Brazilian Journal of Geophysics 42 (2024), 2, 1-63
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v42i2.2322

SANTOS BASIN AS AN EXAMPLE OF A SHEAR-DRIVEN CORE COMPLEX IN A TRANSFORM MARGINAL PLATEAU

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ABSTRACT. It is proposed a new model on the kinematics of strain partitioning for the breakup of the Santos and Namibe conjugate basins. The model is based on observed strike-slip corridors and low-angle detachments with metamorphic core complexes, which accommodated the deformation in a mega relay zone. Through detailed reconstructions of this segment of the South Atlantic, collecting multidisciplinary data from previous researchers, and considering the relative relationship between Africa and South America during the breakup process, it is herein reexamined key evidence of how the Brazilian side became so wide, and acted as an accommodation zone during the Aptian. The 600 km Long transpressional-dextral Proterozoic Ribeira Belt is the cradle of the transtensional-sinistral Santos-Namibe strike-slip rift propagator. These conjugate basins evolved as a large-scale relay zone, developing an oblique-left-lateral extensional corridor during the Aptian, balancing mechanically coeval deformations from two sub-parallel spreading branches, traveling from North and South, but hundreds of kilometers apart from each other. Proterozoic inheritance, and the dynamic clockwise rotation of South America (far-field stresses) controlled strain partitioning between the Campos/Benguela basins and the Pelotas/Walvis basins. The onset of seafloor spreading around the Falkland (Malvinas) Island, triggered the relative clockwise rotation of the southernmost tip of the South America plate, and the intrusion of transversal dike swarms of the Ponta Grossa Arch, which is interpreted as fissural magmatism, comparable to a regional opening mode(type I) fracture system. Plate kinematic transport direction inferred from plate reconstructions is mainly EW. The step-over oblique-slip of this relay zone widened the Santos Basin in the NW-SE direction, often mistakenly misinterpreted as the extension direction in the Santos Basin. This NW path is the direction of the maximum elongation within an E-W shear corridor. Our work details a new and unprecedented strike-slip structural framework of the Santos Basin, with large-scale basement-involved folding around the Outer High, which evolved to an obliquely sheared active low-angle detachment system, simultaneously influenced by the thermal anomaly of the Tristan-Gough plume, responsible for magmatic thermal weakening and thermal-induced uplift. Magmatic underplating may have facilitated the doming process. The Santos Basin is located at the heart of a Transform Marginal Plateau, as previously proposed. It is composed of a magmatic crust, with fragmented slices of continental crust, obliquely sheared during successive transform movements, with possible magmatic underplating. This kinematically linked system of normal faults, strike-slip faults, flexural folds, and detachment faults has direct impact on understanding the properties of world-class oil and gas reservoirs in the Brazilian Pre-Salt Supergiant Province. With the ongoing regional transgression, the active structural highs were the site of deposition of the carbonate reservoirs that host an in-place volume around a hundred billion barrels of hydrocarbons, considering the whole province.

Keywords: South Atlantic breakup, Santos-Namibe conjugate basins, Oblique hyperextension, Metamorphic core complex, Magmatic underplating, Kinematic strain partitioning, Oblique detachment systems, Tristan-Gough plume

INTRODUCTION

The 3D brittle deformation of the upper crust during continental-scale extensional processes is still a scientifically challenging issue. There was a lot of conceptual improvement, from classic pure-shear 1D thermodynamical models, instantaneous, symmetric, and constrained by a single geometric parameter, to recent polyphasic rift models, quite asymmetric, heterogeneous, and protracted, with crustal-scale displacements, eventually oblique, above low-angle detachments.

Indeed, this paper aims to introduce new alternative models and regional interpretations of oblique low-angle detachment systems associated with continental-scale strike-slip shear zones observed in the Santos Basin. We will describe how these shear zones behaved as large-scale extensional relay zones during the opening of the South Atlantic.

We will not discuss the nature of the hyperextended crustal terrains by means of, so far lousy constrained, local 2D seismic velocity and density models in the ultra-wide Santos Basin. Instead, we will focus on plate kinematic trajectories, and well-defined 3D regional structural patterns, with both strike-slip corridors and low-angle detachments.

GEOLOGIC SETTING

The Santos Basin is the largest offshore sedimentary basin in Brazil, covering over 350,000 square kilometers, from Cabo Frio (Rio de Janeiro state) to Florianópolis (Santa Catarina state). Its counterpart, the Namibe Basin, is a narrow (50 to 100 km wide) and elongated (570 km long) marginal depression located in Southwest Angola and North Namibe (Figure 1). Following Withjack et al. (2002) rift-basin terminology, the Namibe Basin displays a hinged margin, basically a flexural linear structure with absence of a main border fault, with half-grabens bounded by northeast-dipping antithetic normal faults (Figure 1.e).

On the Brazilian side, the published nomenclature is sometimes non-uniform because tectonic and thermal loading vary in time and space. The superposition of tectono-magmatic events led to the development of distinct flexural hinge zones. During the main rift phase, close to the necking zone, tens of kilometers of a curvilinear faulted margin was developed subparallelly to the Proterozoic rock fabric (Figure 1.b, 1.c). After the Early Cretaceous rift evolution, the Santos Basin experienced progressive load redistribution through important post-Albian sedimentary loading on top of a thick Aptian salt layer deposited during the later phase of the rift. Massive progradation during the Campanian-Eocene interval (Moreira et al., 2007), resulted in regional salt withdrawal, basin deepening, lithospheric flexure, and possible rift shoulder uplift (Mohriak et al., 2008).

Commonly, some authors describe the first occurrence of a basin-ward normal fault, generally located within the necking zone, as the "Cretaceous hinge line" of the Santos Basin (Zalán and Oliveira, 2005, Mohriak et al., 2008; Rigoti, 2015, Giro et al., 2021), which are in fact characterizing the border faulted margin. Therefore, morphologically, the Namibe Basin is not as a mirror image of the Santos Basin, as precluded from symmetric rift models. The basin architecture, illustrated in Figure 1, is dominated by east-dipping major faults, with a border faulted margin on the Brazilian side, and a hinged margin on the African side, suggesting that the Santos-Namibe basins evolved through time and space as a continuum. Rift evolution will be addressed according to the model of Stretching, Thinning, and Hyperextension phases, described by Lavier & Manatschal (2006); and Karner et al. (2021). Evidence of crustal detachments developed during the Hyperextension phase of the Santos Basin rift system, characterized by remarkable low-angle normal faults (LANFs) and possible metamorphic core complexes (MCCs) type structures will be presented and discussed later.

The geological asymmetry between these counterpart basins (Unternehr et al., 2010) directly impacts oil exploration. While the Santos Basin is a world-class oil province, house of giant oil and gas fields, the Namibe Basin is still poorly explored. The stratigraphy is mainly inferred from the neighboring Kwanza Basin. A narrow strip of outcrops, parallel to the coastline exposes tholeiitic basalts as the basement, covered by pre-salt sediments and an evaporitic succession (Laurent et al., 2016). These authors recognized an Aptian transgressive SAG sequence with bedded gypsum and microbialitic limestones.

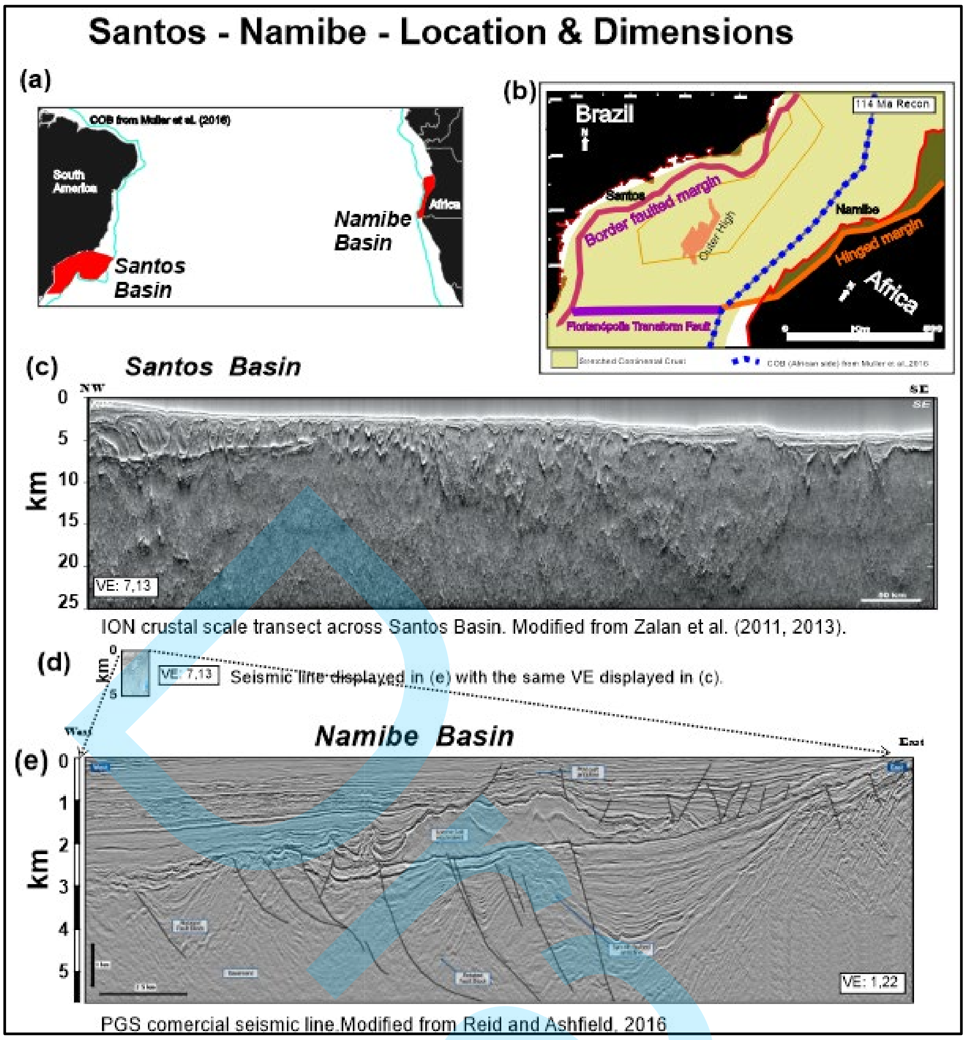


Figure 1. Contrasting width and asymmetry of the Santos-Namibe conjugate basins. South America and Africa are in black, and the conjugate basins are in red polygons. The continent ocean boundary (COB, in light blue line, of Müller et al., 2016) is meant to provide a first order idea of the contrasting width of the stretched continental crust between Santos and Namibe Basins; (b) Plate reconstruction at 114 Ma (from PLATES Project), illustrating the asymmetry between the two basins, with a border faulted margin in the Santos side in contrast with the hinged margin in the Namibe side. The solid yellow line of the polygon represents the legal Brazilian Pre-Salt Polygon, with the Outer High (in peach color). The COB location from the African side is a dashed blue line. (c) Uninterpreted 2D seismic transect through Santos Basin published by Zalán et al. (2011, 2013). Location in Figure 21. It is a PSDM version of a 760 km long seismic line from the ION-GXT (BrazilSPAN Salt Study Survey). Seismic is displayed using the “tecVa” volume of amplitudes seismic attribute techniques. (d) and (e) East-West seismic line crossing the Namibe Basin displayed in two distinct vertical exaggeration (VE), published by Reid and Aschfield (2016). The seismic image in (e) is exhibited with low VE, while the same seismic line became useless (d) if presented with the VE used in the Santos crustal-scale transect (c).

