Influence of Proterozoic Heritage on Development of Rift Segments in the Equatorial Atlantic*

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Abstract

The last phase of Atlantic Ocean opening involved Late Albian rifting and separation of Africa and South America along the Equatorial Atlantic. Prior to the Albian, initiation and northward propagation of sea-floor spreading caused rotation of the South American plate and formation of two main rift systems in NE Brazil and West Africa:

- The Northeast Brazilian Rift System, consisting of the Reconcavo-Tucano-Jatoba (RTJ); Sergipe Alagoas/Gabon (SAG) and
- Cariri-Potiguar (CP) rifts in Brazil and the West- Central African Rift System (WCARS) in Africa.

The Brazilian basins developed inside and around the Borborema Province, a key Proterozoic structure that controlled spatial and temporal differences between these rift systems. Our analysis of a new compilation of onshore and offshore faults of the Equatorial Atlantic led us to the conclusion that the segment bound by the Kribi and Bode Verde fracture zones south of Borborema acted as a link between intracontinental rifting to the north and late rifting stages in the Central Atlantic. During the Albian, this region acted as a ¨buffer zone,¨ balancing, kinematically, in time and space, dextral strike slip rifting in the Equatorial branch, with simultaneous sea-floor spreading in the Central segment. In this article we tie sequence stratigraphic rift sequences to plate kinematic changes described in our new plate model. Attempts to consider the thermal and tectonic evolution of the Central Salt Basins of the South Atlantic as an analog for the Equatorial Margin may lead to wrong predictions in hydrocarbon exploration. The differences in the development of these segments may explain the asymmetry in the distribution of oil and gas reserves along the South Atlantic Margin.

Introduction

Onshore studies of Northern Brazilian basins (Amazonas, Foz do Amazonas, Marajo, Grajau, Sao Luis, and Ilha Nova basins) by Soares et al. (2008, 2011) dated rifting phases from Late Triassic to Albian. The structural styles of the basins were interpreted to be controlled by an interplay between inherited geology during the early rifting stage and by readjustment of the plates at the initiation of the sea-floor spreading (Matos et al., 2017; Krueger 2012; Krueger et al. (2014, 2015a, 2015b). Offshore basins along the Brazilian Equatorial Atlantic margin were previously described as contemporary strike-slip basins, separated by the Romanche Fracture Zone and the northern and southern branches of Sao Paulo Fracture Zone (FZ). We integrated all newly published observations along the margin into a New Plate Tectonic Model, which predicts diachronous development and fits the data, reducing misfit errors along the South American and African margins.

Methodology

This work consists of a compilation of multiple datasets that include: 2D seismic mapping (Krueger, 2012), digitized and edited onshore faults on new tectonic maps of South America (Cordani et al., 2016) and Africa (Meghraoui, et al., 2016), combined with offshore maps from Matos (2000) for South America and from Casey (2014) for Africa. Using our combined seismic data interpretation (Matos, 2000; Krueger, 2012; Casey, 2014) aided by free-air gravity interpretation (Sandwell et al., 2014) (Figure 1) and modeling (Watts and Fairhead (1999), we mapped the limit of oceanic crust on both sides of the Atlantic. Our interpretation was used in the updates for the UTIG PLATES model. We used PaleoGIS software from the Rothwell Group L.P. and the UTIG PLATES Model to restore basement structures and faults from Krueger (2012) together with those from Matos (2004) and Casey (2014) and new structural interpretation of the faults onshore of South America to build the paleogeographic maps for the Lower to Mid-Cretaceous.

Proterozoic Heritage

West Gondwana was a collage of diversified Tonian terranes (1000 – 900 Ma) amalgamated during diachronic Brasiliano/Pan African orogenies (ca. 800 – 500 Ma, Brito Neves at al., 2014). The Trans-Brazilian terranes (TBL) is a complex net of Neoproterozoic mobile belts of Neoproterozoic age, formed as the Brazilian and African cratons moved and collided with the Congo Craton. (Brito Neves et al., 2014). This event is called Brasiliano or PanAfrican. The Brasiliano/Pan African tectonic event produced the main structures of West Gondwana: 1)-The 3000 km-long Trans–Saharan (**TSL**) lineament and 2)-its southward continuation, the Transbrasiliano Lineament (**TBL**, from NW Ceará, in Brazil, all the way to Argentina), also a 3000-km-long shear zone (Figure 2). The **TSL** borders the West African Craton, with associated arc-related Neoproterozoic rocks, ophiolites, and accretionary prisms. The TBL separates the Amazon Craton (Amazonian or pre-Brasiliano domain) from the Brasiliano terranes (Brito Neves at al., 2014). Linked with the **TBL**, the Borborema Province is one important Neoproterozoic cratonic nuclei, formed by a complex framework of orogenic branching system. We named this large polycyclic NNE shear belt in Brazil, and its continuity in Africa, as the Borborema Horsetail Splay (**BHS**) (Fig. 2).

