# Mantle geophysics of SE-Brazil and Angola Craton margins: tectonic interpretation from electromagnetic and seismological global models.

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## Abstract

In the continental margins along the Atlantic Ocean, there are distinct margin types with their structural and magmatic patterns, and the origin of such variation is still challenging. Features along subcontinental lithospheric margins are not well solved by conceptual models, and therefore they must be continuously updated. In this work, we interpret major aspects of electromagnetic and seismic velocity (P-wave) global models, in averaged lithospheric depths at Brazil-Angola rifting system. The interpretation is accompanied by paleo reconstructions of the geophysical data. As a result, we present reconstructed scenarios from the beginning of the plate's movement (145 Ma) to the establishing of the Rio Grande Rise (~80 Ma), in order to make clear the connection between electrical and seismological anomalies in Brazil and Angola. From geophysical maps, we suggest a broad area of dry mantle in the Central and Southern South Atlantic, and an oceanward continuation of the subcontinental mantle in the Angolan margin.

## Introduction

Rifted Atlantic margins have significant contribution for new concepts of lithospheric breakup, and some examples lead the idea of a subcontinental lithosphere termination under oceanic crust (*e.g.,* Manatschal *et al.*, 2007; Szameitat *et al.*, 2018; Szameitat *et al.*, 2020), instead of a sharp lithospheric boundary.

Concerning the pre-rift setting, the Brazil-Angola rifting system was located along a modern-type orogenic belt. In this work, we discuss possible wide lower plate generated by lithospheric detachment due to the continental lithospheric breakup.

In the pre-rift setting, we can expect high heterogeneity within continental lithosphere due to the successive tectonic cycles (Manatschal *et al.*, 2015). In the continental breakup, the rifting evolution in the Brazil-Angola system (continental margins on Figure 1) had a small volume of magmatic rock due to the decompression of the lithosphere. This magmatic setting is characteristic of the breakup of depleted Subcontinental Mantle Lithosphere (SCML) (Muntener and Manatschal, 2006). Conversely, the region in Southern Brazil (Pelotas Basin; PE on Figure 1) and Southern Angola/Namibia (Namibe and Benguela basins) show a huge pulse of magmatism during rifting. We also highlight the occurrence of rift-related magmatism inboard of the Kwanza and Inner Kwanza basins (Angola) that are placed in the context of magma-poor margin environments (Aragão, 2016). Likewise, in the Southern North Atlantic, the Iberia-Newfoundland system coevals with the normal Central Atlantic oceanic spreading center to the south (*e.g.*, Nirrengarten *et al.*, 2018).