SANTOS BASIN RIFT MODELS

Geodynamic models to explain the ultra-wide Santos Basin are debated and not resolved yet. Huismans and Beaumont (2011), through a two-layer numerical modelling, defined type I and type II margins as the result of lithospheric extension. The Santos would be type II, where below a very wide thin continental crust, the continental lower crust and the lithospheric mantle would have been apparently removed. Huismans and Beaumont (2014), through depth-dependent dynamical numerical modelling, recognized three types of margins (types I, II, and III), controlled by the strength of the mid/lower crust. Type III margins are like type II, but the lower crust and the lithospheric mantle may be removed at the Distal and Sag segments of the basin. Through numerical thermo-mechanical modeling, Brune et al. (2014) discussed how lower crust viscosity, coupled with extension rates, affects the final width of the margin within hyperextended continental crust, suggesting that large amounts of lower-crust material are transferred between rift zones. Through 2D modeling of a modeled layered visco-elasto-plastic lithosphere, Ros et al. (2017) predicted that magmatic underplating underlies the wide Santos Basin, and the Continental-Oceanic Transition (COT) is mainly magmatic when developed at ultra-slow extension.

Lu and Huismans (2021), utilizing depth and mantle-temperature dependent thermo-mechanical modeling, demonstrated that, in a volcanic margin, the mantle ruptures before the crust. They proposed a new classification of rifted margins: (i) Mode 1 “normal-magmatic margins”; (ii) Mode 2 “excess-magmatic margins” and (iii) Mode 3 “a-magmatic margins”. Mode 2, representative of the Santos Basin, would be characterized by over-thickened intruded continental and oceanic crust, voluminous Seaward-dipping reflectors (SDRs), and regions of magmatic underplating. Lu and Huismans (2021) results indicate that expressive magmatism could be produced in wide rifts at normal mantle temperature and do not exclude the presence of mantle plumes.

It is controversial how the oceanic and continental lithospheres partition. Karner et al. (2021) proposed a new paradigm, using the location of interpreted SDRs as a fundamental parameter to define the location and timing of continental breakup. They interpreted this magmatic crust as a thickened oceanic/transitional crust, which coincides with the current interpretation of a continental basement based on velocities and densities from wide-angle refraction and gravity surveys (Evain et al., 2015). However, because of their intricate structure and variable composition, Serratt et al., 2022 caution against utilizing SDR-related magnetic anomalies to constrain ages of tectonic events. During crustal extension, the outer SDRs were interpreted by Geoffroy et al., 2020 as a continuous magmatic addition positioned atop a passively exhumed mid-to-lower mafic crust of continental origin.

TIMING AND AGE ISSUES

Matos et al., 2021 described the evolution of the South Atlantic Cretaceous Rift System (SACRS), in time and space, through five tectonic stages (I, II, III, IVa, IVb, and V, Figure 2) after identifying 33 regional tectonic-related events developed during the opening of the South Atlantic. Like any other continental-scale geodynamic model, this evolving synthesis of the SACRS faces the difficulty of conflicts between radiometric data, global stratigraphy, and paleontological data. Figure 2 correlates stratigraphic charts of the Campos- Santos and Pelotas basins during the Barremian-Albian time interval and displays the ICS and the GTS timetables for the Upper Cretaceous.

The ages of Chrons M0, M3, and M10, as well as the corresponding ages in the ICS 2023 chart, are uncertain within the Berriasian-Albian interval. Leandro et al., 2022, recalibrated paleoclimatic events of the Aptian stage, reinterpreting the Barremian-Aptian boundary to an age of ~120.2 Ma (1.2 Ma younger than the ICS 2023 chart).

Considering that our database is built on the oil industry, we will therefore use the Cretaceous time-scale ICS 2023/04 as a basis for our plate reconstructions and adjusting stratigraphic charts published by Petrobras. The onset of seafloor spreading in the Austral South Atlantic begin at Chron M10r (134.2 Ma, Collier et al., 2017). Figure 2 illustrates that during the Barremian-Albian time interval, while siliciclastic sediments deposited in the Santos-Namibe conjugate basin, a volcanic rift valley, overwhelmingly dominated by SDRs, developed on top of a new magmatic crust, or proto-oceanic crust in the Pelotas basin (Paton et al., 2017).

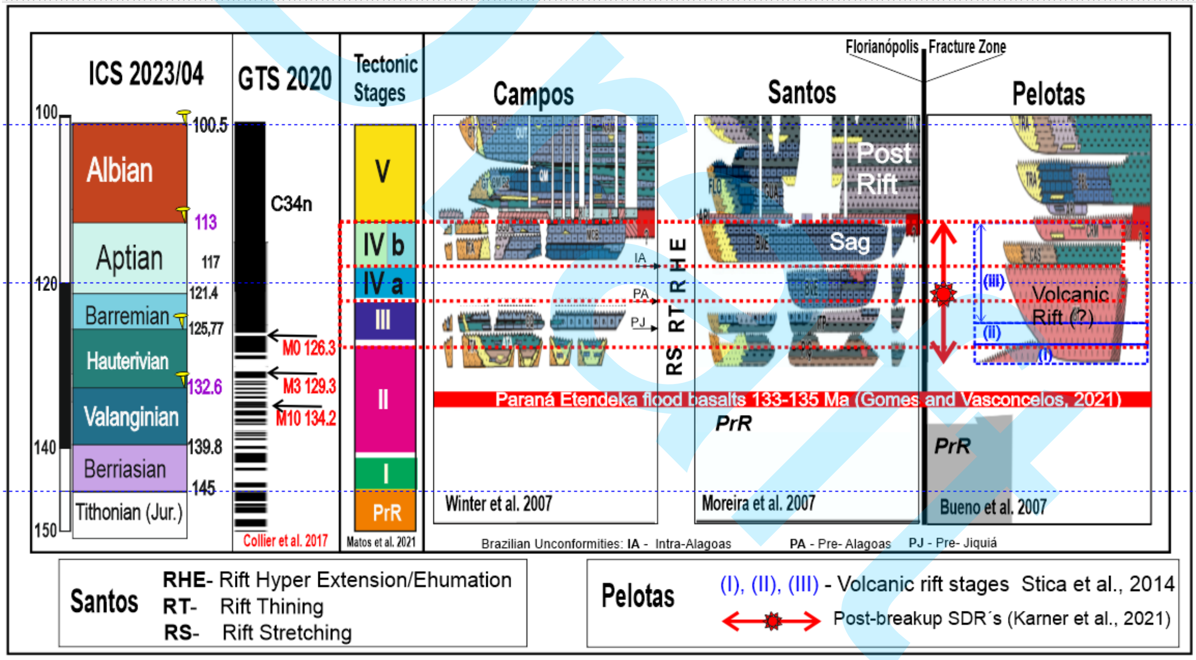


Figure 2. Stratigraphic charts of Campos, Santos, and Pelotas Basin, modified from Winter et al (2007), Moreira et al. (2007), Bueno et al. (2007) and Stica et al., (2014), juxtaposed with the GSSP-ICS and the GTS timetables, the M10-M0 magnetic anomalies described by Collier et al. (2017). The oldest volcanic rift of the Pelotas Basin sequence (I) was developed during seafloor spreading within the Austral Branch. The Florianópolis Fracture Zone (FFZ) is considered to be the northern limit of Austral's SDRs and developed synchronously with the rift and SAG stages of the Santos Basin. The Cabiúnas, Camboriú and Serra Geral formations commonly described as a pre-rift stage (PrR) are the basement of these basins. They are the product of a massive magma eruption of the Paraná-Etendeka Large Igneous Province (LIP) between 135.0 and 133.2 Ma (Gomes et al., 2021).

TWO DIACHRONOUS, COMPETITIVE SPREADING AND RIFT BRANCHES

During the Early Cretaceous, two competing and diachronous spreading and rift branches propagated from NE Brazil/West Africa and from South Argentina/ SW Africa to meet in the Santos/Namibe conjugate Basins (Moulin et al., 2010; Chaboureau et al, 2013;; and later by Matos et al., 2021 and Matos, 2021). Thinning and exhumation within the Campos-Santos/Benguela-Namibe rift axes were synchronous with the development of SDR´s within the Pelotas /Walvis conjugate basins during the 133-113 Ma time interval (Figures 1 and 2).

The model of Karner et al. (2021) suggests a much-reduced time frame for the breakup of the entire Austral Branch in comparison to the interval suggested by Collier et al. (2017) (from 134.2 to 126.3 Ma). Moreover, an organized spreading center at mid-ocean ridges through the South Atlantic was not developed before the end of Albian/early Cenomanian, when the South America plate was completely separated from the African plate (Matos et al., 2021). The rift branching coming from the North was triggered around 145-140 Ma and started its southward migration during the 140-126 Ma interval (Matos et al., 2021).

Our working hypothesis assumes that the Santos Basin is the spot where a rift branch arriving from the North competed, in time and space, with a propagating spreading branch coming from the South (Scotchman et al., 2010). The Florianópolis Fracture Zone (FFZ) marks the boundary or transition zone between these two South American stretching fronts, entering in this region around 130 Ma, after the massive magma eruption of the Paraná-Etendeka Magmatic Province - LIP (PEMP-LIP) at ca. 133.6 Ma (Rocha et al., 2020). According to Gomes et al. (2021), the eruptive stage lasted between 135.0 ± 0.6 Ma, and 133.2 ± 0.3 Ma. The Santos/Namibe margin is the widest asymmetric passive margin. This segment was extremely stretched as the result of the clockwise rotation of South America with respect to Africa (Matos et al., 2021, Matos, 2021) simultaneously with intense magmatic activity due to the movement of the Tristan-Gough plume head beneath these conjugate basins. The São Paulo Plateau, the Rio Grande Rise (RGR), hotspot tracks and/or seamount chains are outstanding submarine features around the Santos and Pelotas Basins (Figure 3). There is an ongoing debate about the nature of the gigantic RGR, if it is a LIP, a detached microcontinent, or slivers of continental crust within a heavily intruded oceanic crust. (Dehler et al., 2016; Galvão & Castro, 2017; Altenbernd et al., 2019). The Tristan da Cunha hotspot trail crosses diagonally the RGR (purple continuous line in Figure 3), and it is the main source of magmatism in the RGR.

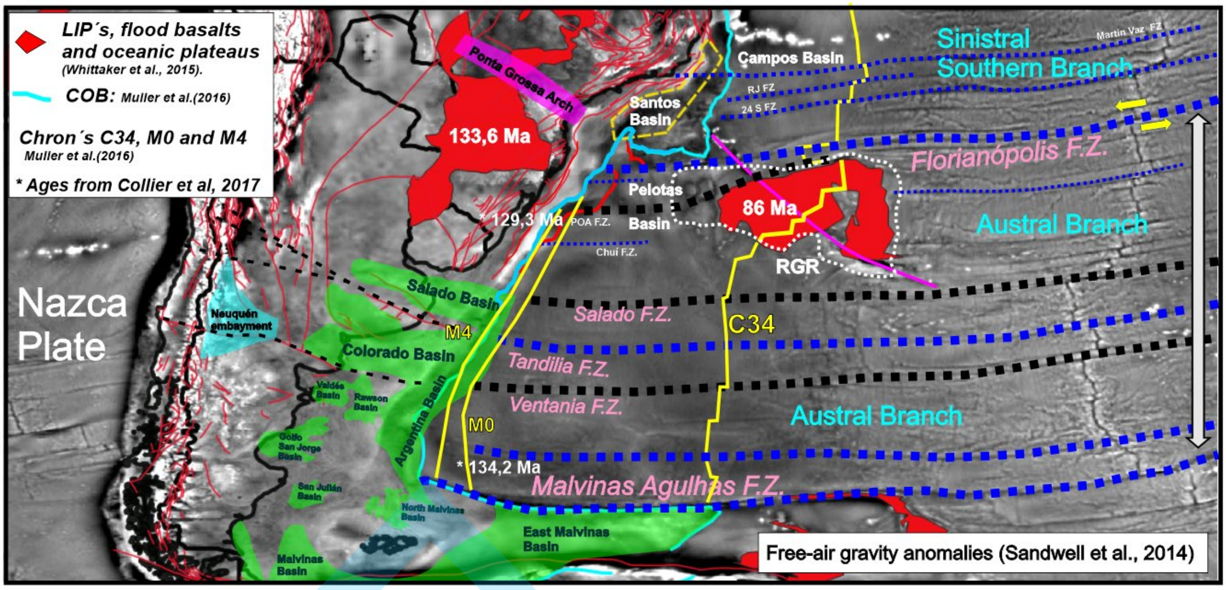


Figure 3. South Atlantic basins, LIP´s, oceanic fracture zones and geomagnetic Chrons superposed on the vertical gradient map of the free-air gravity anomalies derived from satellite altimetry data (Sandwell et al., 2014). RGR: Rio Grande Rise (dashed white polygon). Main fracture zones in and around Santos Basin: Martin Vaz, Rio de Janeiro, 24ºS, Florianópolis (or Rio Grande), Porto Alegre and Chuí. (Coordinate Reference System: WGS 84).