The Transversal Zone (**TZ**) is located in the central domain of the Borborema province (**BHS**) between Patos (**LPT**) and Pernambuco (**LPE**) lineaments; The **LPT** has been recognized as a continental transform linking a recognized magmatic arc at the northern portion of the **TZ** (ca. 635-580 Ma), a product of a Meso- and Neoproterozoic plate-tectonic accretionary processes (Brito Neves at. al (2016),

The eastward extension of the TZ, is represented by the Central African belt or shear zone (**CASZ**), another Neoproterozoic shear zone, a product of a continental collision during which the Nigerian Shield was thrusted onto the Congo Craton.

The Orthogonal Zone (OZ) exploited Neoproterozoic zones of weakness and was active during the Early Cretaceous as initiation and northward propagation of sea-floor spreading caused rotation of the South American plate. To avoid confusion between the Proterozoic kinematic behavior of this Transversal Zone and Cretaceous, here we refer to the Cretaceous kinematic segment as “*Orthogonal Zone*”.

The OZ behaved as a large-scale dextral transfer zone, balancing rift development between the future Equatorial and Central Atlantic branches of the South Atlantic. Two main rift systems in NE Brazil and West Africa formed, exploiting these zones of weakness: 1)- **in Brazil**, the Northeast Brazilian Rift System, consisting of the Reconcavo-Tucano-Jatoba rifts (RTJ); Sergipe Alagoas/Gabon (SAG) and Cariri-Potiguar (CP) rift valleys (Magnavita, 1992, Matos, 1999, Destro et al., 2003; Burke et al. 2003, Brito Neves and Cordani, 1991), and the West and Central African Rift System (WCARS); 2)- **in Africa**, as documented by Brown and Fairhead (1983), Fairhead et al. (2012, 2013), Fairhead and Binks (1991), Fairhead and Green (1989), Hargue et al. (1992), Yandoka et al. (2014), and Yassin et al., (2017). Both rift systems aborted, and final rifting took place along the present day continental margins. This switch was driven by the presence of lithospheric keels under the Nigerian and Borborema shields, not allowing rifting to propagate through them. The last phase of Atlantic Ocean opening finally took place in Late Albian.

Opening of the Equatorial South Atlantic

Initiation and northward propagation of sea-floor spreading in South Atlantic caused rotation of the South American plate with respect to Africa and formation of the two main rift systems in NE Brazil and West Africa. 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; Brune and Autin, 2013; Heine and Brune, 2014). Once yield is reached, hot asthenospheric upwelling and friction softening promote extensive lithospheric weakening (Heine and Brune, 2014).

Basins in and around the Borborema Province records pre-rift and post-rift stages from 145 to 100 Ma. Strike-slip movements in the Equatorial Margin, kinematically linked to the final rifting stages in the Central South Atlantic segment, began during the Aptian (Matos et al., 2017). Therefore, from Aptian to Albian time (120 Ma to 110 Ma) the South Atlantic path of continental rifting moved around the Borborema Province and developed into a system of oblique and narrow rifted basins floored by oceanic crust. Rifts exhibit episodes of transpression and transtension during this phase of deformation controlled primarily by the degree of obliquity of each basin to the plate motion vector (Krueger, 2012). Oceanic crust emplacement in each basin was diachronous. South of the Romanche FZ, outboard of Rio Grande do Norte and Nigeria, oceanic crust began to form around 112 Ma, while north of the Romanche continent-ocean transform fault, oceanic crust emplacement occurred around 110 Ma. Oceanic crust formed outboard of the southeast corner of the Demerara Plateau in French Guiana and Guinea at 116 Ma, at Amapa and Sierra Leone at 114 Ma, and in northern part of Para and Liberia; Piaui, Maranhao, Ivory Coast, and Ghana at 110 Ma (Figure 3).

