Geoscience Frontiers
Article In Press
Acceptation date : October 2024
https://doi.org/10.1016/j.gsf.2024.101934
https://archimer.ifremer.fr/doc/00913/102512/

Paleogeographic significance of unknown hyperextended continental crust in South Atlantic conjugated margin

Teixeira C.D. [1, *], Girelli T.J. [1], Serratt H. [1, 2, 3], Oliveira H.O.S. [1], Cruz M.F. [1], Conti B. [4], Rodriguez P. [4], Chemale F. [1]

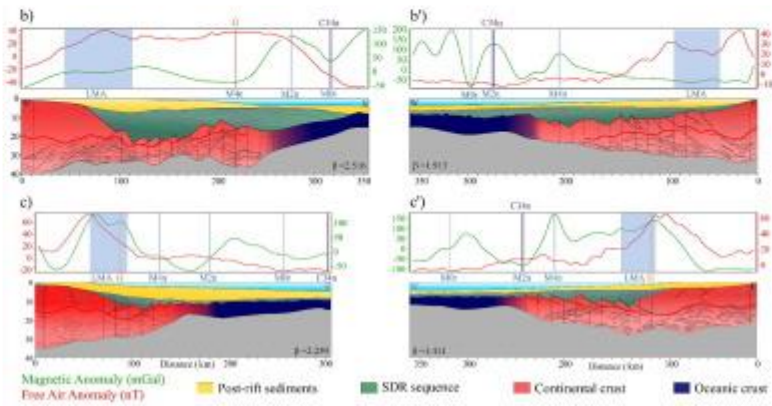
[1] Geology and Geophysics Research Group – NGA, Universidade do Vale do Rio do Sinos, São Leopoldo, RS, Brazil
[2] Geology Graduate Program, Universidade de Brasília, Distrito Federal, Brazil
[3] UMR CNRS-IFREMER-CNRS-UBS 6538 Geo-Ocean, IUEM, Université de Bretagne Occidentale, France
[4] Exploration & Production, ANCAP, Montevideo, Uruguay

* Corresponding author : C. D. Teixeira, email address : claudiadtx@gmail.com

Abstract :

The paleogeographic reconstruction of fragmented and dispersed continents often poses a challenge due to the lack of information regarding the nature of that extend beneath passive margin basins. To define the width of the continental crust beneath passive margin basins and its implications for paleogeographic reconstruction of conjugate continental margins, this study investigates the architecture of the stretched continental crust of the southern South Atlantic conjugate margin. The investigated region encompasses South Africa, Namibia, southern Brazil, and Uruguay, which were formed during the Mesozoic rifting of SW Gondwana. Employing a multi-tool approach combining seismic interpretation, gravity, magnetometry, and U-Pb isotopic data, the research aims to quantify the extension of stretched continental crust and its implications for plate reconstructions. The study reveals that the restored stretched crust spans at least 150 km, emphasizing the significance of considering connections between both margins for realistic paleogeographic reconstructions. Furthermore, the distinct U-Pb zircon age distribution patterns between SW Africa and SE South America reinforce the lack of direct connections despite their Gondwanan origin. The missing link estimated in this study is around 150 km, comparable in size to major mountain ranges such as the Andean or Urals. This work sheds light on critical aspects of Earth's dynamic crustal evolution and emphasizes the need for comprehensive reconstructions considering stretched and eroded crust in the South Atlantic conjugate margin

Graphical abstract



Highlights

► A multi-tool approach reveals at least 150 km of hyperextended continental crust. ► This study highlights the significance of stretching in reconstruction studies. ► Distinct U-Pb zircon age distribution patterns reinforce the lack of direct connections. ► New insights on the dynamics of hyperextended crust. ► A significant portion of the Brazilian/Pan-African orogenic belt is hidden beneath passive margin basins.

Keywords : Hyperextended continental crust, Reconstruction, South Atlantic Ocean, Passive margin, Gondwana

1. Introduction

Throughout the last decades, several studies were carried out on rifted continental margins and hyperextended continental crust in the passive margin, providing knowledge on this topic in the different magma-poor, magma-rich, and sediment-rich passive margins (e.g., Peron-Pinvidic et al., 2013; Doré and Lundin, 2015; Lei et al., 2020). Many of these studies have specifically focused on the extension at rifted continental margins in association with the South Atlantic opening, offering valuable insights into the tectonic evolution of this region (e.g., Rabinowitz and Labrecque, 1979; Moulin et al., 2010; Granot and Dyment, 2015; Chauvet et al., 2021). Although geoscientists understand this process well, accurately determining its impact on paleo-plate reconstructions remains challenging. The challenge lies mainly in precisely characterizing the amount of continental crust stretched. It occurs due to the sedimentary and volcanic package cover over the stretched continental crust (Mutter et al., 1982; Sutra et al., 2013; Nirrengarten et al., 2018). To address this, gravimetry, magnetometry, and seismic data play a crucial role in providing information essential to understanding the dynamic processes shaping the Earth's crust. This information helps create realistic paleogeographic reconstruction models and define subsurface geological structures in conjugate margins separated by the formation of oceans. Regarding this scenario, the South Atlantic Conjugate Margin (SACM), comprising South Africa, Namibia, southernmost Brazil, and Uruguay, provides an ideal opportunity to better understand the effects of stretched crust on paleo plate reconstruction (Fig. 1).

The South Atlantic conjugate margins exhibit significant asymmetry, with uneven extension documented in this region and observations showing significant crustal architecture asymmetry, SDR type distribution, and total volume of SDR (Chauvet et al., 2021). This asymmetry is a crucial consideration in understanding the evolution of the margins and the distribution of stretched continental crust. Quantifying the extent of asymmetric extension is challenging, but it has significant implications for plate reconstructions and understanding the geological history of the region.

Our study aims to quantify the extension of continental crust stretched during the rifting process of SW Gondwana and better understand the impact of this in plate reconstruction models. We combined regional seismic interpretations, gravity, and magnetometry data from the South Atlantic Ocean and onshore emerged margins. Additionally, focusing on evaluating the impact of the lack of geological structures between both sides, we did a comparative analysis based on U-Pb isotopic data from zircons grains in emerged margins. Based on the results obtained by this multiple-tool approach, we could identify that the amount of stretched crust is at least 150 km. Furthermore, the U-Pb data reinforce the lack of direct correlation between these margins, which would be lost in this stretched interval. This study sheds light on three questions: (i) The absence of direct structural correlation between structures in SW Africa and SE South America; (ii) The presence of hyperextended crust on volcanic passive and sedimentary rich margins; (iii) It is critical to consider the structural ties between both margins to discuss the Precambrian tectonic evolution models.

2. Geological settings

The Gondwana history is a common point in the geological history of Africa and South America. The formation of the Gondwana paleo continent took place during the Neoproterozoic era (Veevers, 2004). Our study area (Fig. 1) was affected by the subduction of the Adamastor Ocean during the Gondwana formation (Veevers, 2004; Caxito et al., 2022). This significant event is recorded in the Pan-African/Brasiliano orogenic belts of South America and Africa (e.g., Chemale et al., 2012). This orogenic cycle profoundly influences the NE–SW structures in the southernmost regions of Brazil and Uruguay margins (Fernandes et al., 1994).