Regardless of possible timetable conflicts, the Karner et al. (2021) review agrees with Moreira et al. (2007), Bueno et al. (2007) and Stica et al. (2013), considering that the Hauterivian-Barremian-Aptian sedimentation is progressively younger eastward, evaporites were deposited after breakup and before the emplacement of Penrose oceanic crust. However, Karner et al. (2021) interpret the inner and outer sequences of SDRs of the Pelotas Basin as a post-breakup , subaerial seafloor spreading (red star in Figure 2). SDRs in Pelotas Basin are dated as 126.3 Ma by Collier et al. (2017). Bastow & Keir (2011), Geoffroy (2005), Geoffroy et al. (2020), and Serratt et al. (2022) believe that SDRs develop primarily above continental crust and that their volcanic age and spatial position are not correlated. Karner et al. (2021) views SDR location as a fundamental parameter to define the location and timing of continental breakup. In 2022, Serratt et al. (2022) challenges the previous magnetostratigraphic interpretation of the Pelotas Basin´s SDRs, concluding that the magnetic anomalies of the Austral Branch are not age-related.

CRUSTAL DOMAINS IN THE SANTOS BASIN

There are minor conflicts about the interpretation of the necking domain in the Santos Basin . However, there is not a clear boundary separating the unextended continental crust (CC) from the unambiguous oceanic crust (OC), usually referred to as the continent-ocean transition (COT) in the sense of Davy et al. (2016). The nature, location, and geometry of COTs are debated because the present interpretations are influenced by data resolution and interpreter choices (Pérez-Díaz and Eagles, 2014). The concept of the Proto-Oceanic Crust (POC) domain defined by Gillard et al. (2015) represents the most magmatic part of a distal margin, where the basement might be characterized by serpentinized peridotites, basalts, and gabbros. On the other hand, "Any crust formed entirely by magmatic accretion and/or eruption, produced by decompressive partial melting of asthenosphere at an accreting plate boundary" is the definition of Magmatic Crust (MC) according to Karner et al. (2021).

This MC is usually classified as a thickened oceanic/transitional crust and is commonly interpreted as a continental basement in some wide South Atlantic basins, such as the Santos Basin, Pernambuco-Paraíba basins, and the transtensional basins of Barreirinhas and Ceará Potiguar in the Brazilian Equatorial Margin.

Many COB boundaries have been proposed to the Santos Basin : Gomes et al. (1993), Karner (2000), Mohriak et al. (2001), Meisling et al. (2001), Carminatti et al. (2008), Torsvik et al. (2009), Müller et al. (2016) and Moulin et al. (2016). (Zalán, 2011) interpreted possible regions with an exhumed mantle. Evain et al. (2015) recognized distinct crustal domains defined by Domains N, A: B and C. The positions of three COBs are shown and contrasted in Figure 4.

Taking the COB from Müller et al. (2016), as example, the southeasternmost continental crustal boundary in the Santos Basin has been extended too much eastward, into the Outermost Santos Deep Basin - OSDB (Figure 4). As will be discussed later, plate reconstructions indicate that most of these published COBs are not compatible with the COB from the Namibe side of this conjugate margin, over the 120-113 Ma time span.

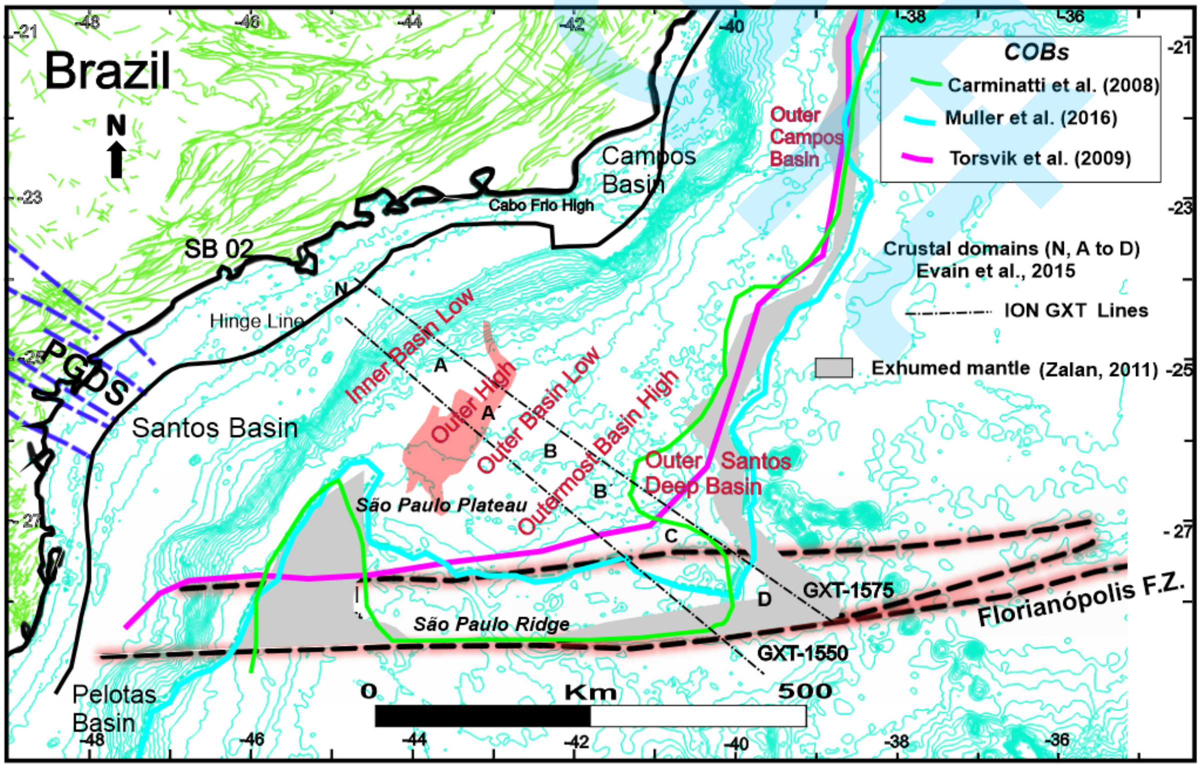


Figure 4. Main structural features of the Santos and Campos basins. Onshore tectonic lineaments in

green lines. PGDS stands for the magnetic signature of the Ponta Grossa Dike Swarm. Outer High as described by Gomes et al. (2002). Based on shallow-water data, the boundaries of Santos Basin are the Florianópolis High (Florianópolis Fracture Zone) and the Cabo Frio High (CFH). GXT-1575 and 1550 are the location of wide-angle seismic lines from the SanBa project, Evain et al. (2015), who recognized distinct crustal territories: Continental Crust defined by Domains N, A: B and C. Domain D is interpreted by Klingelhoefer et al. (2014) as a proto-oceanic crust, while Zalán et al. (2011, 2013) interpreted the southeastern limit of the crustal Domain C as an exhumed mantle. Bathymetry in thin blue lines. The main compartments of the basin are the Inner Basin Low (IBL), Outer High (OH), Outermost Basin High (OMBH), and Outer Santos Deep Basin (OSDB).

Throughout this paper, we use the COB from Müller et al. (2016) as a worldwide convenient reference template (continuous blue lines in the figures), even though we recognize that it does not provide the best interpretation within the Santos Basin. Pérez-Díaz and Eagles (2014) and Eagles et al. (2015) noted and highlighted the lack of agreement on the COB criteria. As shown in Figure 4, COB´s from geophysical data imply observational uncertainty on the range of 10-100 kmkm. Mapping a linear boundary resulting from non-unique continental breakup processes that are still poorly understood is a significant issue. Using worldwide data, Eagles et al. (2015) reviewed and discussed the signature and uncertainties of interpreted COB´s and COT´s based on gravity, magnetic and seismic data (refraction and reflection). The authors concluded that the width of the COT´s are strongly influenced by the interpreter choices, regardless of data resolution, and suggested that COB locations cannot be used as geometric markers in plate kinematic models, without considering the uncertainties. Therefore, it is a major challenge to adjust non-unique seismic velocity and densities inverted models to map a linear boundary resulted from non-unique continental breakup processes.

The location of the Santos Basin (SanBa) wide-angle seismic profiles experiment is seen in Figure 4. Evain et al. (2015) significantly add to our understanding of the Santos Basin, identifying distinct crustal domains, some of them displayed in Figure 4 (N, A, B, C, and D), which will be addressed later.

The greatest divergences among the COBs positions proposed by the various authors occur in the southeast portion of the basin, where a triangular shape protrudes towards Africa. It includes the crustal domains C and D from Evain et al. (2015), the COT of Rigoti (2015), the region interpreted by Zalán et al. (2011, 2013) as an exhumed mantle and the easternmost segment of Müller et al (2016)´s COB.

Biari et al. (2021) reviewed the existing rifting models from wide-angle seismic data of the Atlantic passive margins. Based on the SanBa wide-angle Profile 2, they presented a pre-breakup reconstruction (at 112 Ma), displaying a thick crust on the Brazilian side, with two necking zones (proximal and distal). As interpreted originally by Evain et al. (2015), the easternmost segment of the Santos Basin displays a very thick crust, interpreted as the continental crust (Domain C, Figure 4). Their own 112 Ma reconstruction indicates a clear overlap of continental crust between the Santos and Namibe basins. The Abimael failed rift arm, originally described by Mohriak (2001), was also interpreted by Gomes et al. (2002, 2009), Mohriak et al. (2010) and Scotchman et al. (2006, 2010). Even though there is consensus about the crustal nature of the Abimael anomaly, there is no consensus about the nature of the crust eastward of it (Figure 4). Karner et al. (2021) recognized three classes of MC: The first is a relatively thick-wide and magmatic segment of the crust encompassing the Inner Basin Low (IBL), the Outer High (OH), the Outermost Basin High (OMBH) (Figure 4), and two other structurally overprinted classes, including the possible serpentinized and exhumed mantle in the Outer Santos Deep Basin (Figure 4).

The nature of the interpreted crustal types in the Santos Basin is the source of conflicting geodynamical models. Karner et al. (2021) definition of MC includes magmatic plateaus, SDRs, and oceanic crusts of variable thickness, and may have the same composition as a standard OC. This introduced some nomenclature conflicts because the oceanic crust is commonly understood as the result of decompressive melting of the asthenosphere at a stable spreading center. Furthermore, although density modeling may reasonably describe crustal thickness, it is not possible to clearly differentiate between basement types with granite-gneiss and those with gabbro-basalt. Similarly, seismic reflection, or refraction investigations, and gravity modeling cannot definitively determine the type and nature of the crust.

Determining the amount of magmatic addition during the crustal extension of the Santos Basin , a rifted basin that is obliquely sheared and concurrently affected by the thermal effect of a potential mantle plume that causes thermally induced uplift and magmatic thermal weakening, is an extremely difficult issue. Instead of using Karner's MC interpretation, we will adhere to Davy et al. (2016)'s definition of COT, which is a broad zone extending from the hinge line in the direction of an unequivocal oceanic crust (OC). A key scientific question is when and where in time and space the new-born South Atlantic Ocean province developed a continuous, stable, and self-organized spreading center.