Concluding Remarks

The Borborema Province - Proterozoic element with a cratonic core and the frame of adjacent Pan African fold belts, (Figure 2) acted as an obstacle to northward-propagating rifting of the South Atlantic, thereby delaying rifting and forcing South Atlantic opening to the east, following zones of weakness on the orthogonal zone. We define the term “buffer zone” as a region where rifting was delayed or slowed as rifting followed a path of thinner continental lithosphere, surrounding lithospheric keels. Once the driving forces from the divergent plate movements (from the evolving Central and South Atlantic) reached a critical point, a lithospheric cutting shear zone developed around the Borborema and Nigerian cratons, defining the silhouette of the future Equatorial Atlantic. Because of the Proterozoic heritage, the South Atlantic Equatorial margins developed intrincate NW-SE geometries, which combined with the South American plate rotation led to the diachronicity of the oceanic crust emplacement (Figure 3).

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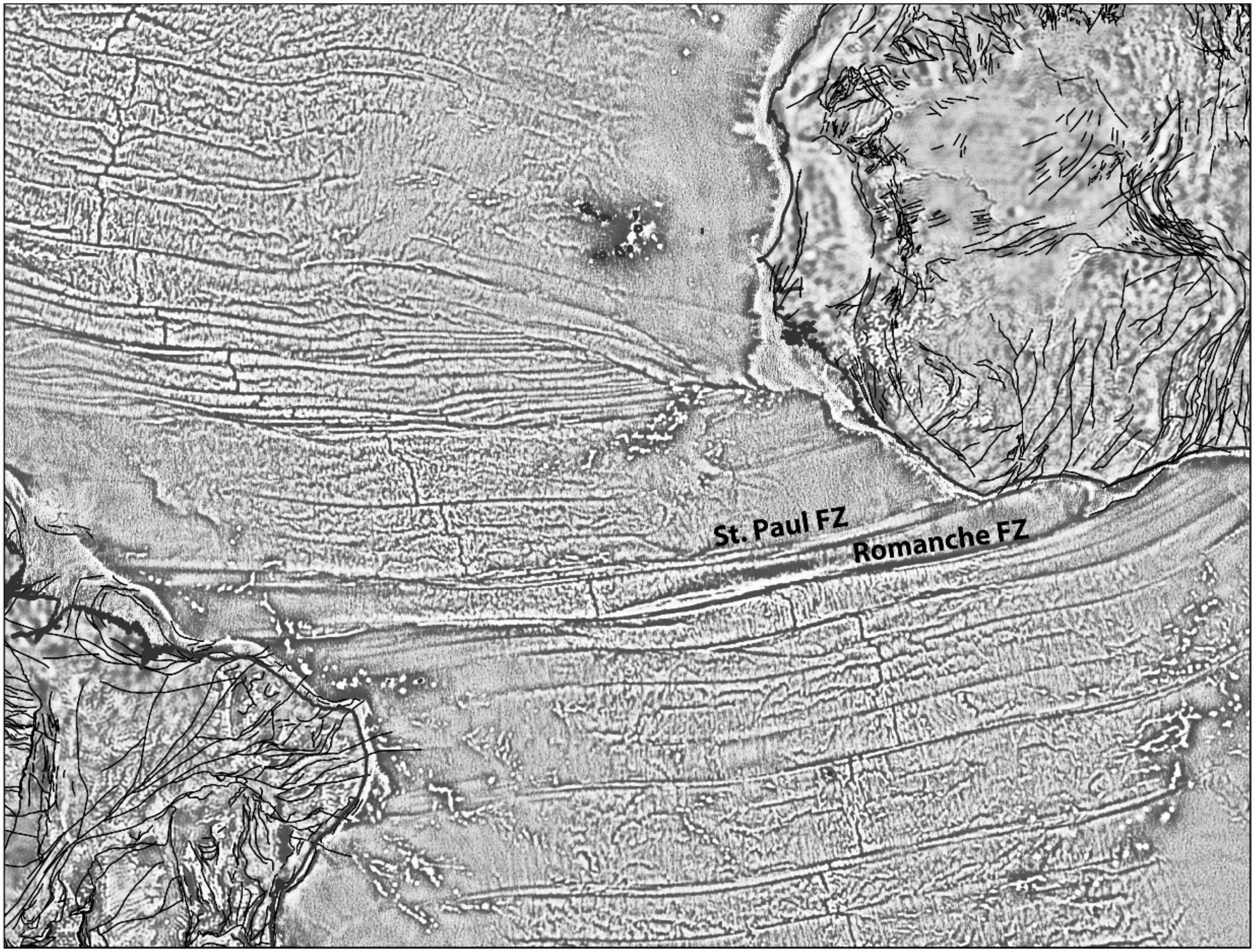

Figure 1. Equatorial Atlantic, vertical gradient of the free-air gravity anomalies derived from satellite altimetry data (Sandwell et al., 2014). Onshore fault interpretation modified from the Commission for the Geological map of the World (CCGM/CGMW) maps of South America (Cordani et al., 2016) and Africa (Meghraoui et al., 2016).