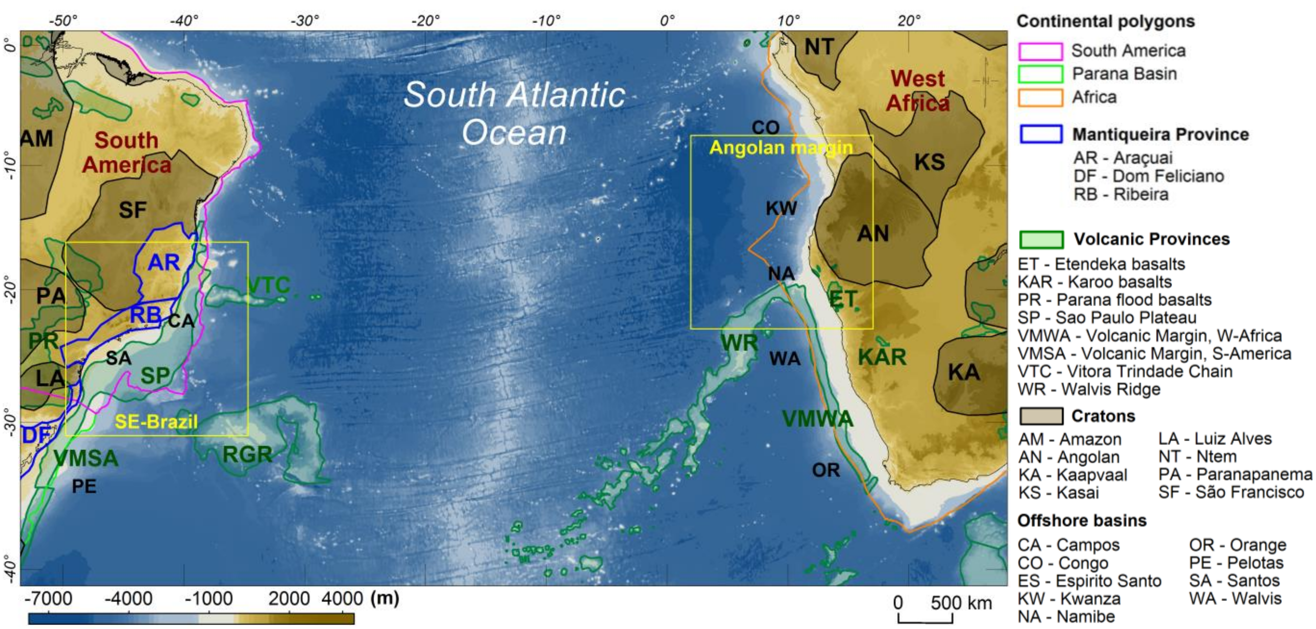


*Figure 1- South Atlantic and study areas. Magmatic provinces from Johansson et al. (2018).*

The age of lithospheric accretion is also considered for continental breakup analysis (*e.g.,* Griffin *et al.*, 2009), since tectonic fabric of younger terranes roughly controlled the location of Atlantic opening (*e.g.*, Vauchez *et al.*, 1997). Actually, thin lithospheric belts tend to trap mantle fluids, promoting basal erosion and fluid infiltration in the lithosphere (*e.g.*, Niu, 2021, O'Reilly *et al.*, 2009).

In this work, the weakness of lithospheric segments were considered according to the SCML types in Griffin *et al.* (2009), as the Angolan upper lithosphere is considered as old and resistant SCLM type (Archon-Proton type; Begg *et al.*, 2009), and the Ribeira Belt is a modern-type domain, which is much more susceptible to breakup.

In Atlantic lithosphere, the existence of SCML fragments under the oceanic crust is sustained by *i.e.* magma contamination from ancient oceanic subductions (*e.g.* Schaeffer *et al.*, 2002; Pires and Bongiolo 2016; Guan *et al.*, 2019; Maia *et al.* 2021; Bonath, 1990; Merle *et al.*, 2012), and unexpected geophysical anomalies, in comparison to a "normal" oceanic lithosphere (*e.g.*, O'Reilly *et al.*, 2009; Schiffer *et al.*, 2020; Szameitat *et al.*, 2020). In the South Atlantic domain, post-rift magmatic provinces that have SCLM contamination may be produced by lithospheric-scale fluid convections, not necessarily with contribution of deep mantle plumes (Colli *et al.*, 2014; Belay *et al.*, 2019).

Regarding the control of upper and lower plates in the Brazil-Angola system, the upper plates have well-developed basins of thermal subsidence ("sag basins"), which are along Campos-Santos and north ward Kwanza basin (Ceraldi and Green, 2017). According to Peron-Pinvidic *et al.* (2019), we consider the SE-Brazilian margin as the upper-plate and the Angolan margin as the lower plate during rifting processes.

Southward Santos Basin, the Pelotas Basin and the conjugate South African margin shows an abrupt change in rifting and magmatic styles, separated by the Florianópolis Fracture Zone in Brazil, and Walvis Ridge in W-Africa. Due to noticeable differences between those margins, they can be referred to as Central and Southern continental margin segments (Meisling *et al.*, 2001).

This work draws attention to the high physical heterogeneity of the Central South Atlantic mantle. From geophysical observations, it is possible to demonstrate that the lithosphere of the distinct continental tectonic provinces could have lateral continuation under the oceanic crust.

## Methods

For geophysical interpretation, we have used data from seismological (P-wave) and electrical conductivity models.

Velocity anomalies are from the P-wave tomography model UUP07 (Amaru, 2007). Not all cratonic SCML segments have positive velocity anomalies, although expected high stability and solidity (Artemieva, 2011). In addition, an experimental study of Schutt and Lesher (2006) argues about negligible deviation of seismic waves caused by cratonic SCLM depletion in major elements. However, spinel peridotites with high-melting extraction can have some effect of P-wave acceleration (0.5% $V_P$ for 20%; Schutt and Lesher, 2006). Therefore, we have prioritized P-wave velocities for this interpretation.