INHERITANCE, RIFTING AND MAGMATISM WITHIN THE COMPETING EXTENSIONAL BRANCHES

Our work goes along with plate reconstructions presented and discussed by Matos et al. (2021), supported by the PLATES Project (UTIG), which follows Heine et al. (2013) solution, using a tight fit in the far southern Atlantic. Our careful reconstruction with a tight fit of West Africa results in a gap between the Demerara Rise and the Guinea Plateau (Figure 5). As described by Matos et al. (2021) and later in this work, this gap was closed mainly during the clockwise rotation of South America with respect to Africa between the Valanginian and the Aptian stages. This rotation was responsible for the development of internal deformations in the South American plate represented the development of the Marajó and Gurupi rift valleys in North Brazil (Tectonic stage II), and by a left-lateral transpressional belt of the Pisco-Jurua Fault (Szatmari and Milani, 2016; and Caputo, 1991) in the Solimões Basin (Figure 5). Tectonic inversion between the Demerara Plateau (South America) and Guinea Plateau (Africa) is characterized by WNW–ESE inverted compressive faults within the eastern edge of the Demerara Plateau (Benkhelil et al.,1995; and Basile et al., 2013. Casey et al., 2015; Casson et al., 2021). The compression is interpreted in seismic data across the Demerara Plateau, characterized by compressional deformation beneath a regional Albian unconformity, as the result of South America's early clockwise rotation away from Africa. Most of the compressional deformation was accommodated by the South American plate within the Demerara Plateau (Casey, 2021). Johnson et al. (2012) recognized three compressional pulses, related to the Aptian-Albian rotation of South America, followed by Santonian trans-African deformation and inversion e finally by Paleogene plate motion adjustments.

A major factor in the evolution of the eastern Brazilian border was structural inheritance. It is distinguished by lithospheric scars created during the West Gondwana Supercontinent's amalgamation, which are represented by the Mantiqueira Province (Silva et al. 2005), a set of folded belts that is approximately 3000 km long and 200 km wide, as seen in Figure 5.

This province is the product of a diachronic oblique continent-continent collision between the Congo and the São Francisco cratons, with the development of NE-SW, NNE-SSW transpressional (dextral) shear zones (Silva et al. 2005). It is composed, from north to south, of the Araçuaí, Ribeira and Dom Feliciano Fold Belts. These fold belts define a large-scale sigmoidal shape on the Brazilian side. The ENE-WSW Ribeira Belt defines the main bend between the regional N-S striking direction of the Araçuaí Belt, to the North, and the NE-SW trend of the Dom Feliciano Belt, to the South. The Ribeira Belt is the cradle of the Santos-Namibe conjugate basins (Figure 5). According to Egydio-Silva et al. (2018), the regional tectonic fabric of the Ribeira Belt is typical of a transpressional belt, characterized by "steep lithospheric-scale orogen-parallel transcurrent shear zones" (SLOPTSZs). The same large-scale sigmoidal morphology of the Ribeira Belt would shape the inverted transtensional shear belt developed during the Cretaceous, as it will be described through plate reconstructions in the next section.

We interpreted these SLOPTSZs as structurally buoyant mantle keels that had a profound influence in the outcome of the high-oblique extension along the Santos-Namibe rift segment. They defined the boundary conditions for the lateral flow of the continental lithosphere and their associated cratonic underplating during the transtensional inversion. This is a kind of unique character in the Santos-Namibe margin, when compared with other wide margin environments. It is a particular case of the type II margin of Huismans and Beaumont (2011).

The Paraná Etendeka Magmatic Province - LIP (PEMP-LIP) is considered the surface expression of the Tristan-Gough (TG) plume head on the continental crust (Storey, 1995; Thiede & Vasconcelos, 2010; Janasi et al., 2011). Rocha et al. (2020) reviewed the PEMP-LIP, based on high-precision U-Pb ages, and demonstrated that the volcanic outpouring of silicic magma in the Brazilian side, erupted rapidly at ca. 133.6 Ma within 0.12 ± 0.11 ky. They concluded that the duration of magmatism is around 700,000 years. According to Gomes et al. (2021), who reviewed the emplacement timing, duration, and rates of magma extrusion of the PEMP-LIP, the first stages of the eruption occurred around 135.0 ± 0.6 Ma, and the eruptions may have stopped at 132.0 ± 0.2 Ma.

In a recent review paper, Gordon et al., 2023 divided the magmatic cycles in the Santos Basin (onshore and offshore) into three categories: i: (135 to 130 Ma) rift-onset (also known as pre-rift); ii: (130 to 112 Ma); and iii: (110 to 40 Ma) - drift (also known as post-breakup). The rift-onset magmatism (flood basalts) into the continental basement of the Santos Basin is interpreted as the offshore extension of the onshore tholeiitic magmatism of the Ponta Grossa dike swarm (PGDS).

Indeed, flood basalts analog to the PEMP-LIP covered the floor of the Campos, Santos, and Pelotas Basin s. These tabular lava flows, represented by the Camboriú Formation, are the economic basement of the Santos Basin. The conglomerates, sandstones, siltstones, and shales of the Piçarras Formation (Moreira et al., 2007) mark the arrival of a rift branch propagating from the North. The same lava flows event is named Serra Geral Formation in the Paraná Basin, recognized as the basement of the Pelotas Basin. Interpreted as a pre-rift section by Bueno et al. (2007), the volcanic successions are covered by the rift sequence of the Imbituba Formation (Barremian- Early Aptian), younger than the Hauterivian Camboriú Formation. Therefore, two competing and coeval rift branches became active during the Barremian in the Santos and Pelotas basins. While biostratigraphic and geochronologic evidence support chronostratigraphy control in the Santos Basin, the M-anomaly geomagnetic polarity timescale (GPTS) is typically used as a chronological reference in the Pelotas Basin and across the basins of the whole Austral Branch.

However, the M-anomalies observed in the South Atlantic crust are not as complete as a full M-anomaly sequences (M0–M25) observed within the central North Atlantic crust (Tominaga and Sager, 2010). Moulin et al. (2010) claimed that M11 and M9 anomalies do not exist and suggested considering the M anomalies as part of a single anomaly named Large Marginal Anomaly (LMA). Based on deep seismic data and magnetic data, Paton et al. (2017) proposed that the SDRs of the Austral segment were produced subaerially on top of proto-oceanic crust resembling oceanic crust. Based on revised magnetic anomaly grids, Collier et al. (2017) recognized along-strike structural segmentation from Malvinas to Pelotas Basins (from M10r to M0). The authors concluded that these magnetic anomalies overlap mapped SDRs and are composed of sheet lava flows and not pillow basalts. Collier et al. (2017) interpreted that the SDRs were fed by dykes and subaerial spreading centers, between 134.2 and 126.3 Ma. M10r (134.2 Ma) is the oldest anomaly, observed between the Falklands/Malvinas TZ and the Colorado TZ. The magnetic anomalies became younger systematically northward up to anomaly M0 (126.3 Ma) in the Pelotas Basin. As a result, rather than dating from pure oceanic crust, the M-anomalies found in the South Atlantic crust are dated from a volcanic rift that formed on proto-oceanic crust. It was not until 113 Ma that pure oceanic crust was created through a seafloor spreading center north of the Florianópolis (Rio Grande) Fracture Zone (Moulin et al., 2010, 2012).

Stica et al. (2014) confirmed that the rift propagated northward within the Pelotas Basin. The authors recognized three volcanic rift stages: (i) 130 - 127.5 Ma; (ii) 127.5 - 125 Ma, and (iii) between 125 and 113 Ma (Figure 2).

The trail of the Tristan-Gough (TG) plume head in the oceanic crust has been mentioned by O'Connor and Duncan (1990), Müller et al. (1998), Meisling et al. (2001), Reuber et al. (2019), O'Connor et al. (2012), and Rohde et al. (2012). Matos (2021) projected a more comprehensive trail of the TG plume head in the continental crust beneath the hyperextended Santos Basin, following

Quirk et al. (2013), who suggested a linear migration path for the TG hotspot track beneath the Santos Basin. The author interpreted an E-W bend in the TG plume trajectory, which deviated from its northwest drifting course, as a direct result of South America's clockwise rotation with respect to Africa, based on a comprehensive plate reconstruction.

The Ponta Grossa Arch is an outstanding northwest striking set of faults, many of them filled with dolerite dykes (Strugale et al., 2007). This structural feature has an exceptional magnetic signature, extending hundreds of kilometers across the Paraná Basin. The possibility of the Ponta Grossa Arch to be associated with a thermal uplift of the Tristan-Gough plume has been explored by many authors (O'Connor and Duncan, 1990; Strugale et al., 2007; Moraes et al., 2020; Matos, 2021). According to Strugale et al. (2007), extensive erosion preceded the dike swarm emplacement and the sedimentation of the aeolian deposits of the Botucatu Formation. Moraes et al. (2020) described field evidence of intercalations of the Botucatu Formation with the volcanic rocks of the PEMP-LIP.

Zalán et al. (1990) suggested a genetic link between the Ponta Grossa Arch and the Curitiba-Maringa fault zone. Conceição et al. (1988) suggested the presence of left-lateral movements in the Curitiba-Maringa fault zone, associated with the clockwise rotation of South America with respect to Africa. Salomon et al. (2017) proposed that the southern portion of South America rotated clockwise away from its northern portion, and from Africa during the breakup. To obtain tight fits between South America and Africa, some authors envisage internal deformation corridors in South America (Unternehr et al. 1988; Torsvik et al., 2009; Moulin et al., 2010). Such models suggested a significant amount of left-lateral displacement along the Ponta Grossa Arch (Torsvik et al., 2009; Moulin et al., 2010).

Based on extensive fieldwork and paleo stress analysis, Strugale et al. (2007) recognized two tectonic events in the Ponta Grossa Arch, named D1 and D2. The first event controlled the generation of brittle structures, progressive deformation, and the emplacement of dike swarms along its NW–SE orientation. Early D1 structures (dikes) are associated with left-lateral N40-55W faults. According to Strugale et al. (2007), "after magmatism, a set of N–S normal, N20W right-lateral, and N50E left-lateral conjugate faults originated by stress-field rotation and reduction in deformation magnitude". The Late Cretaceous-Tertiary D2 event was generated by a transtensional strike-slip system, which activated faults along the dikes during the Late Cretaceous-Tertiary.

Figure 5 illustrates a plate tectonic reconstruction representing the 134-130 Ma interval, or a time snapshot between the 133.6 Ma volcanic outpouring of silicic magma from the PEMP-LIP and the opening of the Malvinas/Falkland segment of Austral Branch (134.2 Ma), followed by the arrival of two contending rift fronts around 130 Ma. With the onset and continuity of seafloor spreading around the Malvinas Island (pink line in Figure 5), the outcome was an increase in the angular and rotational momentum of the southernmost portion of the South American plate. This led to the development of a micro-plate, composed of Chile, Argentina, Uruguay, and parts of southern Brazil, Paraguay, and Bolivia (Figures 5 and 6). We interpret the Ponta Grossa dike swarm as fissural magmatism, emplaced along an opening mode fracture system (type I), as illustrated in Figures 5 and 6.

This interpretation is in line with the kinematic structural study of Strugale et al. (2007), who suggested that additional right-lateral faults during dike intrusion and a 200–300 clockwise rotation of the SHmax stress field were the causes of the D1 tectonic event. A dextral strike-slip deformational component would overprint the opening mode fracture system (type I), even though the rotation quantity is incompatible with plate reconstruction during the dike emplacement project.