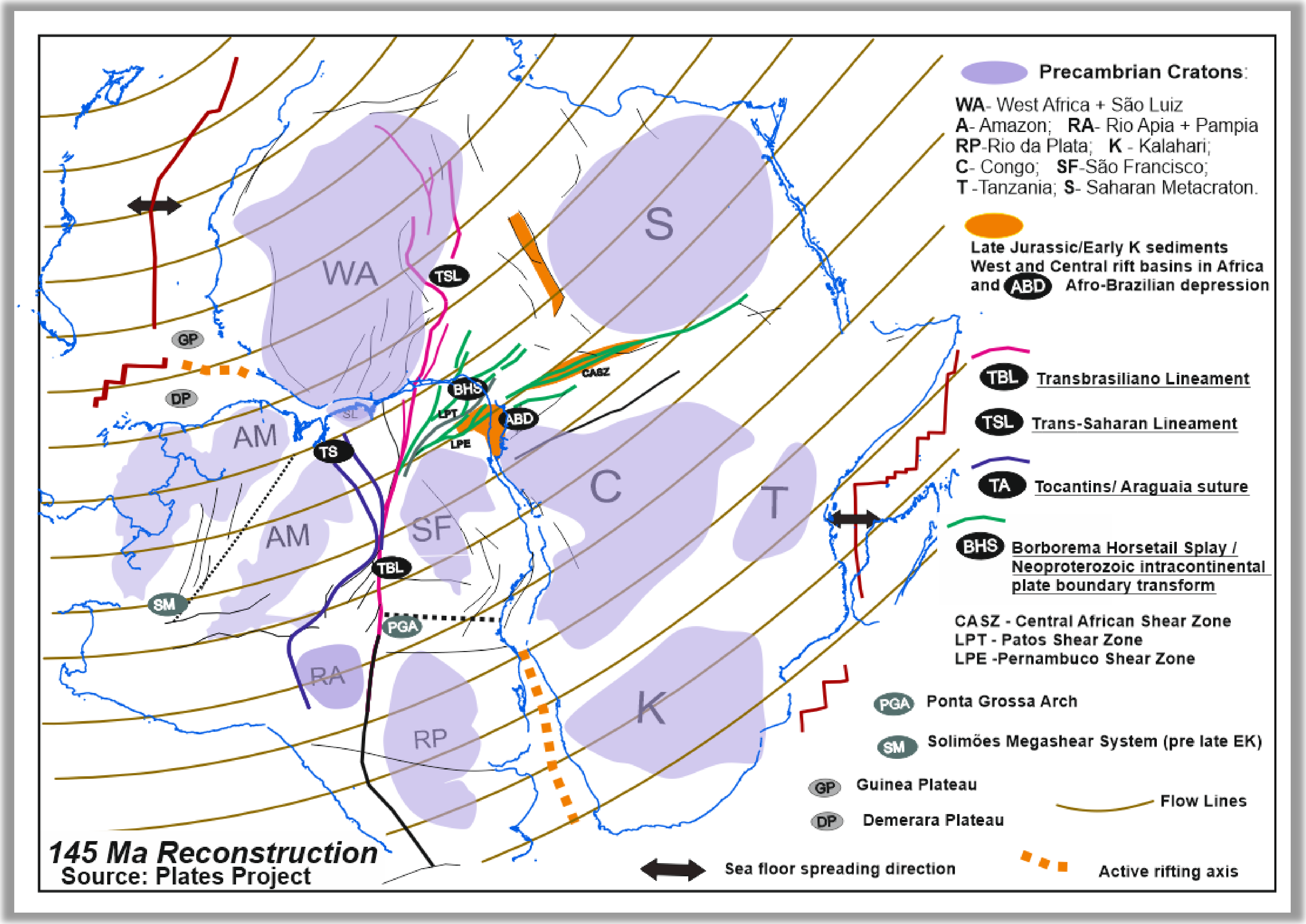

Figure 2. Tectono-structural map of the South Atlantic Ocean at 145 Ma, summarizing main geological terrains and structures that influenced the lithospheric rupture process. Figure also shows the distribution of Pre-rift sediments and active rift axes at 145 MA.

