Oblique rifting of the Equatorial Atlantic: Why there is no Saharan Atlantic Ocean

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ABSTRACT

Rifting between large continental plates results in either continental breakup and the formation of conjugate passive margins, or rift abandonment and a set of aborted rift basins. The nonlinear interaction between key parameters such as plate boundary configuration, lithospheric architecture, and extension geometry determines the dynamics of rift evolution and ultimately selects between successful or failed rifts. In an attempt to evaluate and quantify the contribution of the rift geometry, we analyze the Early Cretaceous extension between Africa and South America that was preceded by ~20–30 m.y. of extensive intracontinental rifting prior to the final separation between the two plates. While the South Atlantic and Equatorial Atlantic conjugate passive margins continued into seafloor-spreading mode, forming the South Atlantic Ocean basin, Cretaceous African intraplate rifts eventually failed soon after South America broke away from Africa. We investigate the spatiotemporal dynamics of rifting in these domains through a joint plate kinematic and three-dimensional forward numerical modeling approach, addressing (1) the dynamic competition of Atlantic and African extensional systems, (2) two-stage kinematics of the South Atlantic Rift System, and (3) the acceleration of the South America plate prior to final breakup. Oblique rifts are mechanically favored because they require both less strain and less force in order to reach the plastic yield limit. This implies that rift obliquity can act as selector between successful ocean basin formation and failed rifts, explaining the success of the highly oblique Equatorial Atlantic rift and ultimately inhibiting the formation of a Saharan Atlantic Ocean. We suggest that thinning of the last continental connection between Africa and South America produced a severe strength-velocity feedback responsible for the observed increase in South America plate velocity.

INTRODUCTION

Lithospheric extension related to the final dispersal of western Gondwana started with the formation of large intracontinental rift systems within and between the Africa and South America plates in the Early Cretaceous (Burke and Dewey, 1974; Unternehr et al., 1988). Four extensional domains developed between the main rigid continental lithospheric blocks during that time (Fig. 1A; Heine et al., 2013): (1) the Central African Rift System (CARS), extending from Sudan to the eastern part of the Benoue Trough (Fairhead, 1986), (2) the West African Rift System (WARS), extending from the eastern part of the Benoue Trough northward toward southern Libya (Burke and Dewey, 1974; Genik, 1992), (3) the South Atlantic Rift System (SARS), comprising the present-day conjugate South Atlantic marginal basins with the Benoue Trough–northeast Brazil at its northernmost extent (Nürnberg and Müller, 1991), and (4) the Equatorial Atlantic Rift System (EqRS), covering the conjugate West African and South American margins from the Guinea Plateau–Demarara Rise in the west to the Benoue Trough–northeasternmost Brazil in the east (Basile et al., 2005). While extension in the SARS and EqRS ultimately led to the formation of the South Atlantic and Equatorial Atlantic (Nürnberg and Müller, 1991; Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013), the CARS and WARS never went beyond rift mode and eventually failed, being preserved as subsurface graben structures (Burke and Dewey, 1974; Fairhead, 1986; Genik, 1992).

Here we investigate the spatiotemporal evolution of continental extension leading to the abandonment of these large intracontinental rift systems and the breakup between Africa and South America. We analyze the geodynamics of rifting by combining plate kinematic and forward numerical models.

PLATE KINEMATIC MODEL

Our study builds upon a new plate kinematic model for the evolution of the West Gondwana rift systems (SARS, CARS, WARS, and EqRS) that quantitatively integrates crustal deformation from Cretaceous African and South American intraplate deforming zones as well as from the conjugate passive margins of the equatorial and South Atlantic (Heine et al., 2013). Stage poles of relative motions between the African plates, describing the lithospheric extension in the WARS and CARS, have been generated from published extension estimates (e.g., Genik, 1992; McHargue et al., 1992) and fitting of restored sediment basin widths (Heine et al., 2013; see the GSA Data Repository[1] for paleotectonic maps in 1 m.y. time steps).