The Proterozoic inheritance, represented by the Ribeira and Dom Feliciano belts and by the Tristan-Gough Plume in the western region of the Paraná Basin would have favored the development of a rotation pivot in the Ponta Grossa Arch. Later in the Aptian, there would be additional rotation-related intraplate deformation that would be recorded by compression along the Demerara and Guinea plateaus and transpressional deformation of the Solimões Mega Shear Zone (Caputo, 1991; and Casey et al., 2015).

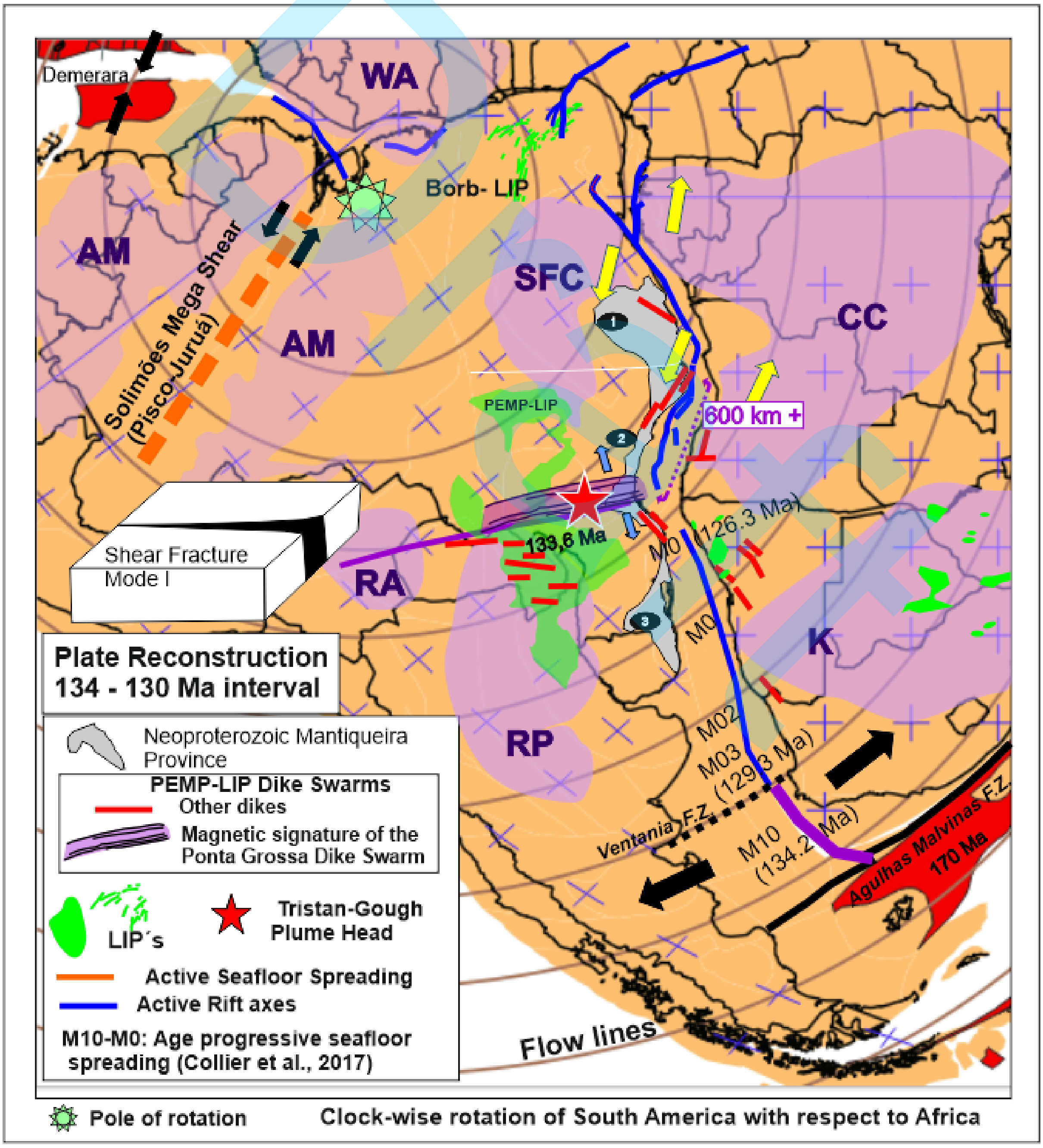
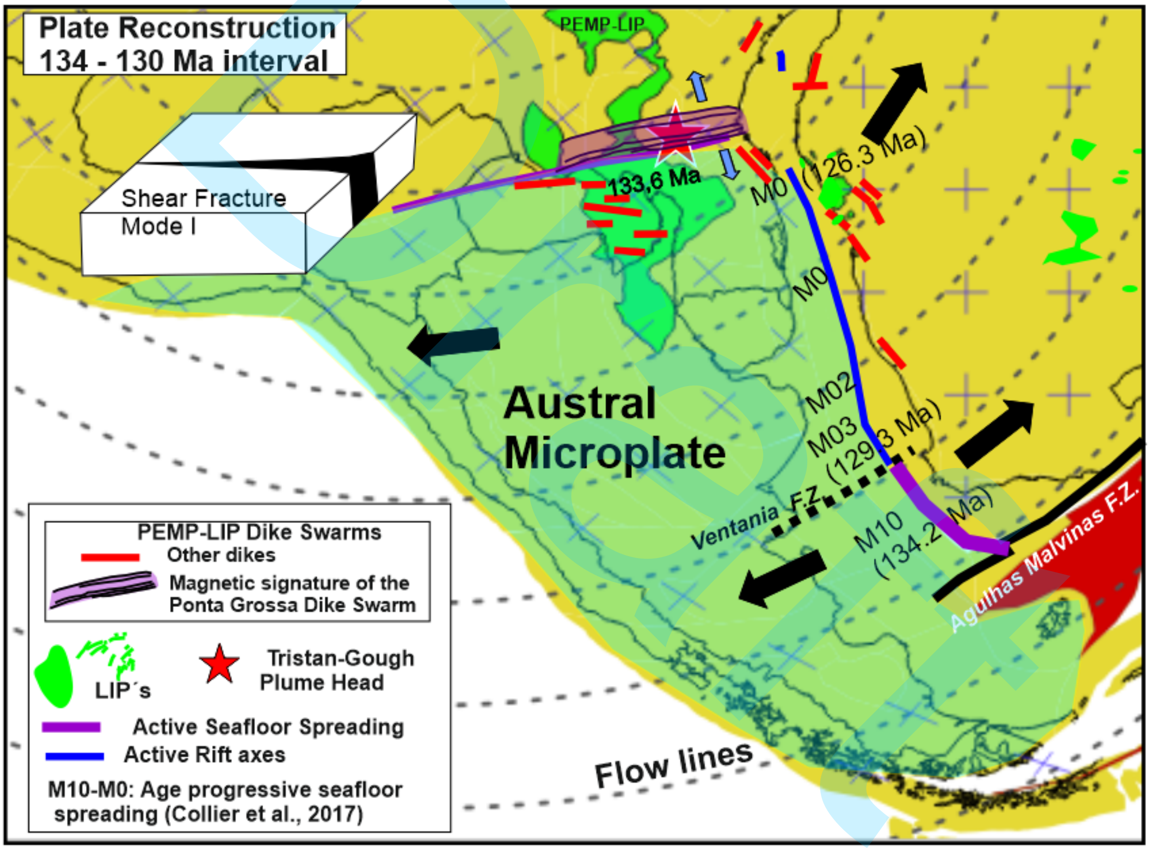


Figure 5. Plate tectonic reconstruction represents the 134-130 Ma interval, with Africa fixed in present-day coordinates (Source: PLATES Project, Matos et al., 2021). Geopolitical boundaries in black lines. South America is starting its clockwise rotation around a pole near the Marajó Basin, in northern Brazil. Active rift axes in blue lines. Small black ellipses are 1- Araçuaí, 2- Ribeira and 3- Dom Feliciano Fold Belts. Seafloor spreading started at 134.2 Ma between the Ventania and Agulhas-Malvinas Fracture Zones (red line, Collier et al., 2017). Aptian intraplate deformation was recorded by the Solimões Mega Shear Zone (dashed orange line, Caputo, 1991) and by compression along the Demerara and Guinea plateaus (Casey et al., 2015). Proterozoic cratons in light pink; CC: Congo; SFC: São Francisco; K: Kalahari; WA: West African; AM: Amazonas; Apa + Pampia; RP: Río de La Plat



Working hypothesis of the Austral Microplate (transparent green)

Figure 6. Zoomed in view of Figure 5 with the possible boundaries of the Austral Microplate, which rotates clockwise away from the continuum segment of northern South America and Africa.

Figures 7 and 8 illustrate the magnetic signature of the Ponta Grossa dike swarm. These magnetic and structural linear features extend between Brazil and East Paraguay, with a maximum width of 100 km. Figure 8 illustrates that these magnetic/structural lineaments can be traced all the way to the Bolivian Orocline.

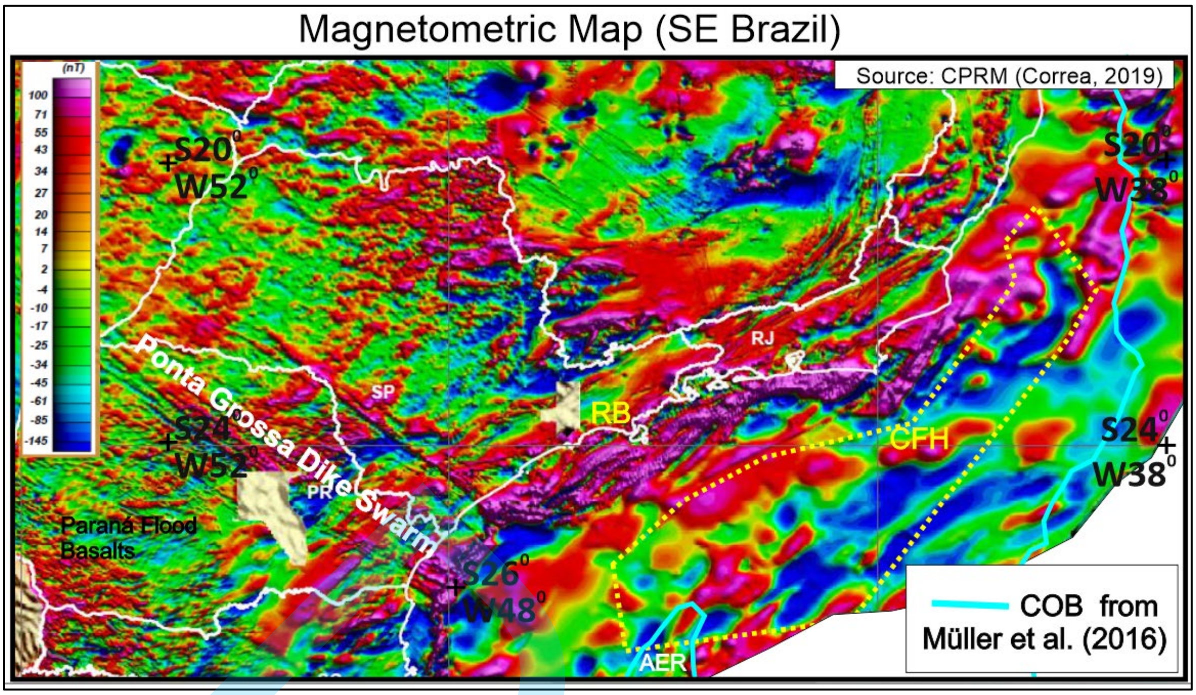


Figure 7. Magnetometric map of SE Brazil. The magnetic signature of the Ponta Grossa dike swarm (NW-SE) is overwhelming, as well as the NE-SW rock fabric of the Proterozoic Ribeira Fold Belt (RB). Dashed dark blue lines define the legal limit of the Brazilian Pre-salt Province, where world-class oil and gas reserves have been discovered since 2006. CFH: Cabo Frio High; AFR: Abimael Failed Rift.