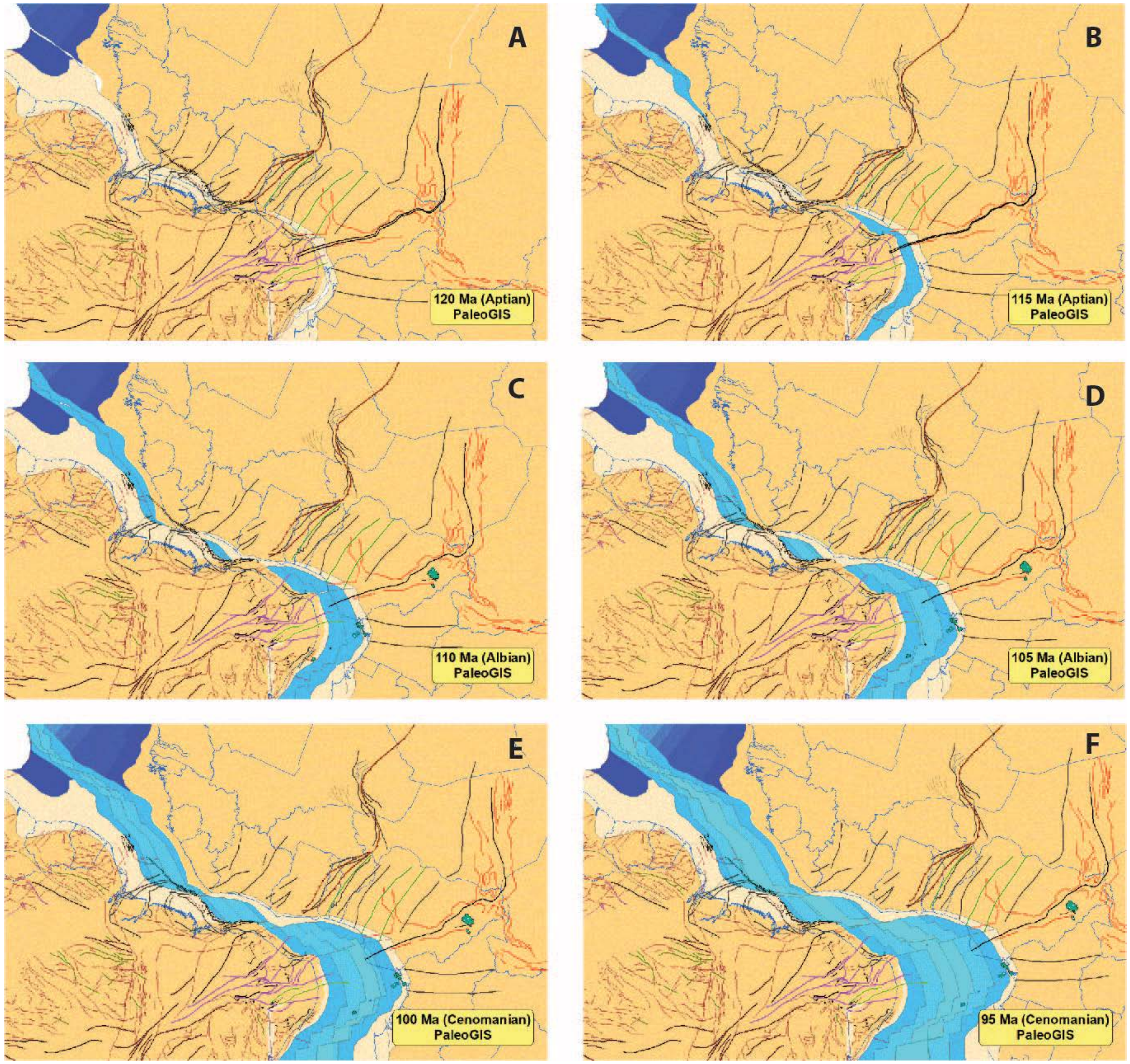

Figure 3. Composite opening of the South Atlantic; restorations for 120, 115, 110, 105, 100 and 95 Ma.