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Research paper

Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift

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A R T I C L E I N F O

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A B S T R A C T

The Early Cretaceous South Atlantic Magmatic Province (SAMP), which includes the Paraná-Etendeka LIP, produced about 8 million km^3 of tholeiitic basalt and diabase over an area of 4 million km^2. Huge pre-salt oil reserves, discovered in 2007 by Petrobras in non-marine carbonates, are estimated at more than 45 billion barrels. Here we show the close causal relationship of the southward increasing width of the wedge-shaped South Atlantic rift with the similarly southward increase in igneous activity, in the thicknesses of non-marine carbonate and salt, and in the size of oil reserves, all controlled mainly by South America's early clockwise rotation away from Africa about a pole in its northeast. Large diabase dike swarms transversal to the rift witness to South America's rotation that opened in its wake the southward widening South Atlantic rift. Westward increasing pressure on the Equatorial margin by South America's clockwise rotation forced open the Benue trough and created pre-late-Aptian folds in the Demerara Plateau and in Brazil's Solimões (Upper Amazonas) basin. Prerift and synrift volcanic activity increases southward, culminating in the Parana-Etendeka LIP and in the offshore volcanic SDRSs that continue southward to the Cape Basin. Berriasian-Valanginian rift sediments deposited from about 145 Ma, 10 Ma before the flood basalts of the Parana-Etendeka LIP. The largest transversal dike swarm continued in the proto-Walvis Ridge that separated the central South Atlantic endorheic rift basin from the sea in the south; erosion and leaching of basalts supplied Ca, Mg, and SiO_2 to the endorheic basin for the deposition of non-marine carbonates and authigenic clays. Basalt flows intercalated with carbonates nearly until salt deposition about 113 Ma. Hypogenic leaching of carbonates by mantle-derived CO_2 created optimal reservoirs. Supergiant oil deposits occur where the widest endorheic basin and the volcanic province overlap.

1. Introduction

The excellent fit of geology between Africa and South America early inspired continental drift (Wegener, 1915; DuToit, 1927) and plate tectonics. Cretaceous rift basins along their facing continental margins showed that South America's eastern margin separated from Africa during the early Cretaceous by a rifting process akin to that now observed in East Africa. The McKenzie model (1978) of rifting as lithospheric stretching by pure shear correctly accounted for syn-rift and post-rift thicknesses in many sedimentary basins along the facing margins of the two continents. An alternative model of stretching the lithosphere by simple shear (Wernicke, 1985) allowed distinguishing between upper and lower plate continental margins.

It remained to be seen how far the stretched continental crust extends below the ocean that now separates the two continents. It was also unclear what caused the southward widening of the South Atlantic rift and early ocean. Finally, what made Gondwana break up after nearly 400 Ma of stability? What was the relationship of the South Atlantic rift to the early Cretaceous large igneous Paraná-Etendeka province? Did the igneous activity weaken the lithosphere permitting its rifting or, conversely, was it the rifting of the lithosphere that permitted the large igneous activity?

Successful petroleum exploration culminated in Brazil in 2007 when Petrobras discovered world-class oil deposits in the presalt carbonates of the Santos and Campos basins (Carminatti et al., 2008, 2009), estimated at 45 billion barrels. The discovery motivated a new wave of extensive surveys such as deep reflection seismic by ION's GX Technology along the Namibian, Argentinian and Brazilian margins, followed by wide-angle and multichannel experiment in the Santos Basin by the SanBa project of Ifremer

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(Aslanian et al., 2013). These surveys, and the rapidly accumulating data from petroleum exploration, provided a rich new database for studies interpreting the South Atlantic: Karner and Gamboa, 2007; Mohriak et al., 2008; Moulin et al., 2010; Magnavita et al., 2011; Zalán et al., 2009, 2011; Blaich et al., 2011, 2013; Aslanian et al., 2009; Aslanian and Moulin, 2010, 2012, 2013; Heine et al., 2013; Almeida et al., 2013; Chaboureau et al., 2013; Stica et al., 2013.

In this paper, we use the terms central segment and south segment of the South Atlantic (Fig. 1) in the sense of Torsvik et al. (2009) and Moulin et al. (2010). We are using the time scale of Gradstein et al. (2012) as modified by the latest version (v2016/04) of the International Chronostratigraphic Chart. Along the Equatorial segment, in the time interval discussed here, rifting barely started; therefore we use the term Equatorial margin for South America's mostly WNW-trending northern margin.