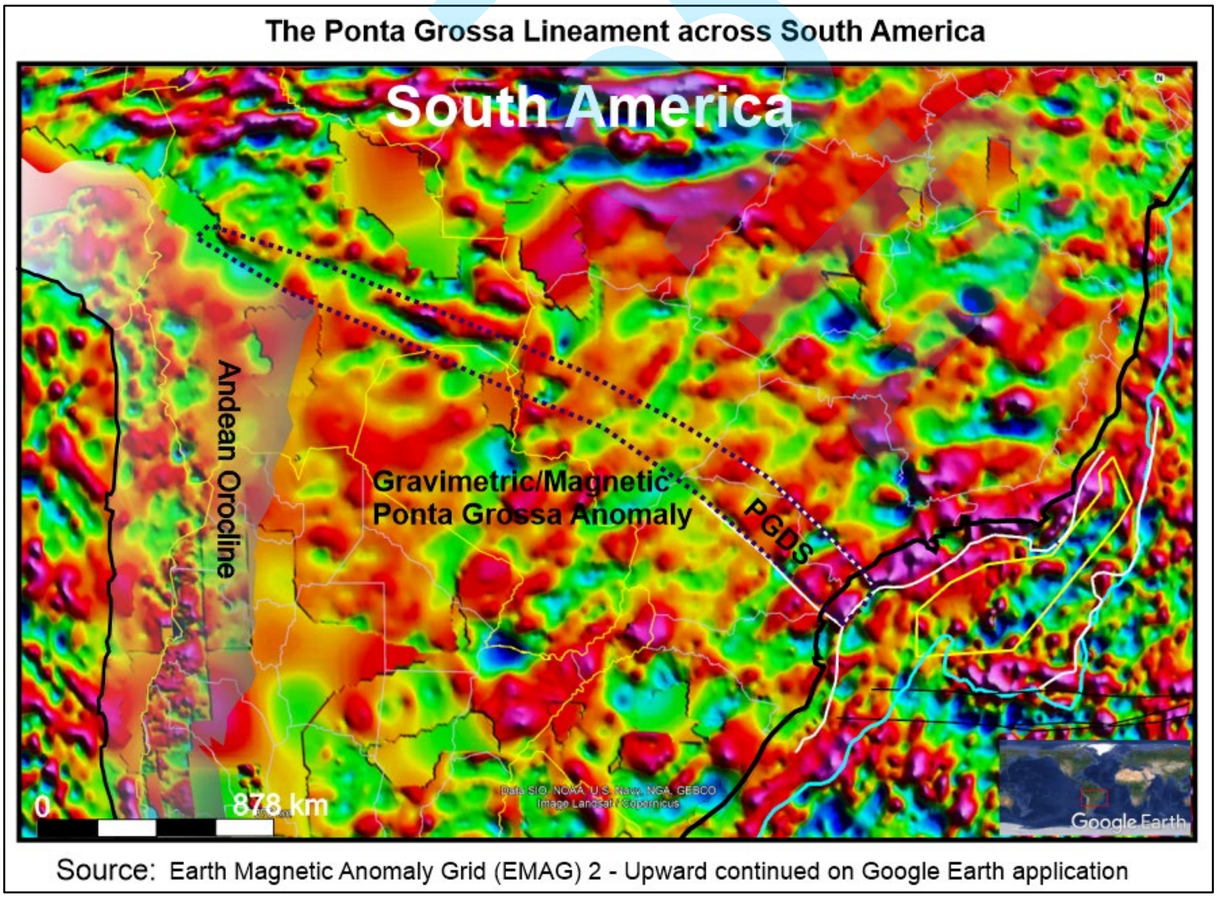


Figure 8. The magnetic signature of the Ponta Grossa Lineament across South America, aligned with

the main tectonic inflexion of the Andean Orocline. Light blue line: COB from Müller et al. (2016). PGDS (Ponta Grossa Dike Swarm) from Figure 7. Yellow polygon is the Brazilian Pre-salt Polygon. The westernmost white line is the Santos Basin´s hinge line.

The Santos-Namibe conjugate basins developed during the 130-113 Ma time interval, following the four Tectonic Stages II, III, IVa, and IVb, proposed by Matos et al. (2021):

- During Stage II (Figure 9a), magmatic activity is represented by the PEMP-LIP and the Borborema Large Igneous Province (BORB-LIP) while South America rotated clockwise about a pole in northern Brazil. This is the time when the two stretching branches first met around the Santos Basin, where this rift stage is represented by the Piçarras Formation (Figure 10).

- In Stage III (Figure 9b), compressional deformation occurred in the Amazon Basin and the Demerara Plateau, while South America continues to rotate clockwise, with a pole in northeastern Brazil. The Northeast Brazilian Intracontinental Rifts were abandoned, a dextral strike-slip system began to form at the Equatorial Branch, and the thinning rift phase started in the Santos-Namibe region. This rift stage is represented by the Itapema Formation in the Santos Basin (Figure 10).

- Africa and South America start their divergent movements during Stage IVa (Figure 9c), giving rise to the Equatorial Atlantic margin, while rifting is initiated at the southern portion of the Orthogonal Rift Branch.

- The deposition of the thick evaporite sequence was developed during the late stages of the Tectonic Stage IVb (113 Ma, Figure 9d), giving birth to the Central Salt Basins. The Orthogonal Branch experienced late intracontinental rifting (Pernambuco-Paraíba Basins), while the Equatorial Branch experienced a restricted marine depositional environment, with isolated rift basins developed under a dextral strike-slip tectonic regime. In the Santos Basin, the Barra Velha Formation represents this regional rift stage, corresponding to the transition from the thinning phase to the hyperextension phase (Figure 10).

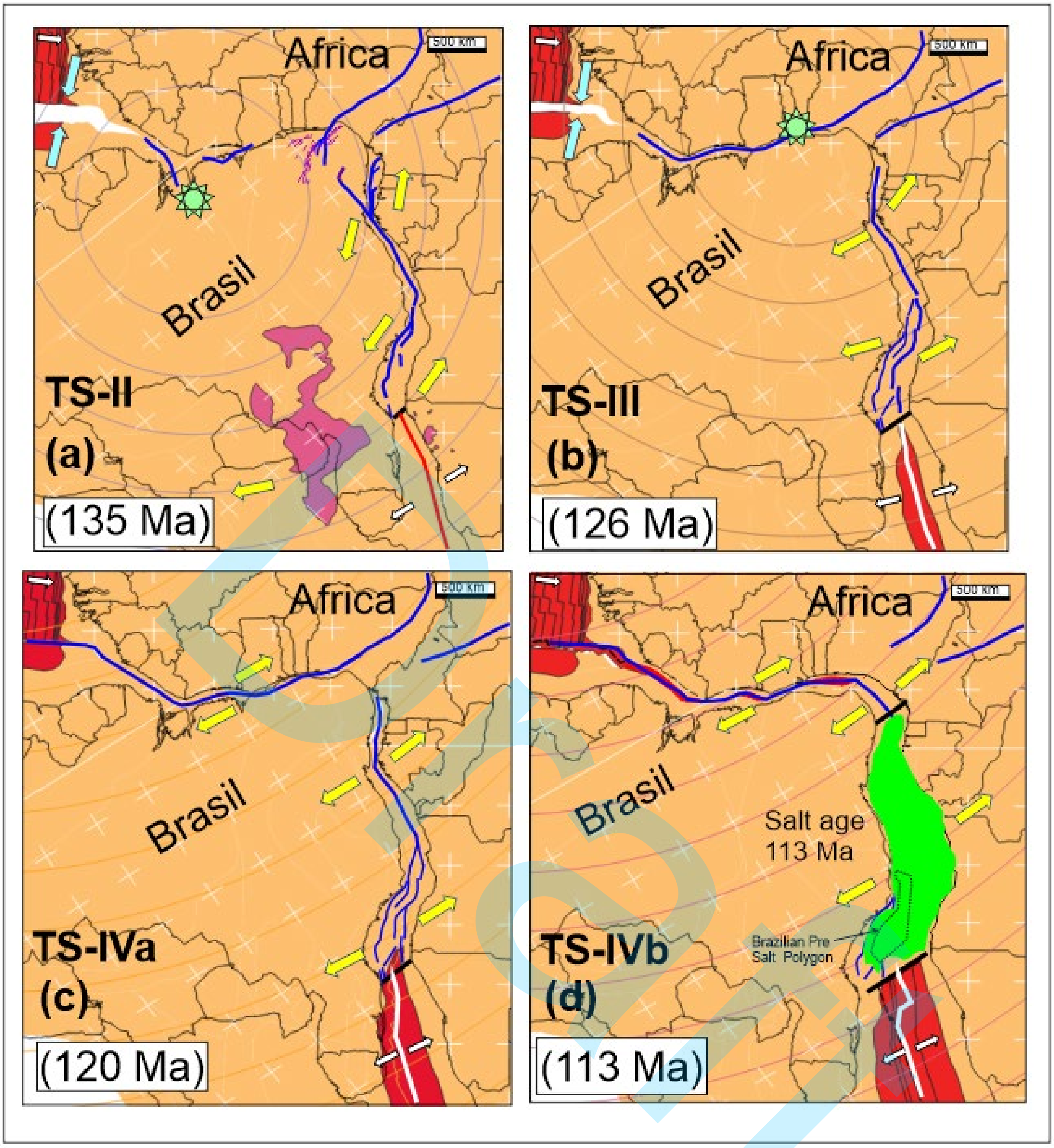


Figure 9. Time-lapse plate reconstructions of the South Atlantic according to Matos et al. (2021). (a) Tectonic Stage II, as displayed in Figure 2. (b) Tectonic Stage III. (c) Tectonic Stage IVa. (d) Tectonic stage IVb. Central Salt Basins (green polygon); Yellow arrows represent changes in plate kinematic transport direction in time and space. Red: Oceanic Crust and/or Proto-Oceanic Crust.

Syn-rift magmatism within the Santos basin was identified and reviewed by Gordon et al. (2023), characterized by Tholeiitic, high Ti basalts, basaltic andesite, trachy-andesite and volcaniclastic samples, observed and dated at the wells: (1) 107-124 Ma (wells SPS104DA, SPS105); (2) 116 & 121–124 Ma (well RJS617D);(3) 125.5 & 120-118 Ma (Mero Field); and (4) 110 to 117 Ma (well SPS86B). Another important syn-rift magmatism event is related to the Coastal dike swarm province, dated between 130 and 123 Ma, composed of basalts, basaltic-andesite, trachy-andesite, trachy-dacite and dacite. The second cycle of magmatism proposed by Gordon et al., (2023) is divided in two sub-cycles: (i) "ca.132-130 to 123 Ma" in the onshore Coastal dike swarm province, and (ii) "ca.123 to 113-112 Ma", within the offshore Santos basin. The first one can be correlated with the rift Stretching–Thinning transition, and the second with the Exhumation-Hyperextension Signature of sequential extensional deformation (SED, Fetter et al., 2018a), as illustrated in Figure 10.

The sedimentary successions of the rift stretching-thinning transition in the Santos Basin are represented by the Piçarras, Itapema, and lower Barra Velha formations. Conglomerates, polymictic sandstones, organic-rich black shales, and intrusive and extrusive magmatic rocks comprise the Piçarras Formation (Moreira et al., 2007). The upper limit of the Piçarras Formation with the overlying Itapema Formation is defined by a regional erosive surface, known as the Pré-Jiquiá unconformity (127 Ma) (Figure 10). At this time, the basin's structural heights were uplifted, and major erosion was under way. The siliciclastic rocks of the Itapema Formation are rich in coquinas and organic-rich dark shales with synchronous magmatism (Ren et al., 2020; Moreira et al., 2007). The Barra Velha Formation corresponds to a huge hyper-alkaline lacustrine system in a shallow environment, which consists of a lower lacustrine rift sequence and an upper lacustrine SAG sequence. The Barra Velha Formation is characterized by a sequence of limestones, stromatolites, microbialites, and dark shales (Moreira et al., 2007; Wright, 2020; Carvalho and Fernandes, 2021), associated with an Aptian chromogenic carbonate factory developed in alkaline lacustrine environments.