Relative motions between the main rigid plates are initiated at 140 Ma and progress at slow extensional velocities, compounding to ~4 mm a^{-1} between South America and southern Africa until 126 Ma (southern Africa fixed reference frame, full spreading rates at 37.5°W, 5°S). Modeled plate motions between South America and northwest Africa result in ~10–15 km displacement during the initial phase. Nondeforming South American and northwest African plates surrounding this region (Heine et al., 2013) imply that an incipient, diffuse plate boundary along the future Equatorial Atlantic region may have existed during the Early Cretaceous, contemporaneous with rifting in the CARS and WARS. Marine magnetic anomalies in the southernmost South Atlantic document breakup and subsequent seafloor spreading in the southern rift segment (Nürnberg and Müller, 1991; Moulin et al., 2010), while the northern part still undergoes continental extension (Torsvik et al., 2009; Moulin et al., 2010; Heine et al., 2013). Relative plate velocities based on seafloor spreading patterns indicate an ~10-fold increase of spreading and/or extensional velocities from 4 mm a^{-1} to >39 mm a^{-1} toward the early Aptian (120.6 Ma; Heine et al., 2013). From then onward, breakup occurs successively in isolated segments of the northern SARS and EqRS, with complete breakup achieved by 104 Ma.

NUMERICAL MODEL SETUP

We investigate the dynamics of rift competition and the reason for the observed multiphase velocity behavior using the three-dimensional (3-D) thermomechanical code SLIM3D (Popov and Sobolev, 2008) with boundary conditions as specified in Figures 1C and 1D. The program solves the thermomechanically coupled conservation equations of momentum, energy, and mass. It includes a free surface and rheological

[1]GSA Data Repository item 2014073, methodological information on numerical model setup, paleo-tectonic reconstruction maps for the Equatorial Atlantic region for the time between 140 and 100 Ma in 1 m.y. time steps, and numerical model animations (Apple Quicktime®), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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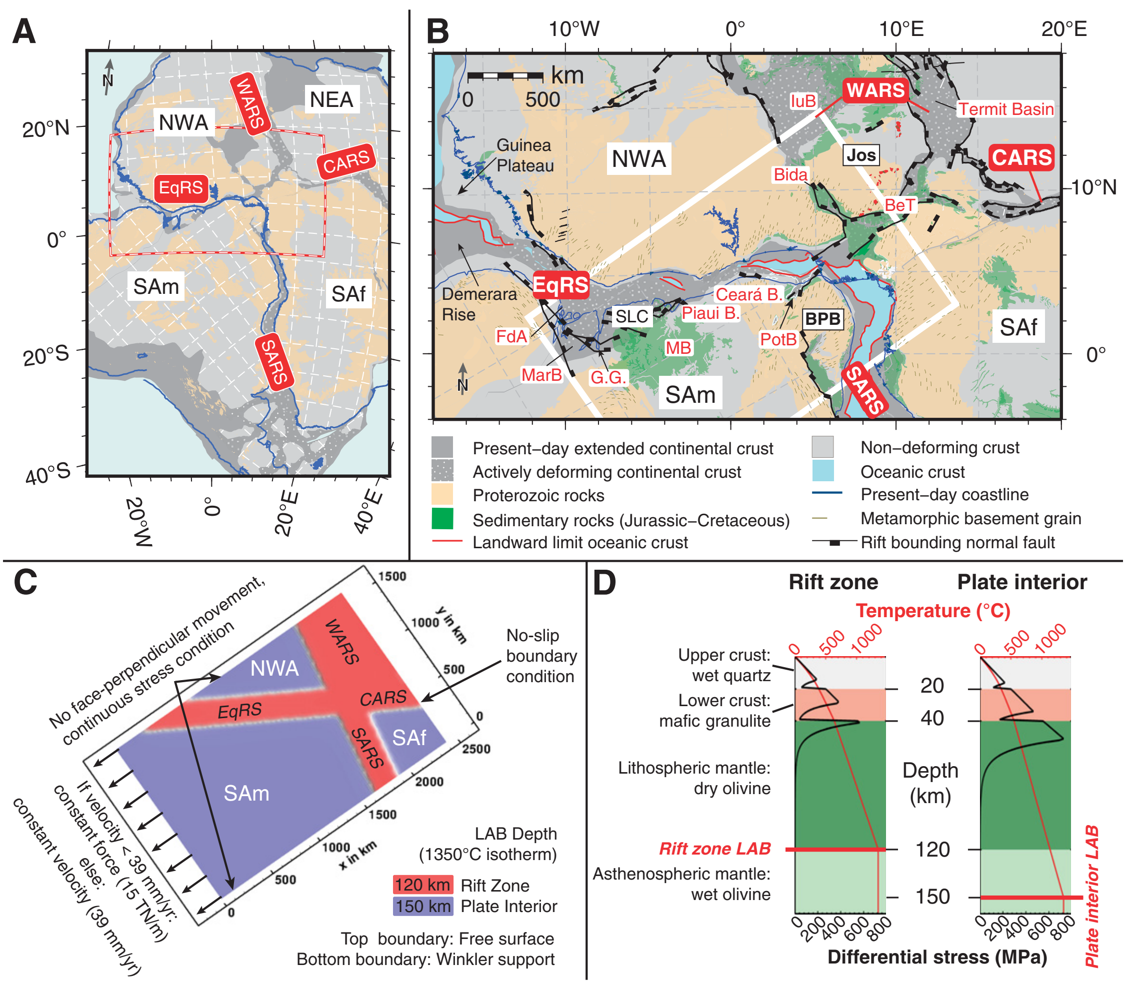