Meanwhile, consensus regarding the subduction direction remains elusive (Basei, 2000; Chemale, 2000), as does the paleogeographic reconstruction of the various orogenic belts from the Neoproterozoic to the Eopaleozoic. This uncertainty is primarily due to a lack of petrotectonic assemblages and more complete rock associations (e.g., juvenile arcs and ophiolites). One of the key areas of interest is the underlying continental crust of the passive margin basin, about which we have little information regarding the nature of these rocks. The local process of Gondwana's break-up unfolded within these structures, as observed by the margin, and aligned parallel these structures in southernmost Brazil and Uruguay. Even the emplacement of syn-rift magmatism during the rifting of the SW Gondwana is intricately linked to these pre-existing structures, which should be considered as the primary magmatic conduit of the SDR (Seaward Dipping Reflectors; Fig. 2; Chauvet et al., 2021; Serratt et al., 2022).

The studied sector is formed of a Precambrian basement that comprises in the eastern side the Kaoko, Damara, and Gariep belts (Begg et al., 2009; Frimmel, 2009; Haas et al., 2021) and in the western sector, the Dom Feliciano Belt (Basei, 2000; Chemale, 2000). The Damara Belt is associated with the docking between the Congo and Kalahari cratons, with an NE–SW direction and subduction towards the north under the Congo Craton (Prave, 1996; Passchier et al., 2002). The Kaoko Belt is characterized by dominantly E–NE-oriented structures and subdivided into eastern, central, western, and southern zones (Miller and Grote, 1988; Porada, 1989). The Gariep Belt is related to a part of the larger network of Pan-African/Brasiliano orogenic belts in SW-Gondwana (Frimmel, 2009). In turn, the NE–SW Dom Feliciano Belt records the docking between Rio de La Plata and Kalahari cratons with main structures-oriented NE–SW (Hartman et al., 2007; Phillip et al., 2016; Basei et al., 2018; Will et al., 2020). These Precambrian belts were partially covered by Phanerozoic sedimentary basins, such as Paraná and Cape-Karoo (e.g., Milani et al., 2008).

This supercontinent, formed during the Neoproterozoic and later incorporated in the Pangaea supercontinent, was fragmented throughout the Cretaceous, giving rise to the conjugate margin of southwestern Africa and southeastern South America. The onset of rifting was marked by extensive magmatism of the Paraná-Etendeka Large Igneous Province (LIP), approximately 134 million years ago, associated with the Tristan da Cunha plume (Gomes and Vasconcelos., 2021). This fragmentation process propagated from the south to the north, forming the Walvis Ridge at around 127–133 Ma (Macdonald et al., 2003; Torsvik et al., 2009; Heine et al., 2013), recording the movement of the African Plate over the mantle hot spot during the separation of the African and South American continents and the formation of the South Atlantic Ocean. This LIP magmatism was preceded by the SDR magmatism, recorded in both margins, and that characterizes both margins as Volcanic Passive Margins (Chauvet et al., 2021; Serratt et al., 2022). The rift and drift sedimentation in the studied sector originated in the offshore basins of Orange, Luderitz, and Walvis in Namibia and Pelotas and Punta del Este in Brazil and Uruguay.

3. Methods and materials

The accurate determination of lithospheric stretching requires a comprehensive, multi-tool approach. Our study employed seismic interpretation as a robust tool for measuring lithospheric stretching, which provided detailed insights into subsurface structures. Additionally, we complemented this approach with gravity and magnetic profiles. The integration of potential data delineated the boundaries of lithospheric stretching, offering a robust understanding of the geophysical characteristics that result from the stretching processes. Lastly, we compared the analysis of U-Pb isotopic data from zircons grains in the emerged margins.

3.1. Lithosphere stretching

The methodology employed for calculating lithosphere stretching encompasses seismic line profile interpretation previously published by Chauvet et al. (2021), crustal thickness estimation, and the calculation of stretching factors, utilizing the concept of "half-space stretching" to ascertain the lithosphere stretching factor (β; McKenzie, 1978), identifying the crust limits, followed by the determination of both non-extended and stretched crustal thicknesses. The stretched crustal thickness is measured from the base of the SDR layer to the Moho boundary. The non-extended thickness was measured as the entirety of the crustal thickness extending inland from the crustal necking. Thickness measurements are taken at various points along seismic profiles. Subsequently, the stretching factor (β) is estimated by considering the thickness ratio between the non-extended and post-extension transition crust (McKenzie, 1978).

To precisely delineate the regions of lithospheric stretching in each seismic profile, we conducted correlation analyses with magnetic and gravity responses using the Free Air anomaly grid from Sandwell et al. (2014) and the Magnetic Anomaly grid from Maus et al. (2009). This correlation allowed to match previously published magnetic anomalies by Rabinowitz and Labrecque (1979; G, M3, M0) and Moulin et al. (2010; LMA, M4, M2, M0) to delineate with more precision the regions with lithospheric stretching.

Our restoration of the stretched continental crust assumes that volcanic dykes comprise 50% of the total volume, based on observations from other volcanic passive margins (Myers, 1980) and supported by seismic, potential, drilling data from the region (Harkin et al., 2020; Serratt et al., 2022). As shown in Fig. 2, the drilling data reveals that the stretched crust consists of volcanic rocks interlayered with pyroclastic and/or sedimentary rocks. The 50% here assumed is the maximum estimation in the Myers study, so based on this, we used this number to have the less extrapolated value. The presence of extensive volcanic dykes and interlayered volcanic and sedimentary rocks can obscure the underlying continental crust, making it difficult to assess its characteristics.

3.2. Isotope record

The use of zircon databases combined with geological data is a powerful tool for estimating the cumulative growth of continental crust and discriminating the source area of different geological terranes. To compare the major source rocks for the onshore basement rocks of the studied conjugate passive margin, we use the U-Pb zircon databases of southern South America and SW Africa. For the South American margin, we compiled 16,692 individual analyses over a hundred studies conducted since 1985 in southern Brazil and Uruguay shields. Similarly, a comprehensive dataset of 16,005 individual analyses from SW Africa, encompassing Pan-African Belts and cratonic areas, was compiled by Puetz (2018) and Puetz et al. (2021). From these data, 7953 in southern Brazil and Uruguay and 2187 in Namibia correspond to zircons in igneous rocks.

3.3. Gravimetric and magnetic data

Gravity and magnetic anomalies provide constraints on the structure of the Earth's crust. It can help to detail their structural connections by integrating these data into the reconstruction.

We reconstruct the pre-to-early stretching process before oceanic crust formation at 150 Ma using GPlates based on the rotational poles from Müller et al. (2019). We analyze the marine gravity and magnetic anomalies preserved on the South American and African plates using the Earth Magnetic Anomaly Model (Maus et al., 2009) and the Satellite Free-air Gravity Anomaly data (Sandwell et al., 2014).

4. Results

The connections between East South America and West African margins have been known since du Toit (1927), and hundreds of research studies improved this knowledge throughout the last century. Nevertheless, despite these efforts, certain geological gaps remain open. Since the development of GPlates Software (Müller et al., 2018), the representation of plate tectonic positions and motions has been substantially improved. In South America and Africa, the stretching process begins at 155 Ma in the southernmost portion, southward of the study area (Jokat et al., 2003). Using this as a time constraint and based on the rotational poles from Müller et al. (2019), we reconstructed the pre-to-early stretching process before oceanic crust formation at 150 Ma (Fig. 3). The reconstruction carried out incorporating the magnetic and gravimetric data to the block models allowed us to establish the lack of a clear connection between structures in both margins. The lack of a direct link raises questions about the extent of the crustal loss during the break-up.