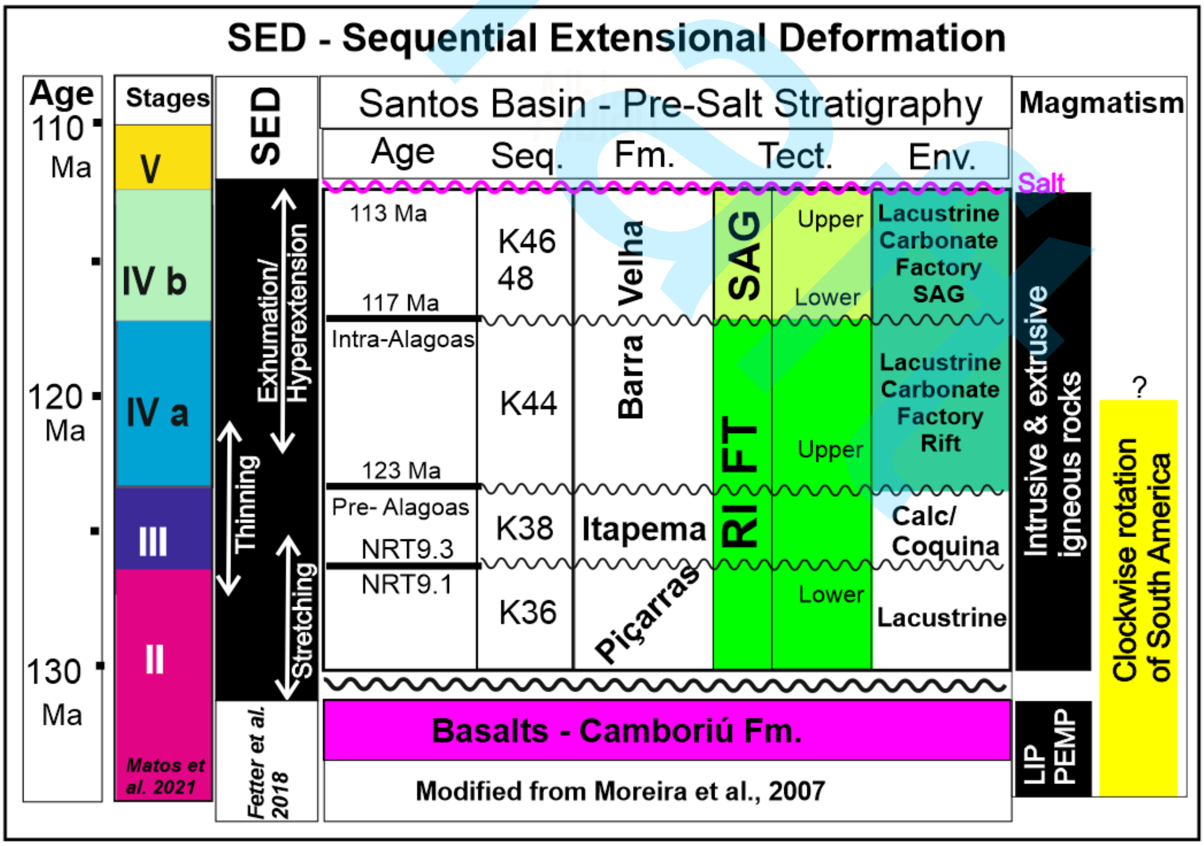


Figure 10. Signature of sequential extensional deformation (SED) of the continental crust in the Pre-salt stratigraphy of the Santos Basin (Modified from Moreira et al., 2007, and from Fetter et al.,

2018a). Rift stages (II, III, IVa, IVb and V) from Matos et al. (2021). The rift phase in Santos Basin had a late start and earlier breakup, when compared to the Orthogonal and Equatorial Branches of the SACRS. The sequences K36, K38, K44 and K46-48 were defined by Petrobras and their limits correspond to regional unconformities. The sequence boundary between K36 and K38 records a regional basin uplift and associated erosion. A thermal uplift is an alternative explanation, which may be associated with the arrival of the TG plume head beneath the basin.

THE SANTOS-NAMIBE BASINS AS A LARGE-SCALE RELAY ZONE OR A STRIKE-SLIP FAULT PROPAGATOR

The hyperextended terrains of the Santos-Namibe basins, first described as the “Buffer Zone” by Moulin et al. (2010), acted as a large-scale relay zone during the Aptian (Matos et al., 2021). Evain et al. (2015) and Moulin et al. (2012), interpreted the conjugate Namibe margin as a transform margin, which accommodated the southward propagation of the active rift zones coming from the north. Their idea of a local transform margin for the Namibe margin is controversial. The entire Namibian margin is an oblique-hinged margin, and the transform movements are restricted within the Florianópolis Lineament. On the other hand, Stica et al. (2014) confirmed that the rift propagated northward along the Pelotas Basin, during the Barremian. Even though the boundary between these two competing rift branches is the proto Florianópolis Fracture Zone, the Santos-Namibe conjugate basins acted as a large-scale relay zone between the Austral and the northern rift branches (Sinistral Southern, Orthogonal, and Dextral Equatorial branches of Matos et al., 2021; Matos, 2021).

Transform Marginal Plateaus, or TMPs, are described as "fragments of continental crust, thinned and individualized by several successive rifting and transform deformation episodes" by Loncke et al. (2020). Apart from the TMPs of the Falklands/Malvinas and Agulhas Bank, they also considered the São Paulo and Walvis plateaus in the South Atlantic, bounded by the Florianópolis Fracture Zone, as other possible candidates to be a TMP. Biari et al. (2021) also interpreted a TMP within the Santos-Namibe conjugate basins based on reconstructions from Evain et al. (2015) around 112 Ma. In this scenario, the TMP functioned as a rift barrier, halting heat flow in the mantle, leading to volcanism before and after rifting.

The Santos-Namibe conjugate basin has most of the characteristics of TMPs, as described by Loncke et al. (2020). The Santos Basin hosts the faulted border margin, while the Namibe Basin hosts the hinged margin. The Florianópolis Transform Fault is the boundary between the Santos-Namibe and Pelotas-Walvis basins.

We use plate-kinematic reconstructions to illustrate how the Santos-Namibe Basins acted as a large-scale relay zone, 600 km wide, accommodating strain partitioning through a strike-slip fault propagator (or extensional step-over). The Santos mega relay was active from the Campos Basin to the North, up to the Florianópolis Fracture Zone, at the border with Pelotas Basin.

PLATE KINEMATICS AND DISPLACEMENT FIELD OF THE SOUTH ATLANTIC

A kinematically admissible displacement field describing the opening of the South Atlantic is illustrated in Figs 11, 12 and Table 1. The displacement fields of graticules pairs (a1, b1; a2, b2; etc.) in Africa and South America are illustrated in Figure 11. The selected graticule-pairs are used to quantify the changes in the linear distance between the pairs in both space and time. They are situated outside of any rift compartment. There is no relationship between the measured distance (elongation or contraction) and the distance to the Eulerian pole of rotation. Vectors of the relative plate motion in space and time are obtained from the change in position of the selected graticules. The position of the selected graticule is tracked at each reconstruction of the plate.

Table 1 shows the variation in length between any pair of graticules. The length and position changes at several time-slice reconstructions are listed in the table, starting at 140 Ma (a pre-rift configuration) and ending at 114 Ma, right before salt deposition, and then continuing until 84 Ma (magnetic anomaly Chron 34).

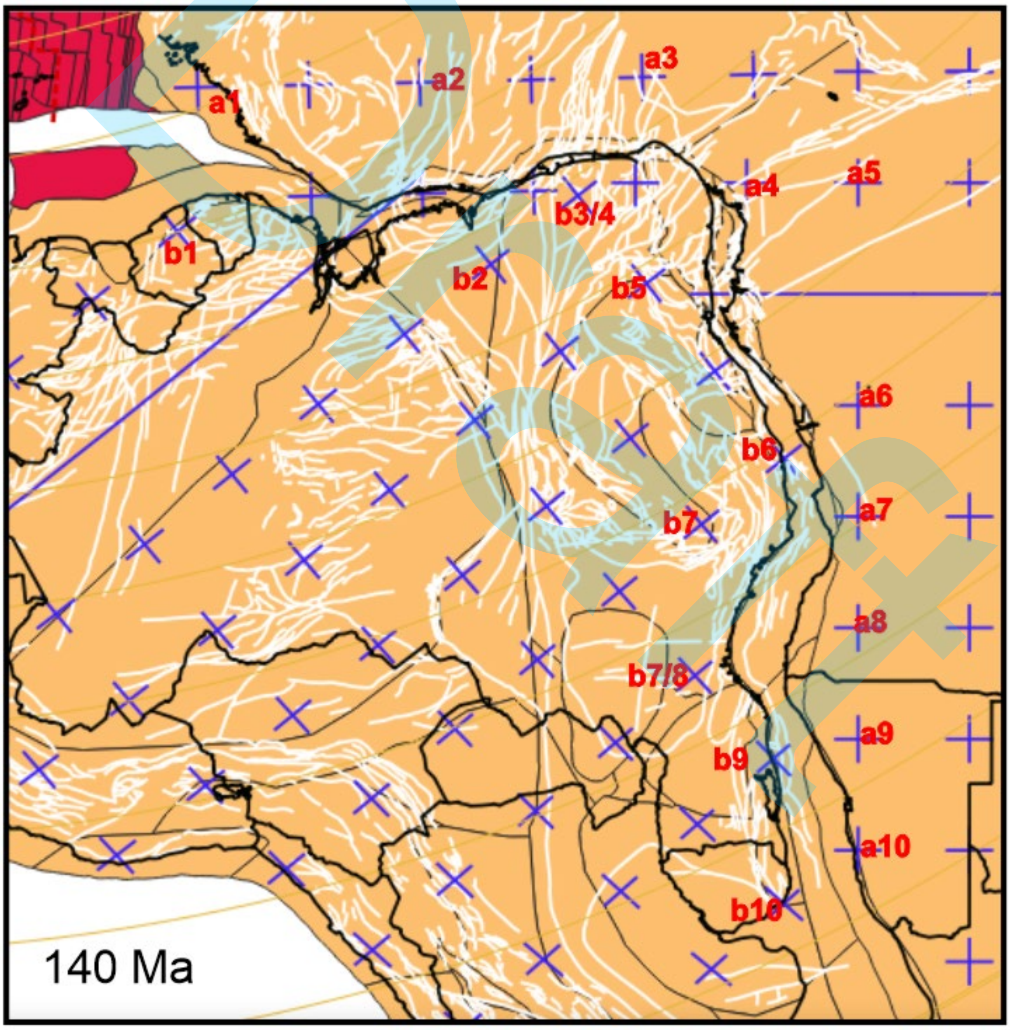


Figure 11. Plate reconstruction at 140 Ma (PLATES Project), showing 10 graticule pairs (a1 to a10 in the African side and b1 to b10 in the Brazilian side) that were used to track the relative plate motion during rifting in the South Atlantic. The movement of these graticules in time and space mimics the relative movement of the South American and African PLATES according to our PLATES Project´s reconstructions and the chosen poles of rotation, as discussed by Matos et al. (2021).

