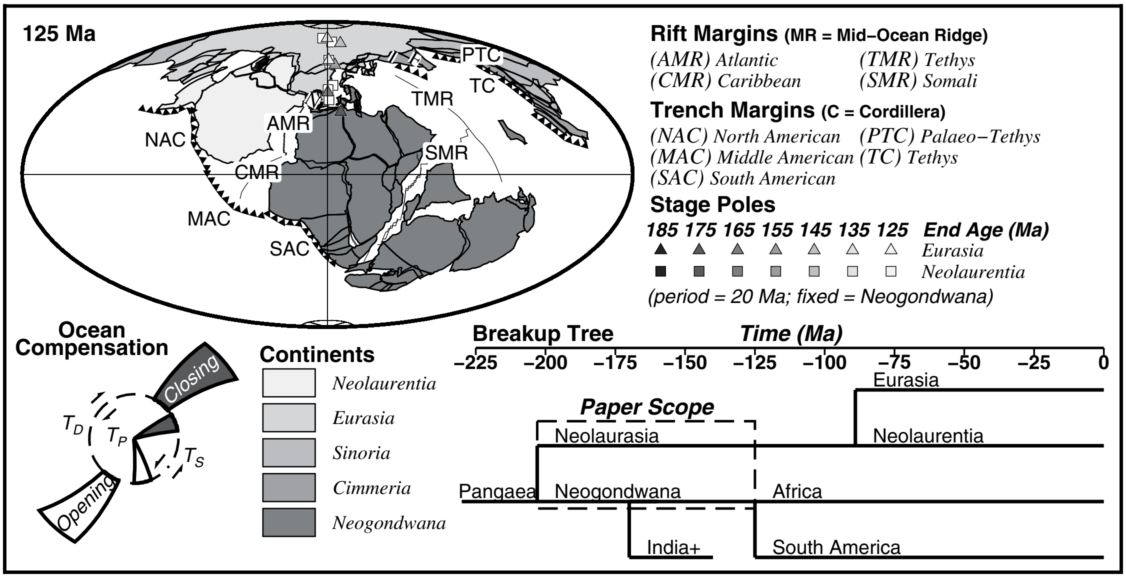

Figure 1. Reconstructed paleogeography of Earth at 125 Ma (after Seton et al., 2012) with South Africa held fixed. The compensation between ocean opening and closing prior to ca. 125 Ma is indicated with light and dark shaded polygons, respectively, in Figures 2–4. Ocean compensation must be connected via one of three end-member transform systems involving sinistral transform (T_S), polar transform (T_P), or dextral transform (T_D) deformation. Labeled continental polygons discussed in text include Newfoundland (N), Iran (I), and Farah (F). Simplified Pangea breakup tree indicates scope of paper.

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Collins, 2003; Kovalenko et al., 2010). The goal of the present study is to evaluate which of these compensation systems governed the early breakup of Pangaea.

Complexities in the Atlantic breakup of Pangaea include the opening of the South Atlantic rift at ca. 125 Ma (Seton et al., 2012), a major change in global tectonics at ca. 105–100 Ma (Matthews et al., 2012), and the opening of the North Atlantic rift at ca. 90 Ma (Seton et al., 2012). For reasons of simplicity and space, I confine the present evaluation of the early breakup of Pangaea to the period of time prior to ca. 125 Ma. However, I also do not consider the late Jurassic breakup of southern Pangaea (or Neogondwana) because it can be shown that the opening of the Somali rift (between Africa–South America and Madagascar-India-Australia-etc.) took place with kinematics broadly perpendicular to the Atlantic breakup investigated here (e.g., Reeves et al., 2004; Seton et al., 2012). The scope of the present paper in space and time is given in Figure 1 relative to a simplified Pangaea breakup tree.

PREVIOUS WORK

Reconstructions of Pangaea and its Mesozoic-to-present dispersal have been iteratively refined for the past 50 yr with the compilation of Seton et al. (2012) used herein. Plate boundaries interpreted to have accommodated Pangaea breakup are based on the compilation of Seton et al. (2012, and references therein) (Fig. 1). These are as follows.