Figure 1. Overview map and numerical model setup. Southern Africa (SAf) is held fixed in present-day position in all reconstructions. A: Lambert azimuthal equal area view of pre-rift configuration at 140 Ma, showing major rigid plates and deforming crustal regions (Heine et al., 2013). Present-day South America and Africa plates are separated into four major rigid plates in region of interest during Late Jurassic–Early Cretaceous: NEA—northeast Africa, NWA—northwest Africa, SAf—southern Africa, SAm—South America. Rift systems (white font, red background): CARS—Central African rift, EqRS—Equatorial Atlantic rift, SARS—South Atlantic rift, WARS—West African rift. Red and white polygon indicates map frame (in B), white dashed lines are present-day 5° graticule. B: 117 Ma reconstruction (Heine et al., 2013). Northernmost segment of SARS is already in seafloor-spreading mode; in EqRS, breakup is incipient. Numerically modeled region is indicated by white rectangle. Minor rigid plates: BPB—Borborema province block (northeast Brazil), Jos—Jos subplate (northern Nigeria), SLC—São Luis craton. Basins (B): BarB—Barreirinhas Basin, BeT—Benoue Trough, FdA—Foz do Amazon Basin, G.G.—Gurupi graben, IuB—Iullemmeden Basin, MarB—Marajó Basin, MB—Maranhão Basin, PotB—Potiguar Basin. C: Initial geometric setup of three-dimensional numerical model involves prospective rift zones as thermal heterogeneities. Model size is 2400 × 1600 km horizontal and 200 km vertical. LAB—lithosphere-asthenosphere boundary. D: Lithospheric segment is vertically divided into four distinct petrological layers, upper crust, lower crust, lithospheric mantle, and asthenospheric mantle. Rheological parameters (see the Data Repository [see footnote 1]) of crust are chosen to represent narrow rift setting as supported by crustal architecture along conjugate equatorial margins (Azevedo, 1991). Rheology of lithospheric and asthenospheric mantle is based on laboratory creep measurements for dry and wet olivine, respectively.

flow laws that are strictly based on experimental rheological data for major rock types (for parameters and model details, see the Data Repository). We adopt rift geometries of the Equatorial Atlantic region (Fig. 1) and thereby extend previous fundamental simulations of oblique rifting (Brune et al., 2012; Brune and Autin, 2013). The model domain is oriented such that two edges are parallel to the extensional direction, composing the rift zones of EqRS, WARS, CARS, and SARS (Figs. 1A and 1B). Because Gondwana rifting reactivated predominantly Pan-African–aged mobile belts (Janssen et al., 1995; Ziegler and Cloetingh, 2004), we introduce prospective rift zones by elevating the depth of the thermal lithosphere-asthenosphere boundary (1350 °C) to 120 km, in contrast to 150 km of the surrounding Proterozoic lithosphere (Fig. 1C; Artemieva, 2006). Each prospective rift is represented by the same thermal heterogeneity (Fig. 1D).