The clues for the lack of a direct connection between these two continents begin to be clear when we interpret the seismic lines from both margins. Through the regional seismic lines in the North Pelotas Basin (Fig. 3a), it is possible to observe the SDR's below the drift sedimentary rocks, represented in detail by the basalt drill core on the right and above the stretched continental crust. A similar pattern can be observed in the Luderitz Basin (conjugate margin, Fig. 3b). So, in the southern South Atlantic Ocean, a hyperextend continental crust occurs below a thick volcanic and sedimentary package of Cretaceous to recent rocks (Fig. 3), as already described by Chauvet et al. (2021). However, determining oceanic and continental crust boundaries in volcanic passive margins is challenging, and it is key information for continental crust restoration. Knowing this, we used previously published magnetic anomalies M2 and M4 (Rabinowitz and Labrecque, 1979; Moulin et al., 2010) to help define these boundaries. The first opening stage occurred between chrons M4 and M2, and the magnetic anomaly M2 denotes early oceanic crust formation (Koopmann et al., 2014; Fig. 3). This initial stage was characterized by basement flexure, proximal SDR deposition, and high-amplitude magnetic anomalies (Serratt et al., 2022). Based on this, we could measure the continental crust that spans up to 450 km beneath the volcanic and sedimentary deposits of the passive margins.

Using this information on continental crust offshore extension, we quantified the pre-drift margin width by the calculated stretching factor. We divided the margin into two main domains: Unstretched Continental Crust (UCC) and Stretched Continental Crust (SCC) (Fig. 3 and Table 1). For the present study, we attributed the (β) as close to one for the unstretched sector, and the information about the extension of this crust is important in quantifying the total crustal gap between the onshore portions. In turn, the stretched sector (SCC) was also measured because it is important to understand the amount of stretched crust that can be restored (Table 1). The restored crust process of stretched crust considered the estimated volcanic dikes (up to 50%; see discussions) and the stretching factor (Table 1). Four sections were used for the present study: two on the South American margin (Fig. 3b and c) and two on the SW Africa margin (Fig. 3b' and c'). These sections show a stretched continental crust covered by the passive margin sedimentary rocks and SDR basalts. The section b, situated in the Pelotas Basin

(PB), displays a stretched continental crust of 177.04 km, while the section of the conjugate margin (Fig. 3b') in the Walvis Basin (WB) has an estimated stretched crust of 187.06 km. Considering the continental crust extension, the conjugate b–b' the crustal stretching factor (β) in the South American margin is between 2.52 in the north Pelotas Basin and 1.91 in the Walvis Basin. The restored for each margin is 74.68 (PB) and 95.72 (LB; Table 1), and the final gap results from the sum of unstretched and restored crust for each side reaching in b–b' the section between northern Pelotas and Walvis basins with 170.40 km (see section b–b' in Fig. 3a).

The conjugate c–c' profiles exhibit a stretched continental crust (SCC) of 110.90 km for the Punta del Este Basin profile (PLB; Fig. 3c) and 229.57 km for the Lüderitz Basin profile (LB; Fig. 3c'). The values on the eastern Atlantic margin are from 1.91 in the Walvis Basin and 1.41 in the Luderitz Basin. The restored margins width range between 141.19 km and 123.37 km, respectively, in the Punta del Este (Fig. 3c) and Lüderitz (Fig. 3c') basins (Table 1). The final gap results from the sum of unstretched and restored crust for each side reaching in b-b' the section between Punta del Este and Lüderitz basins with 267.56 km of gap, taking into account the 50% of suppression in the stretched crust.

We compare the tectonic similarities between these regions by analyzing the distribution of zircon age patterns in the onshore rocks from the conjugate margins of southern South America and SW Africa. A compilation of 16,592 zircon grains from Southeast South America and 16,005 from southwestern Africa offers a comprehensive overview of the main crustal cycles in both areas (Fig. 4). This analysis allows us to distinguish the age pattern distribution along the continental onshore margins of southern South America and SW Africa. The age spectra in Southeast South America (in blue, Fig. 4) are distributed in three main peaks. Two of these correspond to Neoproterozoic events related to the Dom Feliciano Belt: (I) the most important one corresponds to the Ediacaran–Cryogenian interval related to the collisional stage; (II) the second one corresponds to the Tonian period, related to the arc stage; the last one (III) corresponds to the Paleoproterozoic, Rhyacian–Siderian period, related to the accretion of Rio de La Plata Craton units. These peaks are similarly identified in the igneous rocks of the region. In turn, southwestern Africa (in red, Fig. 4) presents three major peaks: (i) at the Mesoproterozoic, Stenian to Ectasian period, (ii) at the Paleoproterozoic Statherian to Orosirian period, and (iii) Meso to Paleo-Archean. Regarding the Namibian igneous rocks, the main peak is restricted to the Stenian to Ectasian period.

5. Discussion

5.1. The connections between South America–South Africa margins

The connections between East South America and West African margins have been known since du Toit (1927), and hundreds of research studies improved this knowledge throughout the last century (e.g., Selton et al., 2012; Blaich et al., 2013). Nevertheless, despite these efforts, certain geological gaps remain open. Since the development of GPlates Software (Müller et al., 2018), the representation of plate tectonic positions and motions has been substantially improved. In South America and Africa, the stretching process begins at 155 Ma in the southernmost portion, southward of the study area (Jokat et al., 2003). Using this as a time constraint and based on the rotational poles from Müller et al. (2019), we reconstructed the pre-to-early stretching process before oceanic crust formation at 150 Ma (Fig. 5). The reconstruction incorporating the magnetic and gravimetric data to the block models allowed us to establish the lack of a clear structure connection between the margins. The lack of direct correlation between structures on opposing margins raises significant questions about the amount of crustal loss during the continental break-up process. This discrepancy suggests that our current understanding of crustal evolution during rifting may be incomplete or oversimplified. This apparent disconnect could indicate limitations in the current reconstruction modeling approaches. They may incorrectly extrapolate features across the margins or fail to capture the full complexity of the breakup process.

The structural features of the conjugate margins of southern South America and Africa present distinct orientations that suggest these margins were not perfectly aligned prior to the opening of the South Atlantic. While the fabric of southern South America strikes NE–SW, the structural trend of the African counterpart strikes E–W (Fig. 5). This divergence in structural fabric indicates that the connection between both margins was located in a geotectonic boundary among blocks with different geological histories. A similar setting has been described for the conjugate margins of North America, where a collapse of the Caledonian orogenic belt preceded the formation of the North Atlantic Ocean (Schiffer et al., 2020). This orogenic collapse may have also occurred between southern South America and Africa during the initial stages of the rifting of SW Gondwana, which led to the development of the South Atlantic Ocean basin. This scenario is quite different from the São Francisco-Congo cratons, which were rifted inside the cratonic area where the geology of both margins reflects a more continuous structure (Heilbron et al., 2016). In the South Brazil/Namibia conjugate margin, the geology does not show an obvious geological correlation and indicates that the Atlantic margin was locally formed in an orogenic belt zone between cratons. The major Precambrian structures strongly controlled the South Atlantic opening, so it has the same structural orientation as the Pan-African/Brasiliano belt. These inherited structures might be worked as the main conduit of the SDR magmatism (Serratt et al., 2022) as well controlled the LIP volcanism and dyke orientation (Tomazzoli et al., 2008; Gomes Vasconcelos, 2021). In this way, the inherited structures are a weak zone in the lithosphere and should make a quick break-up with adiabatic mantle decompression.