Continuous east-dipping subduction is conventionally inferred along the western margins of North, Middle, and South America from the late Triassic to present time (Dietz and Holden, 1970; Pindell and Dewey, 1982; Miall and Blakey, 2008; Fig. 1). The alternative possibility of west-dipping subduction off the west coast of North America—under Cordilleran terranes with a hypothetically allochthonous origin—has also been proposed (Moores, 1970; Johnston and Borel, 2007; Sigloch and Mihalynuk, 2013). Detrital zircon data indicate that many of the outboard Cordilleran terranes have a peri-Laurentian provenance by Triassic time (Colpron and Nelson, 2009), but debate persists on the timing, orientation, and polarity of Cordilleran subduction zones throughout the Jurassic and Cretaceous (Johnston and Borel, 2007; Miall and Blakey, 2008; Sigloch and Mihalynu, 2013). A few studies have suggested that Tethyan—not Panthalassan—closure compensated for early Atlantic opening instead (e.g., Collins, 2003; Kovalenko et al., 2010).

North-dipping subduction is conventionally inferred along or adjacent to the southern margins of Eurasia and, subsequently, Cimmeria to accommodate the respective closures of the paleo-Tethys and then Tethys Oceans (Moores, 1970; Collins, 2003; Gaina et al., 2013). Seafloor spreading in the Tethys Ocean would have accommodated the transfer of Cimmeria from East Africa to southern Europe (Golonka, 2007). For convenience, the term Greater Tethyan domain is used here to name the total oceanic domain that encompassed both the paleo-Tethys and Tethys Oceans in the Mesozoic. The tectonic connection between the Atlantic and Greater Tethys remains uncertain (Gaina et al., 2013), but this connection has been discussed in terms of rifting in the Atlantic domain propagating into the Greater Tethys or vice versa (e.g., Golonka, 2007; Sibuet et al., 2012). An alternative perspective is that a broadly sinistral shear system connected the Atlantic and Greater Tethys domains instead (Gaina et al., 2013; Fig. 1).

METHODOLOGY

Stage poles for the net motion of North America (Neolaurentia) away from South Africa (Neogondwana) were calculated using 20 m.y. stage intervals for 10 m.y. time steps between 185 Ma and 125 Ma (squares in Fig. 1). Similarly, stage poles for the net motion of Eurasia toward South Africa were calculated (triangles in Fig. 1). These poles constrain how northern Pangaea (Neolaurentia + Eurasia) moved with respect to southern Pangaea (Neogondwana) before 125 Ma. The implications of these motions for opening and closing oceanic domains are then illustrated by constructing unshaded (ocean opening) and shaded (ocean closing) parallelograms for the net relative motion of the major plates away from or toward one another, respectively, for given stage intervals (Figs. 1–4). Kinematic consistency between an opening ocean domain and a closing ocean domain requires one of three possible transform connections: (1) a dextral-transform connection (T_D, Fig. 1), (2) a polar transform connection (T_P, Fig. 1), or (3) a sinistral-transform connection (T_S, Fig. 1).

In Figures 2–4, the net opening of the Atlantic domain and corresponding closure of Greater Tethys was calculated for early Jurassic (203–170 Ma), late Jurassic (170–145 Ma), and early Cretaceous (145–125 Ma) stages, respectively. The reconstructions in Figures 2–4 are centered on the relative stage poles for Neolaurentia/Neogondwana relative motion for the corresponding stages of time using azimuthal equidistant projections. This projection technique enhances the ability to identify the compensation system(s) governing the opening of the Atlantic domain because the net motion of Neolaurentia away from Neogondwana is parallel to

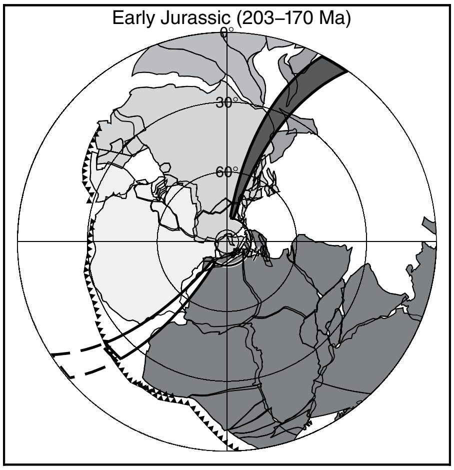

Figure 2. Reconstructed paleogeography of Earth at 170 Ma in a relative reference frame for North America–South Africa net motion between 203 Ma and 170 Ma indicating the hypothesis of a sinistrally linked Atlantic-Tethys compensation system. Legend and geographic references from Figure 1.