2. The South Atlantic rift formed by clockwise rotation of South America

2.1. Clockwise rotation of South America about a pole in NE Brazil

The separation of South America from Africa (Fig. 1) was incompletely understood because it extended into the Cretaceous Normal Superchron (CNS; 120.6 Ma to 83.5 Ma; Granot and Dyment, 2015). Bullard et al. (1965), fitting the 2000 m bathymetry, showed that the angles enclosed by the Equatorial and South Atlantic margins of South America and Africa differ by about 7°. Based on detailed comparison of linear gravity and magnetic anomalies offshore southern South America and southern Africa, on conjugate sides of the ridge crest, Rabinowitz and LaBrecque (1979) proposed that South Atlantic rifting and early oceanic opening took place in the Early Cretaceous by rigid plate rotation of South America relative to Africa about an Euler pole located offshore NE Brazil, near the eastern end of the Equatorial margin (about 2.5°S 45.0°W relative to South America). According to these authors, rotation opened the southward widening, wedge-shaped South Atlantic, where salt deposited mostly over oceanic crust, while it caused westward increasing compression along South America's Equatorial margin (Fig. 2).

Rabinowitz and LaBrecque (1979) suggested that rifting started about anomaly G at M13 in early Valanginian-late Berriasian time and ended before the end of salt deposition, when the Euler pole moved to a position far north and the South Atlantic started to open along its whole length. Hawkesworth et al. (1992) proposed, also on the basis of magnetic anomalies, that rifting south of the Walvis Ridge-Rio Grande Rise system proceeded from south to north between ~131 and 126 Ma.

Pindell and Dewey (1982) replaced this model of early rotation of South America relative to Africa with one that treated Africa as two plates astride the Benue Trough and the related Early Cretaceous rift and strike slip system of Central Africa. In their model, South America rotated together with West Africa during the opening of the South Atlantic.

The kinematics of the opening of the South Atlantic was reviewed more recently by Torsvik et al. (2009), Aslanian et al. (2009), Moulin et al. (2010), and Heine et al. (2013). Key to the kinematics of the opening of the South Atlantic is the period of rifting during which the continental crust was stretched and thinned

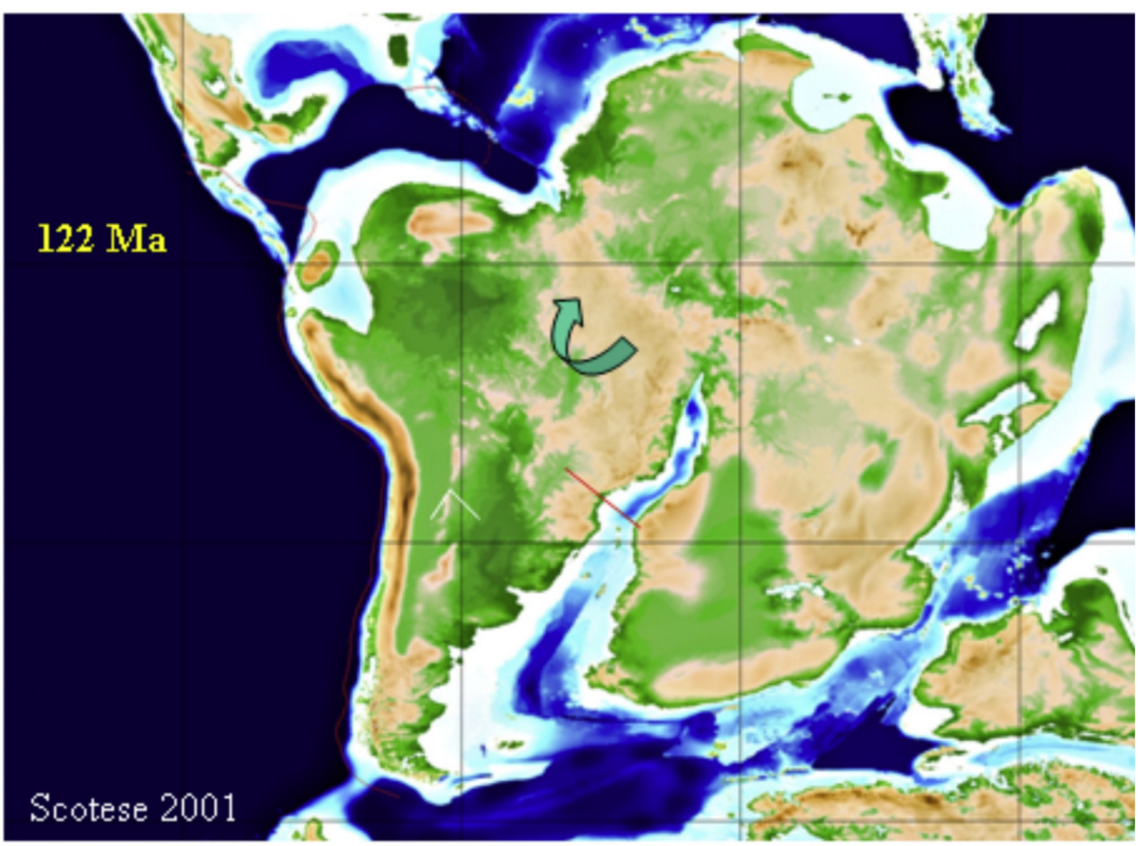

Fig. 1. The rifting of western Gondwana by separation of South America from Africa along the South Atlantic rift, by rotation about a nearby pole. After Scotese, 2001, 2014. Offshore continuation of the Ponta Grossa dike swarm added in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)