5.2. Recognizing the stretched crust

The clues for the lack of a direct connection between these two continents begin to be clear when we interpret the seismic lines from both margins. A hyperextended continental crust occurs below a thick volcanic and sedimentary package of Cretaceous to recent rocks (Figs. 2 and 3; Chauvet et al., 2021). However, determining oceanic and continental crust boundaries in volcanic passive margins is challenging. It involves significant uncertainties and subjectivity, leading to varying estimates of its location by 100–200 km or more across different studies focusing on the same margin (Eagles et al., 2015). These discrepancies arise from the limitations in geophysical data resolution and differences in data interpretation methodologies. For instance, features such as SDR or a high-velocity lower crust pose challenges, as they can be interpreted as either altered continental crust or igneous oceanic crust.

Additionally, the interpretation of gravity data introduces non-uniqueness, with the uncertainty in continental-oceanic boundary (COB) location often exceeding 100 km (Eagles et al., 2015). Linear gravity lows produced by oceanic fracture zones offer valuable indicators of the seaward extent of oceanic crust, but they are sporadic features, providing an intermittent COB estimate. Also, according to early models, oceanic-type accretion generates pairs of linear magnetic anomalies, indicators of oceanic crust, and can be related to isochrons formed by seafloor spreading. However, seaward-dipping reflectors at conjugate volcanic passive margins also produce linear magnetic anomalies (Geoffrey et al., 2022). Consequently, identifying an accurate COB remains challenging, underscoring the need for caution when utilizing COB estimates for reconstructions or plate kinematic modeling.

Considering this background, we utilized the previously documented magnetic anomalies M2 and M4 (Rabinowitz and Labrecque, 1979; Moulin et al., 2010) as tools to delineate these boundaries. The initial rifting phase occurred between the M4 and M2 chrons, with the magnetic anomaly M2 indicating the onset of oceanic crust formation (Koopmann et al., 2014; Fig. 3). This early stage was marked by the flexure of the basement and the extrusion of proximal Seaward Dipping Reflectors (SDRs), which caused pronounced magnetic anomalies (Serratt et al., 2022). Drawing on these findings, we were able to estimate the extent of continental crust, which spans up to 350 km beneath the volcanic and sedimentary layers of the passive margin basins along the conjugate margins in southern Brazil/Uruguay and Namibia/South Africa.

Restoring the crust involves a 125–250 km continental crust section covered by volcanic and sedimentary rocks in the Pelotas, Punta del Este, Walvis, Luderitz, and Orange basins. However, it is important to note that the methodology assumes that the bulk extension in the margin is pure shear, which is not always the case. One way to address the issue is by estimating lower-bound values of horizontal extension rates. This can be achieved by dating pairs of cross-cutting pre-flexure and post-flexure dykes, as done in eastern Greenland (Lenoir et al., 2003). Another challenge is the emplacement of dykes in the margins. In a volcanic passive margin, the volume of dykes can exceed 50% (Myers, 1980). Therefore, the restored section will be 50% smaller, with a real extension of continental crust reaching 125 to 250 km in length. This estimative is almost the most conservative scenario and does not consider the denudation that occurred in these sections; even in this more conservative scenario, the impacts of this in the geotectonic models and the understanding of the geology of this region are critical and have not been considered previously.

5.3. SW Africa, SE Brazil, and Uruguay geological correlation challenges

South America and Africa were amalgamated throughout the Pan-African/Brasiliano tectonic cycle along the Neoproteroic (Caxito et al., 2021). The comparison of U-Pb data from both margins can yield valuable insights into the crustal growth history and the main geological events that have shaped the region (Gehrels, 2014; Roberts and Spencer, 2015) and how this crustal growth history is different on both sides of South Atlantic crustal margins (Figs. 2 and 4). Although both margins shared the same Cryogenian to Ediacaran age peak, recording the continental docking during the Gondwana supercontinent amalgamation, which was less represented on the African side but still occurring, the older basement history is almost entirely different. The U-Pb zircon age distribution patterns in SW Africa show major peaks at Archean, Orosirian, and Stennian. Conversely, southern Brazil–Uruguay shows dominant peaks at Rhyacian and Tonian, revealing their distinct crustal growth history. It is clear that both margins, which were merged during the Gondwana supercontinent amalgamation, have previously undergone different crustal evolutions. This distinct crustal growth record is associated with the lack of continuity in the geological structures, and the identified stretched crust well demonstrates the geological significance of this section in correlation studies.

In trying to provide a geological model of the Neoproterozoic orogenic belts of this region, several authors proposed different models (e.g., Chemale, 2000; Basei et al., 2008; Konopásek et al., 2020). Most proposed models do not consider the unknown stretched continental crust under the passive margin basin. Here, through GPlates reconstruction and deep seismic profiles analysis presented by Chauvet et al. (2021) along both margins, we point out that the lithosphere stretching estimated the missing of at least 150–300 linear km of continental crust that is hyperextended beneath the Punta del Este (Uruguay), Pelotas (southern Brazil) and Orange, Luderitz, Namibia, and Walvis basins (southwest Africa). This result indicates that a significant portion of the Pan-African/Brasiliano orogenic belt and its underlying basement is missing. The present size of the Dom Feliciano Belt, which is the expression of Pan-African/Brasiliano orogeny in southernmost Brazil and Uruguay, is smaller than this. This missing continental crust section is comparable in size to the main sections of the Andean, Rocky, or Ural mountains.

This unknown stretched crust, comparable in size to the Earth's largest orogens and covered by Cretaceous rocks of the passive margins, must be considered in any paleogeographic and geotectonic model that intends to evaluate the connection of Pan-African/Brasiliano belts. The question is, what is the nature of this continental crust? May we speculate that the missing puzzle of the Pan-African/Brasiliano petrotectonic assemblages can be there, such as juvenile Ediacaran island and magmatic arcs, ophiolite slabs of the Adamastor Ocean, and others? Is it possible to have a more robust idea of the direction of the subduction paleo plates?

These questions remain largely unanswered, posing significant challenges to many proposed geotectonic models without considering the existence of extended continental crust covered by thick volcanic and sedimentary layers in passive margin tectonic settings. This oversight includes the previously unrecognized stretched continental crust in the Atlantic Ocean, which is the physical extension of the Neoproterozoic to Eopaleozoic Dom Feliciano, Saldania, Gariep, and Kaoko belts (e.g., Porada, 1989; Rapela et al., 2011; Konopásek et al., 2020). The 150–300 km gap in the continental crust harbors key petrotectonic assemblages essential for understanding the processes by which these terranes were amalgamated. However, our understanding of the composition and characteristics of these assemblages remains incomplete. Even with the development of plausible tectonic models, critical puzzle pieces concerning mobile belts exposed in the emerged sections of the conjugate margins will often remain speculative.