North of the Benoue Trough, Early Cretaceous intraplate magmatism of the Jos Plateau (Wilson and Guiraud, 1992) as well as faulting and subsidence in the Bida and Iullemmeden Basins (Fig. 1B; Petters, 1981; Ojo, 1990; Genik, 1992) confirm distributed extension west of the WARS and perturbance of lithospheric temperature gradients. We include these areas in our definition of the WARS extensional domain and therefore simplify the complex junction of WARS and CARS (Figs. 1A and 1B) by homogeneously weak lithosphere (Fig. 1C). During the rift process, we keep the extensional force constant (15, 16, or 17 TN m^{-1}), allowing for self-consistent evolution of extensional velocities. This approach is feasible because the model domain composes a large region, the strength of which is a major component in the overall force balance of the involved plates. Upon transition from rifting to seafloor spreading in nature, lithospheric strength at the plate boundary becomes negligible, such that extensional velocities evolve independent of the local stress balance, and become affected primarily by global-scale plate tectonic forcing (e.g., slab pull, mantle drag). We account for that transition by applying the force boundary condition only until velocities equate local seafloor spreading rates derived from the plate kinematic model (~39 mm a^{-1}), and use this criterion to link numerical model time with the plate kinematic model to evaluate the spatiotemporal rift evolution.

EVOLUTION OF THE EQUATORIAL ATLANTIC

In our preferred numerical model (15 TN m^{-1}) strain initially accumulates simultaneously along all three rift domains (SARS, EqRS, southwest WARS; Fig. 2, 10 m.y. model time). Modeled extensional velocities for these

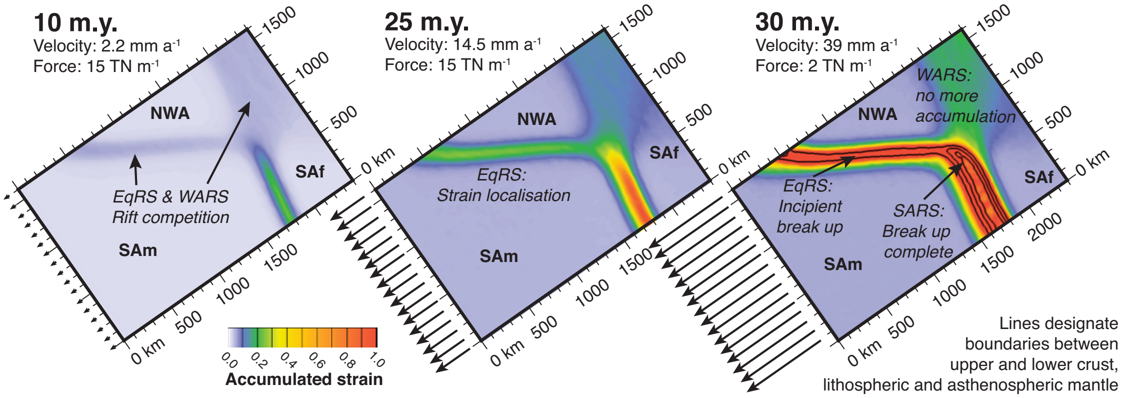

Figure 2. Accumulated strain over 30 m.y. after 10, 25, and 30 m.y. of model run time. Strain magnitude is colored, arrow length at bottom left boundary corresponds to velocity. For model animation in 1 m.y. time steps, see the Data Repository [see footnote 1]; abbreviations as in Figure 1.