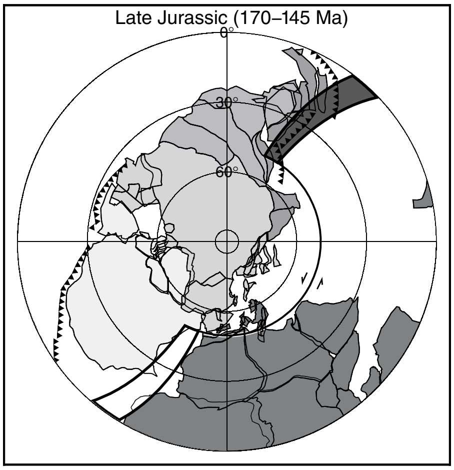

Figure 3. Reconstructed paleogeography of Earth at 145 Ma in a relative reference frame for North America–South Africa net motion between 170 Ma and 145 Ma indicating the hypothesis of a sinistrally linked Atlantic-Tethys compensation system. Legend and geographic references from Figure 1.

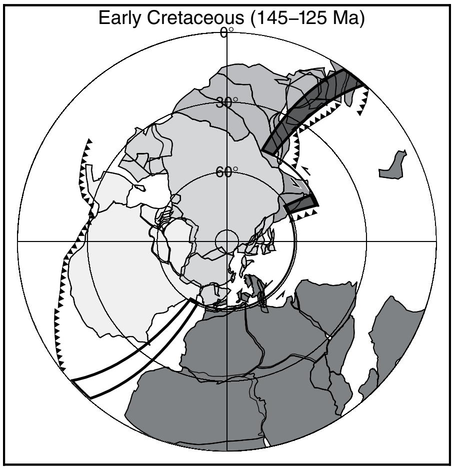

Figure 4. Reconstructed paleogeography of Earth at 125 Ma in a relative reference frame for North America–South Africa net motion between 145 Ma and 125 Ma indicating the hypothesis of a sinistrally linked Atlantic-Tethys compensation system. Legend and geographic references from Figure 1.

lines of projected latitude and perpendicular to lines of projected longitude (Keppie, 2014a).

ANALYSIS

Stage poles that governed the opening of the Atlantic and the closure of Greater Tethys between 203 Ma and 125 Ma mostly lay within reconstructed Europe (Fig. 1). This means that North America and Eurasia pivoted together in a clockwise fashion about the northern edge of Africa prior to ca. 125 Ma (e.g., Collins, 2003; Kovalenko et al., 2010). It was this pivoting action that governed the concurrent opening and closing, respectively, of the Atlantic and Greater Tethys domains. The western Cordilleran margin of North America lay mostly parallel to the motions involved in Atlantic–Greater Tethys during this period. If the Cordilleran margin was a subduction zone during these times, as conventionally inferred (e.g., Miall and Blakey, 2008), rifting within Panthalassa must have taken place at rates exactly equal to convergence rates across the Cordilleran subduction zone(s). The Cordilleran margin may have accommodated a component of strike-slip displacement associated with the Atlantic–Greater Tethys compensation system as well.

The easternmost limit of the central Atlantic rift (southern Newfoundland; Fig. 1) appears to correspond to the western limit(s) of the closing paleo-Tethys and Tethys Oceans in the Jurassic and early Cretaceous, respectively (Figs. 2–4). The western limit of the closing paleo-Tethys and Tethys Oceans changed through time along the southern Eurasian margin in conjunction with the arrival and collision of Cimmeria (Figs. 2–4). During the early Jurassic, late Jurassic, and early Cretaceous stages, Greater Tethyan closure extended to southern Europe (Fig. 2), was limited to the region east of Iran and Farah (Fig. 3), and renewed within western Tethys (Fig. 4), respectively. A sinistral-transform connection through the southern Mediterranean (T_S; Fig. 1) between the poleward limits of the opening Atlantic and closing Greater Tethys domains is inferred here for the Jurassic and early Cretaceous stages (Figs. 2–4). This inference is based on the sinistral offset apparent between Neolaurentia + Europe and Neogondwana along the southern margin of Newfoundland (Fig. 1) from the adopted plate polygon model of Seton et al. (2012). However, future studies are needed to test whether the hypothesized sinistral deformation is compatible with the Mediterranean rock record or whether components of other end-member tectonics such as polar transform (T_P; Fig. 1) or dextral transform (T_D; Fig. 1) deformation accommodated the Atlantic–Greater Tethys compensation system.