6. Conclusion

This study enhanced our approach to understanding the conjugate margins of the South Atlantic Ocean, bringing new insights into pre-rifting geological terrain assemblage models of Pangea and SW Gondwana. The geophysical anomalies, seismic interpretations, and U-Pb isotopic data contribute to a nuanced understanding of the geological evolution in the southwestern Gondwana supercontinent, delineating the extent of the stretched crust and now concealed beneath passive margin basins. However, they are insufficient for precisely determining this extended crust's nature and composition for further geological correlation of the SW Gondwana supercontinent. The integration of paleo reconstruction models with offshore seismic interpretation profiles of hyperextended margins has revealed the inherent limitations of directly reconstructing and connecting geological terranes across different margins, such as those of southeastern South America and southwestern Africa. Consequently, current paleogeographic reconstructions and the associated geological models for the emerging continental margins of the South Atlantic lack the accuracy to account for the extensive and concealed hyperextended crust. After restoring the hyperextended crust, these previous reconstruction models fail to account for a substantial portion of the continental crust, estimated to be at least 150–300 km. This study significantly advances our knowledge of hyperextended passive margins and contributes to a more realistic portrayal of Precambrian terrane evolution.

Acknowledgments

This study was supported by the UNISINOS-PETROBRAS and UNISINOS-CNODC Cooperation Agreements. We also thank the National Administration of Fuels, Alcohols, and Portland (ANCAP) and the Brazilian National Agency for Petroleum, Natural Gas, and Biofuels (ANP) for providing data access. We are grateful to Sequeent and Eliis for granting academic licenses for the Oasis Montaj and PaleoScanTM software, respectively. FCJ acknowledges the Brazilian National Council for Scientific and Technological Development (CNPq) for grant #408194/2021-9. We are particularly grateful to Bruce Eglington, Dengliang Gao, and an anonymous reviewer for their insightful comments. Finally, we acknowledge editors M. Santosh and Richard Damian Nance for their efforts in handling the publication of this manuscript.

References

Basei, M.A.S., Frimmel, H.E., Nutman, A.P., Preciozzi, F., 2008. West Gondwana amalgamation based on detrital zircon ages from Neoproterozoic Ribeira and Dom Feliciano belts of South America and comparison with coeval sequences from SW Africa. Geological Society, London, Special Publications 294(1), 239-256.

Becker-Kerber, B., Paim, P.S.G., Junior, F.C., et al., 2020. The oldest record of Ediacaran macrofossils in Gondwana (~ 563 Ma, Itajaí Basin, Brazil). Gondwana Res. 84, 211-228.

Begg, G.C., Griffin, W.L., Natapov, L.M., et al., 2009. The lithospheric architecture of Africa: Seismic tomography, mantle petrology, and tectonic evolution. Geosphere 5(1), 23-50.

Blaich, O.A., Faleide, J.I., Tsikalas, F., Gordon, A.C., Mohriak, W., 2013. Crustal-scale architecture and segmentation of the South Atlantic volcanic margin. Geological Society, London, Special Publications 369(1), 167-183.

Caxito, F.A., Hartmann, L.A., Heilbron, M., Bruno, H., Pedrosa-Soares, A., Basei, M.A.S., Chemale, F., 2022. Multi-proxy evidence for subduction of the Neoproterozoic Adamastor Ocean and Wilson cycle tectonics in the South Atlantic Brasiliano Orogenic System of Western Gondwana. Precambrian Res. 376, 106678

Chauvet, F., Sapin, F., Geoffroy, L., Ringenbach, J.C., Ferry, J.N., 2021. Conjugate volcanic passive margins in the austral segment of the South Atlantic–Architecture and development. Earth-Sci. Rev. 212, 103461.

Chemale Jr, F., 2000. Evolução geológica do Escudo Sul-rio-grandense. Geologia do Rio Grande do Sul, 13-52.

Chemale Jr, F., Mallmann, G., de Fátima Bitencourt, M., Kawashita, K., 2012. Time constraints on magmatism along the Major Gercino Shear Zone, southern Brazil: implications for West Gondwana reconstruction. Gondwana Res. 22(1), 184-199.

Doré, T., Lundin, E., 2015. Research focus: Hyperextended continental margins—Knowns and unknowns. Geology 43(1), 95-96.

Du Toit, A.L., 1927. A geological comparison of South America with South Africa (No. 381). Carnegie Institution of Washington.

Eagles, G., Pérez-Díaz, L., Scarselli, N., 2015. Getting over continent ocean boundaries. Earth-Sci. Rev. 151, 244-265.

Fernandes, L.A.D., Tommasi, A., Porcher, C.C., 1992. Deformation patterns in the southern Brazilian branch of the Dom Feliciano Belt: A reappraisal. J. South Am. Earth Sci. 5(1), 77–96. doi:10.1016/0895-9811(92)90061-3.

Frimmel, H.E., 2009. Trace element distribution in Neoproterozoic carbonates as palaeoenvironmental indicator. Chem. Geol. 258(3-4), 338-353.

Gehrels, G., 2014. Detrital Zircon U-Pb Geochronology Applied to Tectonics. An. Rev. Earth Planet. Sci. 42, 127-149

Gomes, A.S., Vasconcelos, P.M., 2021. Geochronology of the Paraná-Etendeka large igneous province. Earth-Sci. Rev. 220, 103716.

Heilbron, M., Cordani, U.G., Alkmim, F.F. (Eds.), 2016. Sao Francisco Craton, Eastern Brazil: Tectonic Genealogy of a Miniature Continent. Springer.

Heine, C., Zoethout, J., Müller, R.D., 2013. Kinematics of the South Atlantic rift. Solid Earth 4(2), 215-253.

Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of early Gondwana break-up. J. Geophys. Res.: Solid Earth 108(B9).

Konopásek, J., Cavalcante, C., Fossen, H., Janoušek, V., 2020.Adamastor – an ocean that never existed? Earth-Sci. Rev. 205, 103201. https://doi.org/10.1016/j.earscirev.2020.103201

Koopmann, H., Schreckenberger, B., Franke, D., Becker, K., Schnabel, M., 2014. The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust. Geological Society, London, Special Publications 420(1), 315-340.

Lei, C., Alves, T. M., Ren, J., Tong, C., 2020. Rift structure and sediment infill of hyperextended continental crust: insights from 3D seismic and well data (Xisha Trough, South China Sea). J. Geophys. Res.: Solid Earth 125(5), e2019JB018610.

Lenoir, X., Féraud, G., Geoffroy, L., 2003. High-rate flexure of the East Greenland volcanic margin: constraints from ^{40}Ar/^{39}Ar dating of basaltic dykes. Earth Planet. Sci. Lett. 214(3-4), 515-528.

Macdonald, D., Gomez-Perez, I., Franzese, J., et al., 2003. Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic. Marine and Petroleum Geology 20(3-4), 287-308.

Maus, S., Barckhausen, U., Berkenbosch, H., et al., 2009. EMAG2: A 2-arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. Geochem. Geophys. Geosys. 10(8).

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett. 40(1), 25–32. doi:10.1016/0012-821x(78)90071-7

Milani, E.J., De Wit, M.J., 2008. Correlations between the classic Paraná and Cape–Karoo sequences of South America and southern Africa and their basin infills flanking the Gondwanides: du Toit revisited. Geological Society, London, Special Publications 294(1), 319-342.

Miller, R., Grote, W., 1988. Geological Map of the Damara Orogen, South West Africa/Namibia 1: 500 000. Geological Survey.