domains (2–4 mm a^{-1} full rates) are in accordance with slow rifting compared to the plate kinematic model (Fig. 3). Tholeiitic dike swarms intrude the Ceará, Piaui, and Maranhão Basins (Ceará-Mirim dikes, Sardinha Formation) between 145 and 130 Ma (Bellieni et al., 1992). Crustal uplift, extension, and volcanism are reported from the Gurupí Graben and the Marajo, Foz do Amazon, and Potiguar Basins along the EqRS in pre-Aptian time (Azevedo, 1991; de Matos, 1992; Basile et al., 2005; Soares Júnior et al., 2011), indicating early extensional and transtensional deformation in the central EqRS at low strain rates. After 25 m.y. of model time, strain increasingly starts to localize along the proto–Equatorial Atlantic (Fig. 2; cf. 122 Ma reconstruction), with the rift tip of the SARS turning sharply west, converging into the weakness zone of the proto–Gulf of Guinea while subtle extension continues to affect the WARS. The numerical model suggests that increased strain accumulation in the EqRS and the simultaneous strain rate decrease in the WARS are due to their respective orientation toward plate divergence (EqRS, 60°; WARS, 30°), because all other parameters are the same. Analytical, numerical (Brune et al., 2012), and analogue models (Chemenda et al., 2002) corroborate these results, showing that highly oblique rifts are mechanically favored in both the elastic and viscous deformation regimes. The underlying reason is that oblique deformation requires less strain and as much as two times less force in order to reach the brittle yield stress (Brune et al., 2012). Once yield is reached, hot asthenospheric upwelling and friction softening promote extensive lithospheric weakening. While rift velocities remain low and both EqRS and WARS deform simultaneously until the ~25 m.y. model time (Fig. 2), the highly oblique EqRS accumulates more strain, causing lithospheric necking and strength loss. Subsequently, rifting accelerates in order to satisfy constant force boundary conditions. This nonlinear feedback between lithospheric strength and extensional velocity results in a strong velocity increase between the African and South American plates (Fig. 3) once strain localizes in the EqRS. Note that the duration of the plate velocity increase in the numerical model compares extremely well with independently derived kinematic plate reconstructions (Fig. 3; Nürnberg and Müller, 1991; Torsvik et al., 2009; Heine et al., 2013). From late Barremian time onward (ca. 123–112 Ma), rifting affects most proximal margin segments along the EqRS (Azevedo, 1991; Basile et al., 2005; Soares Júnior et al., 2011). Full lithospheric breakup along the EqRS is achieved in our numerical model after 34 m.y. due to further strain localization, whereas postrift thermal subsidence along the conjugate divergent Equatorial Atlantic marginal basins commences in late Aptian–early Albian time (ca. 114–106 Ma; Fig. 2; Azevedo, 1991; de Matos, 1992).

In order to constrain the effect of the boundary force, we recompute the evolution of numerical models with different forces of 16 and 17 TN m^{-1} but otherwise identical parameters; in both models, the strength-velocity feedback initiates earlier breakup along the EqRS at 23 and 18 m.y. model time, respectively (Fig. 3). However, the duration of the velocity increase remains the same, indicating that it is solely