The electrical conductivity model is the GlobalEM-2015 (Sun *et al.*, 2015), a 2x2 degree global 3D inverse model based on records from ground geomagnetic observatories. Electrical conductibility is highly improved by high fluid concentration (*e.g.*, Karato, 2000). On the other hand, dry olivine mantle can be responsible for lowering electrical conductivity, in either ancient continental lithospheres or oceanic high-melting extraction zones (Artemieva, 2011).

The terrane model is based on Sandwell (2021), ca. 1x1 km cell-sized (30 seconds). The land data is based on the USGS SRTM30 data (NASA Shuttle Radar Topography Mission) toghether with the GTOPO30. Data for oceanic area is based on Smith and Sandwell (1997), and some higher resolution data (see description in Sandwell, 2021).

In this work, Atlantic lithospheric mantle thickness is considered up to 200 km deep, according to the following aspects from Artemieva (2011): a depth of 220-250 km for the decoupling of continental lithosphere, as indicated by changes on seismic anisotropy (vertical anisotropy prevail in deep mantle); and the base of the electrical lithosphere about 200-250 km deep. The depths of interpreted slices are close to the averaged lithospheric depth: 90 km for $V_P$ anomaly, and 75 km for the electrical conductivity model.

The paleo reconstructed map allow us to estimate the position of interpreted SCLM segments. We have used GPlates 2.3 for paleo reconstruction (Muller *et al.*, 2018). The envisaged continental plate includes the extended domains of continental crust included in the GPlates package, and alternative interpretation of the continental domain in Aragão (2016). Isochrones on Figure 2 were adapted from Seton *et al.* (2014).

## Results

Analyzed geophysical maps and discussed anomalies are expressed on Figure 2. From the electromagnetic data slice, we defined two main anomalies: Angolan low electromagnetic anomaly (ALEMA) and Southern low electromagnetic anomaly (SLEMA).

On the $V_P$ deviation map, it is noticed an acceleration of P-wave on Angolan Craton, and lowering of velocities under Ribeira Belt. The Southern volcanic margin in South America and Africa does not have similar anomalies.

Both electromagnetic and P-wave anomalies of the Angolan offshore lithosphere have a correspondent fitting under the Ribeira Belt: electromagnetic data have low values off Angolan Craton, but high values under Ribeira Belt; and P-wave deviation is positive off Angolan Craton, but negative under Ribeira Belt.

From paleo-reconstructed scenarios, the offshore continuation of Angolan SCLM have a good fitting under South America on pre-rift setting (Ribeira Belt and Central-Northern Parana Basin in Brazil; 146 Ma black polygon on Figure 3). Regarding the African margin architecture, the interpreted offshore extension of SCLM is under the extended crustal domain in Aragão (2016).