Moulin, M., Aslanian, D., Unternehr, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean. Earth-Sci. Rev. 98(1-2), 1–37. doi:10.1016/j.earscirev.2009.08.001

Müller, R.D., Zahirovic, S., Williams, S.E., et al., 2019. A global plate model including lithospheric deformation along major rifts and orogens since the Triassic. Tectonics 38(6), 1884-1907.

Müller, R.D., Cannon, J., Qin, X., et al., 2018. GPlates: building a virtual Earth through deep time. Geochem. Geophys. Geosyst. 19. https://doi.org/10.1029/2018GC007584.

Mutter, J.C., Talwani, M., Stoffa, P.L., 1982. Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by "subaerial seafloor spreading". Geology 10(7), 353-357.

Myers, J.S., 1980. Structure of the coastal dyke swarm and associated plutonic intrusions of East Greenland. Earth Planet. Sci Lett. 46(3), 407-418.

Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N., Sauter, D., 2018. Kinematic evolution of the southern North Atlantic: Implications for the formation of hyperextended rift systems. Tectonics 37, 89–118. https://doi.org/10.1002/2017TC004495.

Passchier, C.W., Trouw, R.A.J., Ribeiro, A., Paciullo, F.V.P., 2002. Tectonic evolution of the southern Kaoko belt, Namibia. J. Afr. Earth Sci. 35(1), 61-75.

Peron-Pinvidic, G., Manatschal, G., Osmundsen, P.T., 2013. Structural comparison of archetypal Atlantic rifted margins: A review of observations and concepts. Marine and Petroleum Geology 43, 21-47.

Porada, H., 1989. Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. Precambrian Res. 44(2), 103-136.

Prave, A.R., 1996. Tale of three cratons: Tectonostratigraphic anatomy of the Damara orogen in northwestern Namibia and the assembly of Gondwana. Geology 24(12), 1115-1118.

Puetz, S.J., Spencer, C.J., Ganade, C.E., 2021. Analyses from a validated global U-Pb detrital zircon database: Enhanced methods for filtering discordant U-Pb zircon analyses and optimizing crystallization age estimates. Earth-Sci. Rev. 220, 103745.

Rabinowitz, P.D., LaBrecque, J., 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margins. J. Geophys. Res. 84(B11), 5973. doi:10.1029/jb084ib11p05973

Rapela C.W., Fanning C.M., Casquet C., Pankhurst R.J., Spalletti L., Poiré D., Baldo E.G., 2011. The Rio de la Plata craton and the adjoining Pan-African/Brasiliano terranes: Their origins and incorporation into southwest Gondwana. Gondwana Res. 20, 673-690.

Roberts, N.M.W., Spencer, C.J., 2015. The zircon archive of continent formation through time. In: Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S., Clift, P.D. (Eds.), Continent Formation Through Time. Geological Society, London, Special Publications, 389, 197 – 225.

Salomon, E., Passchier, C., Koehn, D., 2017. Asymmetric continental deformation during South Atlantic rifting along southern Brazil and Namibia. Gondwana Res. 51, 170-176.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., Francis, R., 2014. New global marine gravity model from Cryo-Sat-2 and Jason-1 reveals buried tectonic structure. Science 346(6205), 65-67. doi: 10.1126/science.1258213.

Schiffer, C., Doré, A.G., Foulger, G.R., et al., 2020. Structural inheritance in the North Atlantic. Earth-Sci. Rev. 206, 102975.

Serratt, H., Teixeira, C.D., Girelli, T.J., Kehl de Souza, M., Vargas, M.R., Silva, A.M., Chemale Jr, F., 2022. Seaward-dipping reflector influence on seafloor magnetostratigraphy–A Pelotas Basin view. Geophys. Res. Lett. e2022GL100382.

Seton, M., Müller, R.D., Zahirovic, S., et al., 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth-Sci. Rev. 113(3-4), 212-270.

Sutra, E., Manatschal, G., Mohn, G., Unternehr, P., 2013. Quantification and restoration of extensional deformation along the Western Iberia and Newfoundland rifted margins. Geochem. Geophys. Geosyst. 14, 2575–2597. doi:10.1002/ ggge.20135.

Torsvik, T.H., Rousse, S., Labails, C., Smethurst, M.A., 2009. A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin. Geophys. J. Int. 177(3), 1315-1333.

Veevers, J.J., 2004. Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma break-up: supercontinental tectonics via stratigraphy and radiometric dating. Earth-Sci. Rev. 68(1-2), 1-132.

Vermeesch, P., 2018. IsoplotR: A free and open toolbox for geochronology. Geosci. Front. 9(5), 1479-1493.

Figures and table captions

Fig. 1. (a) Distribution of main cratons in the West Gondwana context. WA–West Africa Craton; AM–Amazonian Craton, SF–São Francisco Craton; CO–Congo Craton; K–Kahalari Craton; RP–Rio de la Plata Craton; (b) detailed view of main Brasiliano/PanAfrican belts and surroundings cratonic areas. DFB–Dom Feliciano Belt; KB–Kaoko Belt; DB–Damara Belt; GB–Gariep Belt; SB–Saldanha Belt (after Becker-Kerber et al., 2020).

Fig. 2. Seismic profiles b–b' and well data across the conjugate margins of the northern Pelotas (a) and Lüderitz (b) basins (Fig. 3). Well 2-BPS-6A, located in the Pelotas Basin, sampled volcanic units inserted in (a). The Lüderitz Basin profile (b) was adapted from Chauvet et al. (2021).

Fig. 3. (a) Sketch of SW Gondwana map reconstructed at 118 Ma according to the global plate model that includes plate deformation along major rifts and orogens of Müller et al. (2019), with the position of studies seismic profiles; background data: topography SRTM1 grid. The red areas correspond to the outcropping of Brasiliano/Pan-African terranes in the SW Gondwana. The top right inset with South America and Africa maps is 118 Ma. 2D seismic interpretation profiles are modified from Chauvet et al. (2021): (b and b') above: gravimetry and magnetic profiles; below: schematic interpretation seismic profiles b and b'; and (c and c') above: gravimetry and magnetic profiles; below: schematic interpretation seismic profiles c and c'. The gray line on the magnetic profile shows magnetic anomaly from Rabinowitz and Labrecque (1979) and Moulin et al. (2010). The darker red lines in the profiles mark the boundary of the upper and lower continental crust. The crustal stretching factor (β) is calculated along the stretched crust with regular spacing (black dashed vertical line). The boundary between the hyperextended continental crust and oceanic crust (dark blue) is unclear in seismic interpretations. Basins: NB – Namibia; SB – Santos; WB – Walvis; LB – Luderitz; PB – Pelotas; PLB – Punta del Este; OB – Orange; SLB – Salado; and CB – Colorado.

Fig. 4. U-Pb zircon data from Southeastern South America, encompassing southeast Brazil, Uruguay, and SW Africa (Pan-African Belts). The U-Pb data were plotted using IsoplotR online (Vermeesch, 2018).

Fig. 5. Sketch of SW Gondwana map reconstructed according to the global plate model of Müller et al. (2019) showing the lack of connection between the structures of South America and African margins. White line: Large Magnetic Anomaly. Reconstructions use (a) the Earth Magnetic Anomaly Model from Maus et al. (2009) and (b) Satellite Free-air Gravity Anomaly data from Sandwell et al. (2014). Basins: NB – Namibia; SB – Santos; WB – Walvis; LB – Luderitz; PB – Pelotas; PLB – Punta del Este; OB – Orange; SLB – Salado; and CB – Colorado.