In the early Jurassic, compensation between the Atlantic and Tethyan domains may have been incomplete (Fig. 2) because the net closure of Greater Tethys extended across a zone extending from 80° to 0° of tectonic latitude, but the net opening of the Atlantic zone may have only extended across a conjugate zone extending from 80° to 20° of tectonic latitude (Fig. 2). For the late Jurassic, the inferred closure of the Greater Tethys domain as a whole was limited to the west by the 50° line of tectonic latitude (Fig. 3). Notably, the region to the east of this line corresponds to the eastern segment of the paleo-Tethys ocean that was still open at ca. 170 Ma (Fig. 3). For the early Cretaceous, renewed closure of Greater Tethys domain offshore Iran and Farah is implied from the continued operation of the Atlantic–Greater Tethys compensation system (Fig. 4).

DISCUSSION

The present analysis indicates that an Atlantic–Greater Tethys compensation system governed the breakup of Pangaea across the central Atlantic during the Jurassic and early Cretaceous (Collins, 2003; Kovalenko et al., 2010). This interpretation contrasts with the more common view that an Atlantic-Panthalassan compensation system governed the early breakup of Pangaea (e.g., Miall and Blakey, 2008) and has several first-order implications.

First, the western margin of North America was parallel to lines of tectonic latitude relative to the Atlantic–Greater Tethys compensation system. This relationship is depicted here to ca. 125 Ma (Figs. 2–4), but remained as such through to ca. 105–100 Ma when a major change in global tectonics took place (Matthews et al., 2012). This means that prior to ca. 105–100 Ma, the evolution of the North American Cordillera must be evaluated independently from the opening of the Atlantic. Jurassic and early Cretaceous rifting linked to Cordilleran subduction would have taken place entirely within the Panthalassan domain. Critically, a continuous history of east- or west-dipping subduction beneath the Cordilleran terranes of western North America cannot be assumed on the basis of an inferred Atlantic-Panthalassan compensation relationship that was not the case. It is also possible that the conventionally inferred subduction zone or transform boundary along the western Caribbean region during the Jurassic (Fig. 1; Seton et al, 2012) lay further to the west than generally hypothesized in order to respect the balance implied between Tethyan closure and Atlantic opening (Fig. 2).

Second, the present analysis provides a boundary condition for tectonic models of the Mediterranean region during the Jurassic and Early Cretaceous Periods. Critically, some combination of the three end-member transform links possible between the poleward limits of the Atlantic rift and Tethyan subduction zones is required (i.e., sinistral transform, polar transform, or dextral transform; Fig. 1). The sinistral transform hypothesis inferred herein is tentative (Figs. 2–4) and requires testing in the Mediterranean rock record. However, existing interpretations of Mediterranean geology—in which the Atlantic and intra-Tethyan rifts are inferred to be direct or offset extensions of the other (e.g., Golonka, 2007)—are inconsistent with the findings of the Atlantic–Greater Tethys compensation system investigated here. This study makes clear that rift zones within the the Atlantic and Greater Tethys domains lay along the same zones of tectonic latitude during the Jurassic and early Cretaceous and thus were not connected to one another.

Finally, the late Paleozoic suture zones that were re-activated in the central Atlantic during Pangaea breakup (Wilson, 1966) were parallel to the Tethyan subduction zones in the corresponding relative tectonic reference frames (Figs. 2–4). Thus, these suture zones were optimally oriented to fail in preference to differently oriented structural lineaments within Pangaea, if subduction-derived stresses from Greater Tethys controlled the breakup process. Further, the location where Tethyan subduction is inferred to have terminated at its western end appears to correspond to the tectonic latitude where Atlantic rifting is inferred to have terminated at its eastern end. The kinematics of Atlantic opening appears to have been sensitive to, and shifted in synchroneity with, the diachronous collision of Cimmeria with southern Eurasia (Fig. 2–4; Keppie, 2014b). Although it is possible that a superplume or other mantle processes located beneath the central Atlantic may have instigated the breakup of Pangaea, this hypothesis would imply a remarkable set of coincidences in the evident links documented in the Atlantic–Greater Tethys compensation system. In contrast, if the sinking of Tethyan slabs imparted extensional stresses to Pangaea at the Tethyan subduction zones, then the numerous connections between the geometry and kinematics of Greater Tethyan subduction and the rift evolution of the central Atlantic would have direct and simple explanations and provide a rival hypothesis for the breakup of Pangaea.

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