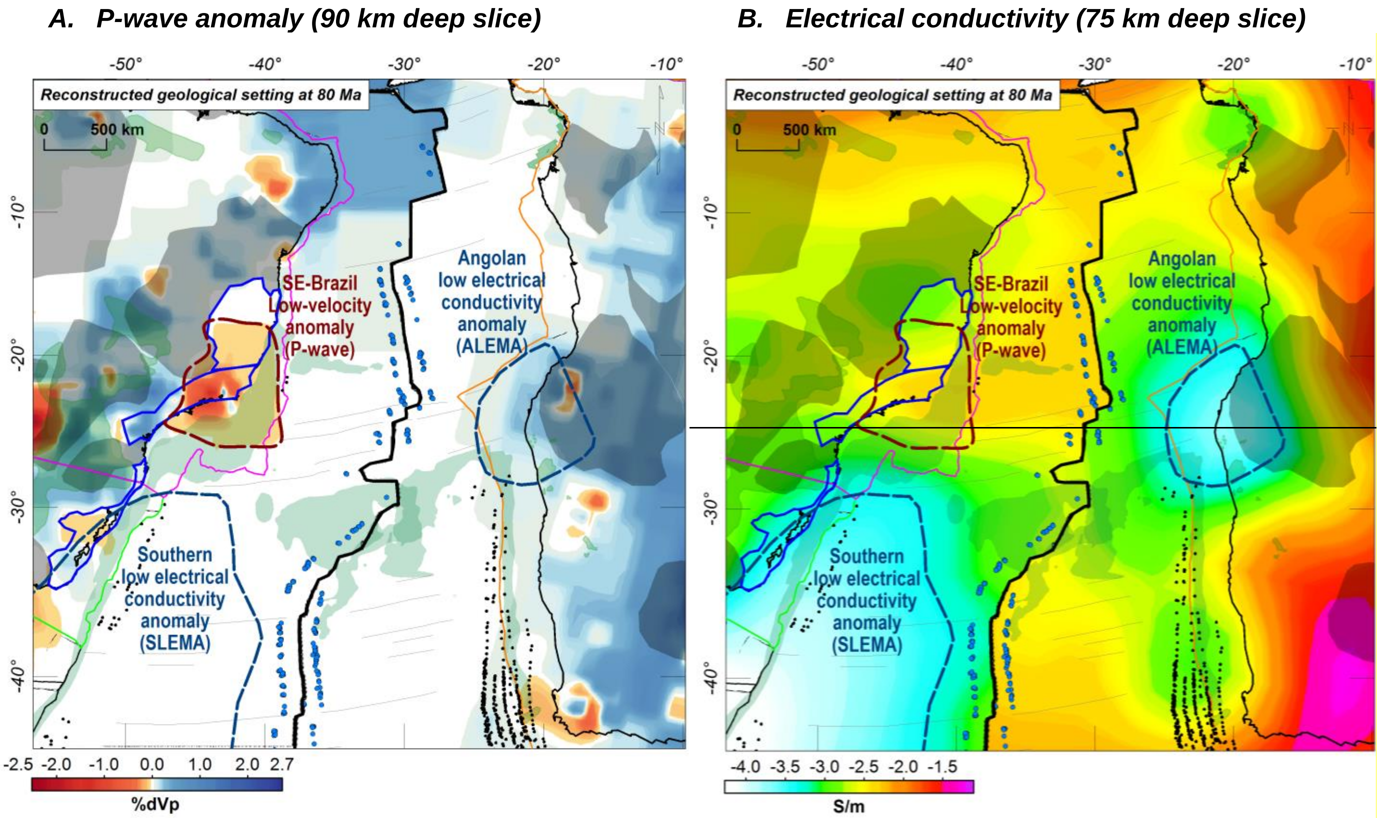


*Figure 2 – Interpreted geophysical slices of seismic tomography (A) and electrical conductivity (B). Blue dots are picked anomalies of the end of C34 isochron, and black dots are older marine magnetic anomalies, from the data compilation by Seton et al. (2014). Other features: legend on Figure 1.*

In the applied paleo reconstruction model (Scotese *et al.*, 2016), the first analyzed phase starts at 145 Ma **(Phase 1, 140-120 Ma;** Figure 3). From 140 to 120 Ma, the SCLM block in ALEMA drifts to ESE (98-102N azimuth) with relatively low velocity (less than 2 cm/year), and the lithospheric block in ALEMA gets off the Brazilian continental crust. This phase coevals with the Rift Phase on Santos basin. From the continental breakup to ~120 Ma (Early Aptian), ALEMA and SLEMA have developed a kind of ESE-WNW strike-slip zone between Santos and Pelotas basins.

During **Phase 2 (120-110 Ma)**, the change on relative movements between South American and African plates (direction and drifting velocity) around 120 Ma was followed by the onset of oceanic spreading in Walvis Basin (W-Africa) and magmatic events on São Paulo Plateau. In this time interval, the anomalous SCLM block is underneath Santos basin. During this phase, the velocity magnitude progressively increases from ~2 to ~6 cm/year, exactly when the anomalous block gets off the continental area and reaches the region of the future Santos Basin. Additionally, the kinematic Phase 2 is accompanied by the deposition of post-rift packages and the beginning of the drift phase. By the end of this phase, the spreading ridge jumps from Abimael Propagator to the east (~112 Ma).

Finally, during **Phase 3 (110-83 Ma)**, the anomalous SCLM block drifts out of Santos-Campos basin area. This phase shows accelerated plate drift, while the mantle block in ALEMA is out of Santos basin area. During this phase, the onset of Rio Grande Rise and Walvis Ridge magmatic provinces have occurred.