Table 1 UCC: Unstretched Continental Crust; SCC: Stretched Continental Crust; β: stretching factor, magnitude of the extension; a Unstretched crust for sections b–b' and c–c'; b stretched restored crust considering 50% of volcanic dikes; c stretched restored crust considering 50% of volcanic dikes for sections b–b' and c–c'; d final gap: sum of unstretched and restored crust for both sections.

- A multi-tool approach reveals at least 150 km of hyperextended continental crust.

- This study highlights the significance of stretching in reconstruction studies.

- Distinct U-Pb zircon age distribution patterns reinforce the lack of direct connections.

- New insights on the dynamics of hyperextended crust.
- A significant portion of the Brazilian/Pan-African orogenic belt is hidden beneath passive margin basins.

Figure 1

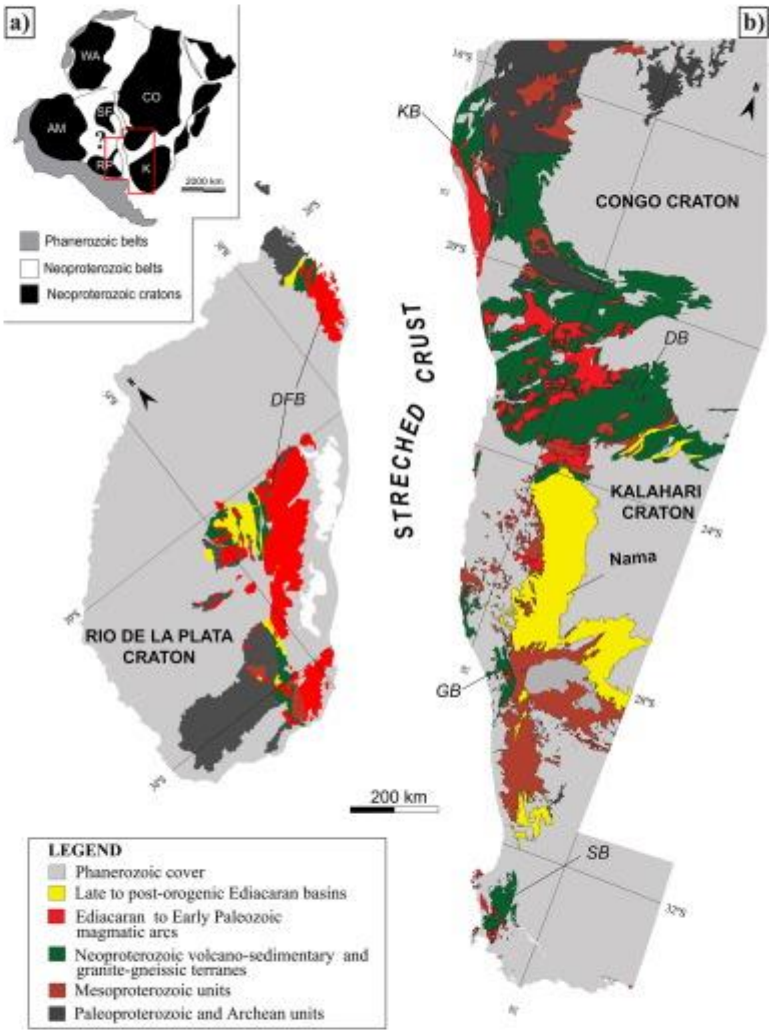


Figure 2

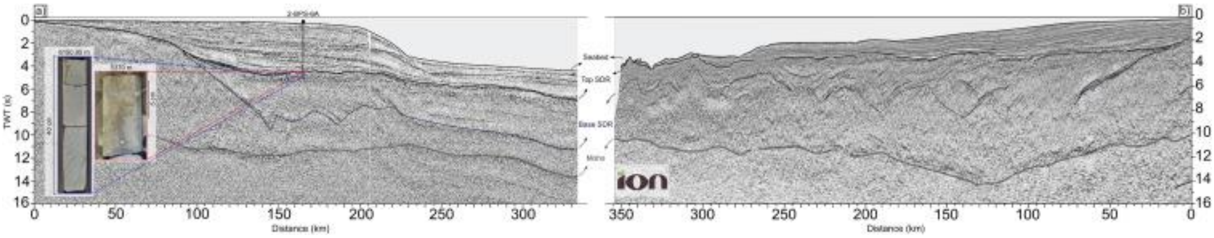


Figure 3

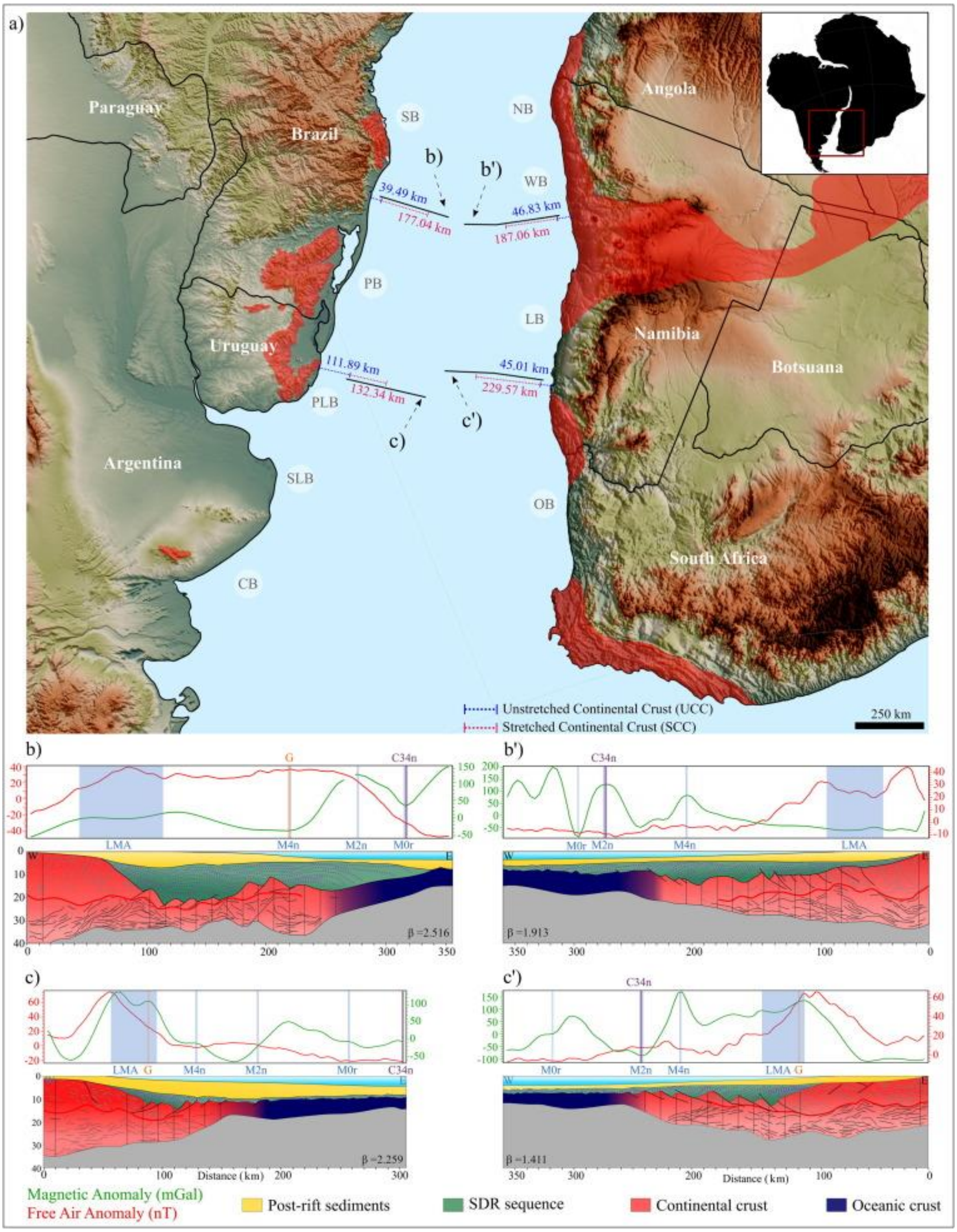

a)
Paraguay