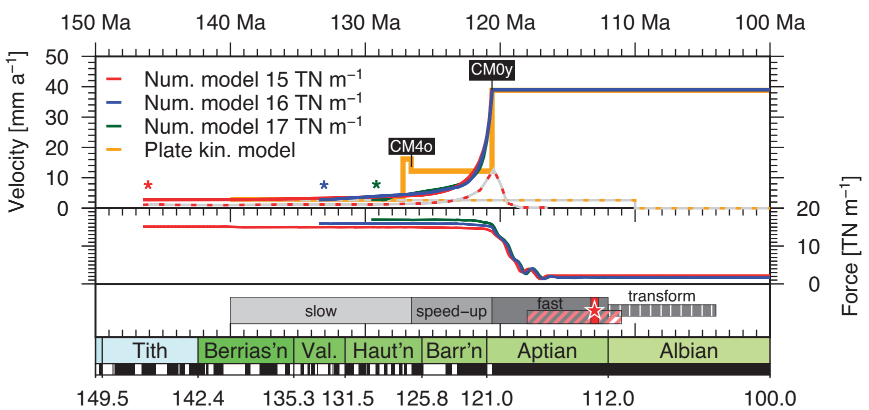

Figure 3. Velocities (top), forces (middle), and continental deformation along Equatorial Atlantic Rift System (EqRS, bottom) for selected forward numerical (Num.) models and plate kinematic (kin.) model (only velocities). Full extensional velocity calculated from plate kinematic model at 37.5°W, 5°S (on present-day South America plate, SAm) relative to fixed southern Africa (SAf). Magnetic anomalies: CM4o—anomaly CM4, old end (126.57 Ma), CM0y—anomaly CM0, young end (120.6 Ma). Stage pole for SAm-SAf rotations is based on cumulative extension in West African Rift System (WARS) and Central African Rift System (CARS) between fit reconstruction (140 Ma) and CM4o position (126.57 Ma), and allows for transtensional motion between SAm and northwest Africa (NWA). Rotations for CM4o–CM0y stage are derived from magnetic anomaly patterns in southern South Atlantic (Heine et al., 2013). Asterisks in upper plot indicate rift initiation time for numerical models. Dashed velocity lines on gray background indicate relative motions between northwest and northeast Africa as proxies for extensional velocities in WARS. Bottom: slow, speed-up, and fast indicate relative extensional velocities between rift onset and breakup along EqRS. Red line and star denote predicted breakup from numerical model. Oblique stripe pattern indicates duration of diachronous breakup along EqRS based on plate model. White vertical line pattern and transform denote transform stage after breakup that occurred along passive margin segments. Time scale shows geological ages; white and black scale below denotes magnetic polarity chrons (black—normal polarity, white—reversed polarity); absolute ages are based on hybrid time scale (Heine et al., 2013). Tith.—Tithonian; Berrias'n—Berriasian; Val.—Valanginian; Haut'n—Hauterivian; Barrem'n—Barremian.

affected by internal rift dynamics. Note that the required force to maintain rifting is relatively high in our models; however, it would decrease drastically if melt generation and dike emplacement were accounted for (Bialas et al., 2010).

WHY THERE IS NO SAHARAN ATLANTIC OCEAN

In conclusion, this joint plate kinematic and 3-D numerical modeling study elucidates the dynamics of rift competition during the final separation of South America and Africa in the Early Cretaceous. We are able to demonstrate that after ~20–25 m.y. of coexistence, strain localization along the EqRS caused the abandonment of the African intraplate rift systems (WARS-CARS) and hence inhibited the formation of a Saharan Atlantic Ocean during the Cretaceous. The success of the EqRS was strongly supported by its higher obliquity (60°), while orthogonal or less oblique extensional domains within the African plate became inactive. After 20 m.y. of slow rifting, a dramatic increase of the relative extensional velocity between the African and South American plates occurred over a short (~6 m.y.) period, followed by fast extension until final separation of the continental lithospheres. Our models suggest that the long period of rift competition was terminated by a severe strength-velocity feedback once the continental bridge between South America and northwest Africa had been weakened sufficiently.

Because rift evolution depends heavily on extensional velocity, we propose that the two-stage extension history of the South Atlantic and Equatorial Atlantic Rift System had a large impact on the evolution of the conjugate West African–Brazil margins in the northern and central South Atlantic segments. The acceleration of the South American plate also correlates with a change to a predominantly compressional regime along the South American Pacific margin, with existing backarc basins being successively closed (Maloney et al., 2013).

Our modeled multivelocity history of the South America plate during continental extension indicates a distinct control on the architectural evolution of the conjugate South Atlantic margin segments with an initial slow rifting episode in pre-Aptian time and subsequently increasing extensional velocities. This is supported by subsidence patterns of marginal basins in Angola and Gabon (Karner and Driscoll, 1999). Our results also call for a reevaluation of the timing of deformation along the frontier conjugate Equatorial Atlantic margins.

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