**Discussion**

According to the outcropping geology, ALEMA (nearby Angolan Craton) and SLEMA (Pelotas Basin, Dom Feliciano Belt and vicinities) areas have diverse lithospheric composition and rifting evolution (*e.g.*, Meisling *et al.*, 2001). However, their low electrical conductive areas in the mantle can be reconstructed as a single anomaly in the pre-rift scenario, which was splitted in the Ponta Grossa Arch area.

In the case of the Angolan area (AN), the cratonic nature of the SCLM may contribute to lowering the electrical conductivity (Artemieva, 2011). A pre-rift relationship between ALEMA and SLEMA can be farsighted by linking LA and AN cratonic areas (Bruno *et al.*, 2019). However, the wide SLEMA mantle encompasses the Dom Feliciano Belt and Pelotas Basin, which are modern-type terranes. As a result, we consider that ALEMA and SLEMA origin is not related to their lithospheric origin.

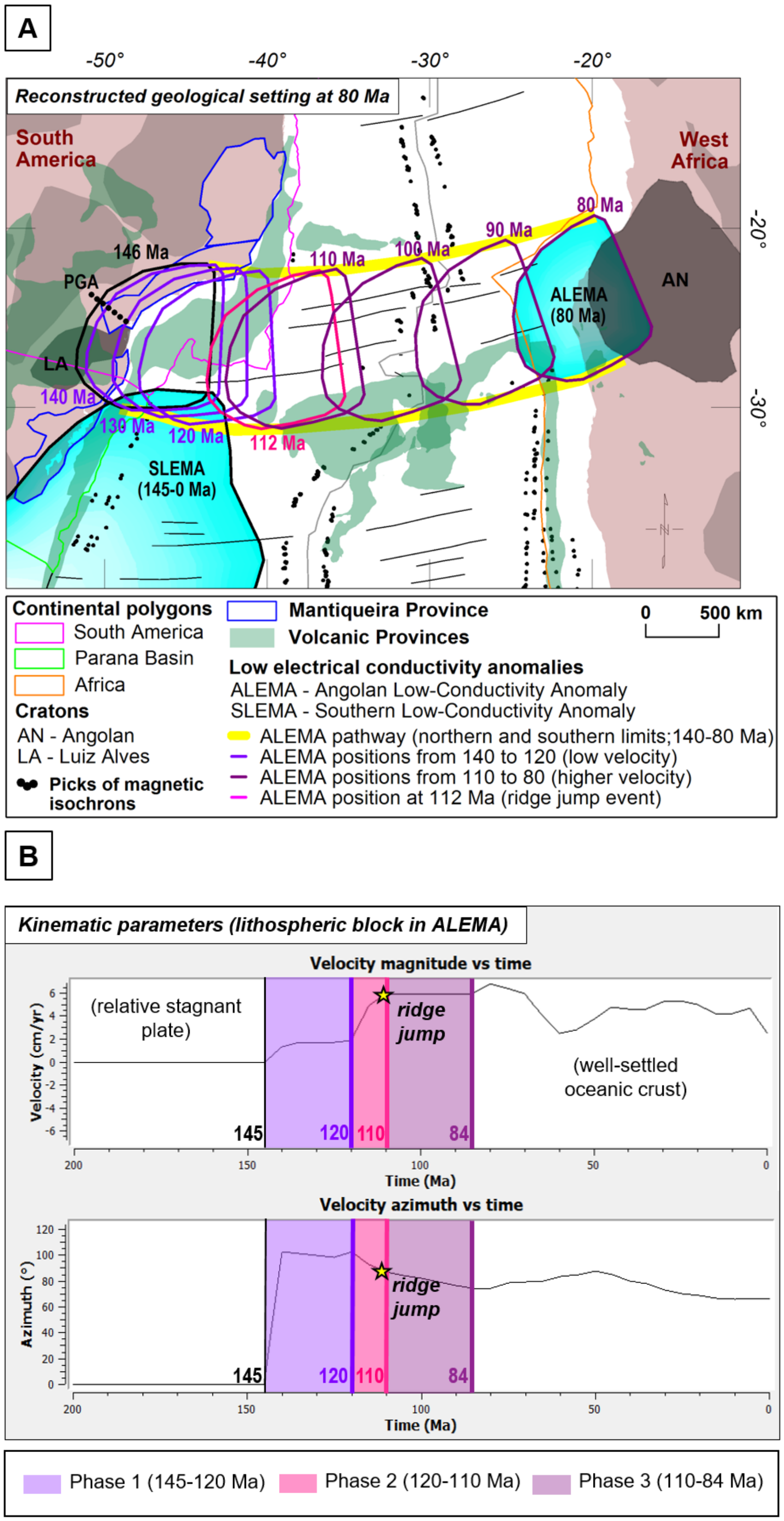


*Figure 3- Kinematic evolution of anomalous SCLM in ALEMA area. A. Horizontal pathway of ALEMA from 145 Ma to the beginning of the unquestionable oceanic crust and the onset of the Rio Grande Rise (80Ma), according to Johansson et al. (2018). PGA: Ponta Grossa Arch. B. Changes in velocity magnitude and azimuth, and kinematic phases through the time.*

Regarding the critical role of fluid content on changing electrical properties (*e.g.*, Karato, 2000), we interpret the low electrical conductivity anomaly in the mantle as caused by high melting depletion. We observe the agreement of both low electrical conductivity domains with voluminous magmatic events in this area (pre-, syn- and post-rift; figures 2 and 3). Large-scale volcanic events are listed as follows:

a) Floods of the central Paraná-Etendeka Large Igneous Province (LIP), and related dyke swarms in Brazil. They are coincident in geographic position with the pre-rift ALEMA, and the lithospheric strike-slip motion between ALEMA and SLEMA. Also, Serra Geral floods stated about 140 Ma on Central-Northern Paraná floods sub-province (Licht *et al.*, 2018);
b) Extrusive magmatic activity over SLEMA mantle during the Mesozoic breakup in Pelotas Basin (~130-112 Ma, Imbituba and Curumim formations; Stica *et al.*, 2014);
c) Pre-rift magmatic units over reconstructed ALEMA position in Santos (Camboriú Formation; Moreira *et al.*, 2007) and Campos (Cabiúnas Formation; Winter *et al.*, 2007) basins;