Brazil
Uruguay
Argentina
Angola
Namibia
Botsuana
South Africa
SB
NB
WB
PB
LB
PLB
SLB
OB
CB
b)
b')
c)
c')
39.49 km
177.04 km
46.83 km
187.06 km
111.89 km
132.34 km
45.01 km
229.57 km
Unstretched Continental Crust (UCC)
Stretched Continental Crust (SCC)
250 km
LMA
G
C34n
M4n
M2n
M0r
β =2.516
β =1.913
β =2.259
β =1.411
Distance (km)
Magnetic Anomaly (mGal)
Free Air Anomaly (nT)
Post-rift sediments
SDR sequence
Continental crust
Oceanic crust

Figure 4

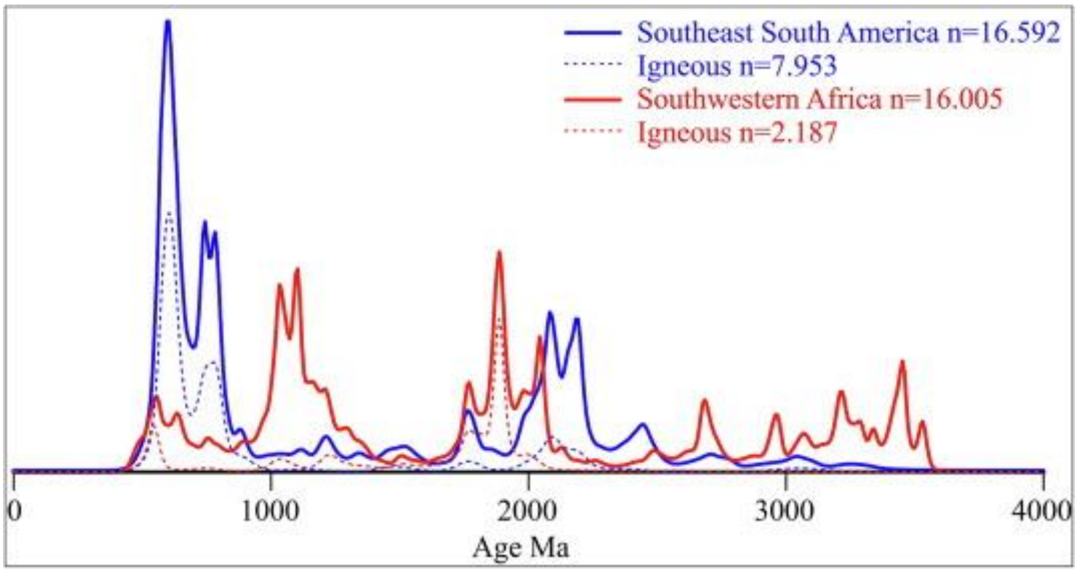


Figure 5

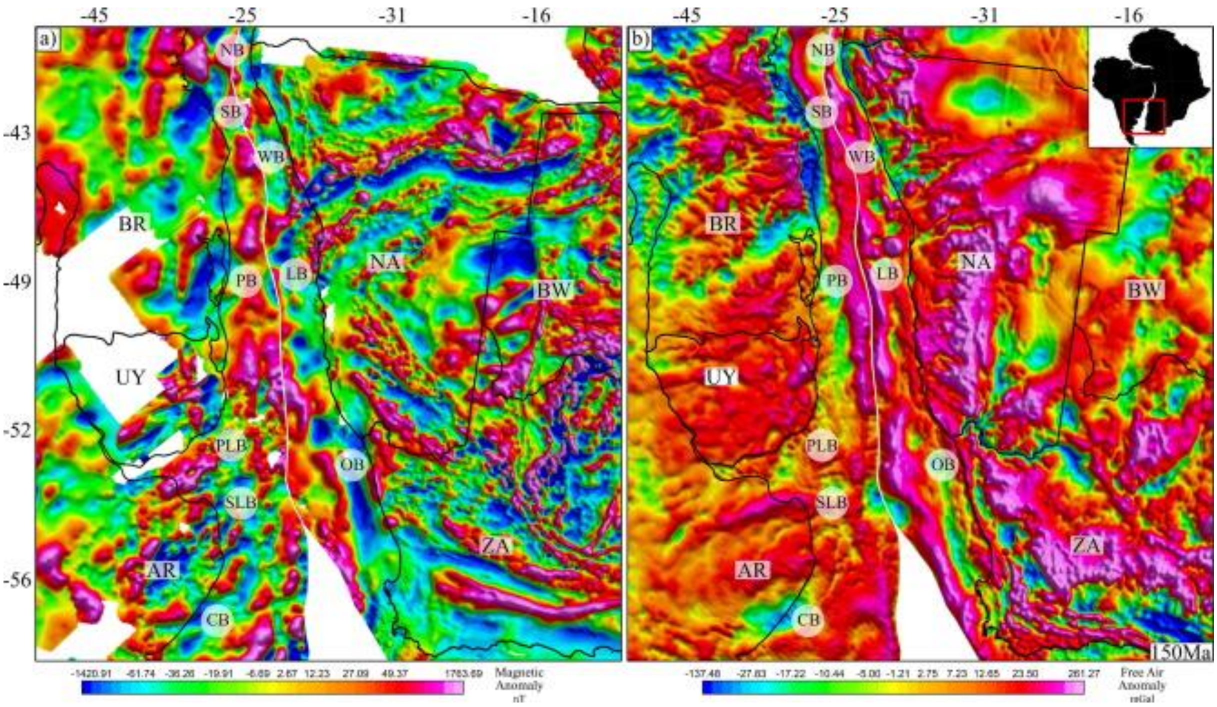


Table 1

Section	CCU	CCS	β	Stretched	Stretched 50 %[a]	Restored[b]	Unstretched[c]	Stretched 50 %[d]	Gap[e]
Northern Pelotas and Walvis basins (Section B-B')									
B	39.49	177.04	2.52	70.3656598	35.18	74.68	86.33	84.07	170.40
B'	46.83	187.06	1.91	97.783586	48.89	95.72			
Punta del Este and Lüdertiz basins (Section C-C')									
C	111.90	132.35	2.26	58.5878707	29.29	141.19	156.92	110.64	267.56
C'	45.02	229.57	1.41	162.700213	81.35	126.37			