d) The pathway of ALEMA's lithospheric block hosts volcanic provinces (Figure 3), such as Rio Grande Rise and Walvis Ridge to the south; and further volcanic buildings of Vitoria Trindade Chain (VTC) and Abrolhos to the north.

About the faulting-like lithospheric movement, the expected mechanism for shallow lithospheric deformation is dislocation creep (creation of slip planes in the crystalline lattice), and diffusion creep (diffusion of atomic vacancies) deformation for >50 km deep mantle and lithospheric weak planes; Heron *et al.*, 2019 and references therein). However, studies from Eaton *et al.* (2009) proposed that dislocation creep might rule deep lithospheric deformation under dry mantle conditions. Despite of that, orogenic environments leave a plane of weakness that can be reactivated during the lithospheric breakup (Heron *et al.*, 2016; Heron *et al.*, 2019)

The African Continental plate shows noticeable change in velocity magnitude between 120 and 110 Ma. This time interval overlaps the period when ALEMA leaves the continental crust of the Santos Basin. The end of this interval is accompanied by the change of the continental drift direction (110 Ma), and the oceanic ridge jump in Santos Basin (~112 Ma), towards abandoning the Abimael Propagator (*e.g.*, Kukla *et al.*, 2018).

The tomographic model of $V_P$ deviation adds an independent suggestion of offshore continuation of the SCLM. The occurrence of SCLM under the South Atlantic crust was previously indicated by high S-wave velocities (O'Reilly *et al.*, 2009), interpreted as in-place SCLM and buoyant segments of it offshore. Conversely, we assume a roughly maintenance of a SCLM segment attached to the Angolan Craton, incorporated from the nearby Ribeira Belt. It implies lithospheric delamination of the Brazilian SCLM. In accordance with this interpretation, the conjugated margin (Campos and Santos Basins) has a low $V_P$ anomaly under the Ribeira Belt. In this case, the removal of Ribeira Belt roots created a lithospheric "vacancy" and the access of mantle fluids and enriched mantle material.

The proposed interpretation adds complexity to the lithospheric breakup in the Central South Atlantic. However, a complex tectonic evolution may justify discrepancies on tectonic reconstructions between SE-Brazil and W-Africa (*e.g.,* Aslanian *et al.*, 2009). These observations show the importance of considering the variability of physical properties of lithospheric terranes for mapping tectonic plates and for studying magmatic processes.

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