Finite Strain (change in length) through time												
Graticule Pairs		140	134	140-134 %	126	134 -126 %	120	126-120 %	114	120-114 %	Finite Strain 140-114 Ma	
Distance (km)	a1-b1	650	646	(0.62%)	588	(8.98%)	519	(11.73%)	604	16.38%	(7.08%)	Demerara
	a2-b2	883	879	(0.45%)	893	1.59%	893	0.00%	947	6.05%	7.25%	Equatorial
	a3-b3/4	608	618	1.64%	647	4.69%	658	1.70%	813	23.56%	33.72%	
	a4-b3/4	756	768	1.59%	757	(1.43%)	773	2.11%	927	19.92%	22.62%	Orthog Zone
	a5-b5	1056	1066	0.95%	1104	3.56%	1145	3.71%	1328	15.98%	25.76%	SSB
	a7-b7	705	722	2.41%	812	12.47%	912	12.32%	1117	22.48%	58.44%	
	a7-b7/8	1023	1050	2.64%	1188	13.14%	1308	10.10%	1536	17.43%	50.15%	Santos
	a8-b7/8	764	787	3.01%	933	18.55%	1066	14.26%	1297	21.67%	69.76%	Pelotas
	a9-b9	390	426	9.23%	600	40.85%	758	26.33%	996	31.40%	155.38%	Austral
	a10-b10	409	452	10.51%	670	48.23%	864	28.96%	1111	28.59%	171.64%	Branch
				red numbers - shortening								
				black numbers -stretching								

Table 1. The relative change in length of 10 graticules pairs (original position illustrated in Figure 11) are listed through time (140, 134, 126, 120 and 114 Ma). The a1-b1 graticule pair recorded the shortening between the Demerara and Guinea plateaus. The amount of shortening and stretching is not uniform at different time intervals, reflecting changes in plate kinematics. The continuous increase in total elongation from the Equatorial Branch towards the Austral Branch is related to the increase in the length of an arc, measured from different poles of rotation, early situated in the North Atlantic (140 Ma), in North Brazil (135 Ma), Northeast Brazil (126 Ma) and back to North Atlantic (114 Ma).

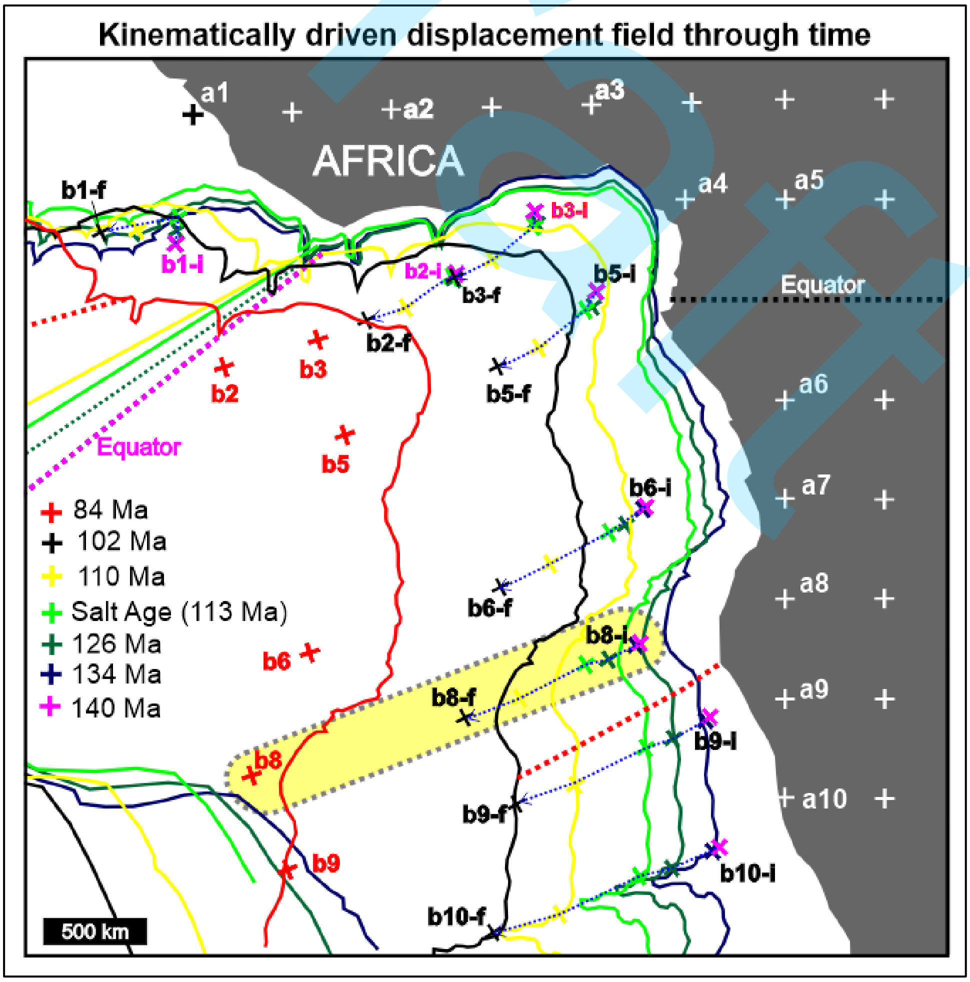


Figure 12. Set of global plate kinematic reconstructions for the time interval 140-84 Ma. The path of the South American plate during rifting is illustrated by the change in space and time of the graticules b1 to b10 (from the Guyana's towards Argentina). The dashed blue arrows illustrate the change in the position of any specifically chosen graticules initiating at 140 (dashed-i) and finishing at 102 Ma (dashed-f). Plate kinematic transport direction is illustrated by these colored crosses, from its original (pre-rift) position at 140 Ma (pink cross) towards its position at 102 Ma (black cross). Red represents the reconstruction during the time of geomagnetic anomaly 34 (84 Ma). As there is no consensus about COBs or breaking boundaries along the South Atlantic, plate drifting is illustrated using the actual shorelines of Africa and South America in time and space. Africa is kept at this actual position, while the South American plate is moving westward. The transparent yellow polygon, with dashed gray line illustrates the displacement of the graticule b8 in the South America plate through time, within the Santos Basin.

Although there are four distinct positions for the poles of rotation within the time frame between 135 and 113 Ma (Figure 9), the displacement vector in the Santos Basin is approximately E-W (with respect to Brazil in its actual position). Refer to Figure 12. Rather than the intricate model of internal structural blocks in a transform passive margin put out by Moulin et al. (2012), we present a straightforward kinematic model in which the strain partitioning aligns with the initial description of an oblique-sinistral extensional system by Macedo (1990).

THE STRUCTURAL FRAMEWORK OF THE SANTOS BASIN

Probably due to the strong competition for giant oil and gas accumulations in the Brazilian pre-salt province, there are no industry-born, up-to-date structural framework maps for the Santos Basin. Most of the published structural data pre-dates the giant oil discoveries of Petrobras and is not focused on ultra-deep water. Giro et al. (2021) recently published a simplified geological map of the Santos Basin with the distribution of normal faults and picked NE trending magnetic anomalies, near parallel to the rift faults of the basin. Rigoti (2015) offers a good and consistent review of the entire Santos Basin. The author recognized two tectonic domains: (i) Proximal and (ii) Distal. The Distal domain (deep-water) is subdivided into Internal Rift, External Rift, and Resistant Block. The author also recognized two "Core-Complex type" detachment systems located within the Internal and External Rift domains, respectively.

The Outer High of Santos Basin (Gomes et al., 2002) or the Santos External High (Carminatti et al., 2008) hosts most of the giant deep-water oil and gas fields discovered in the Brazilian Pre-Salt Province (Gomes et al., 2012). This is a 200 km long, 60 to 40 km wide-syn-rift basement high (Figure 4), developed during the Aptian hyperextension of the continental crust. This basement high can be defined as an "isostatic body", as defined by Peacock and Banks (2020), where the uplift is isostatically driven by syn extensional magmatism (Matos, 2021), with tectonic denudation along low-angle normal faults (Fetter et al., 2018a, 2018b). The terrain was sculpted by footwall uplift at the points of rotational fault blocks, with younger syn-rift sediments being deposited around and above these structural highs, with erosion on the crestal portion of these basement tips (Peacock and Banks, 2020).

The structural framework of the Santos Basin was created by a deformation process that began with “Andersonian high-angle normal faults” during the rift's stretching phase and progressed to strike-slip faults and folds during the thinning phase to accommodate the above-mentioned regional E-W sinistral plate movement (Figs 10 and 13). Low-angle normal faults (LANFs) that define detachments with extensional duplexes and metamorphic core complexes accommodated the enormous extensional strain during the transition from the thinning phase to the exhumation-hyperextension phase (Figure 14). The LANFs shown in Figures 14 and 15 share a similar geometry with the shallow-dipping extensional detachment systems of the Gulf of Corinth and the U.S. Basin and Range province. These systems are known to be the result of large-magnitude continental extension caused by the exhumation of the upper mantle and/or lower crust (Whitney et al., 2012).

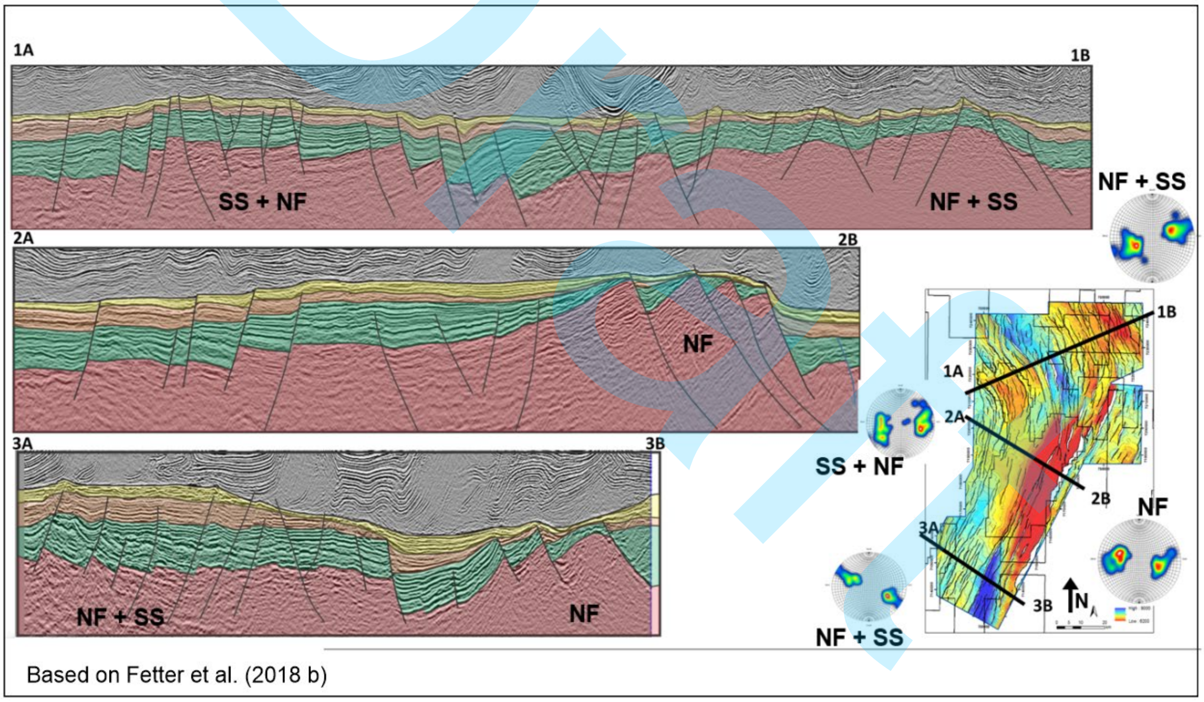


Figure 13. Seismic sections and structural map of the base of the salt around the giant Tupi field showing the deformation related to the interaction of Normal Faults (NF) and Strike-Slip Faults (SS) during the transition between the stretching phase and the thinning phase of the rift. Based on Fetter et al. (2018b). Stereonet patterns of the faults mapped in each subdomain indicate the main kind of fault. NF subdomains are typical half-graben structures with fault dips of 60-70º. SS subdomains have more steep dips, trend rotations, and inverted depocenters. Observe in the map, the S shaped trace (thin black lines) of folded rift structures related with the shortening direction of regional strike-slip kinematics. The regional location of the sections is in Figure 21.

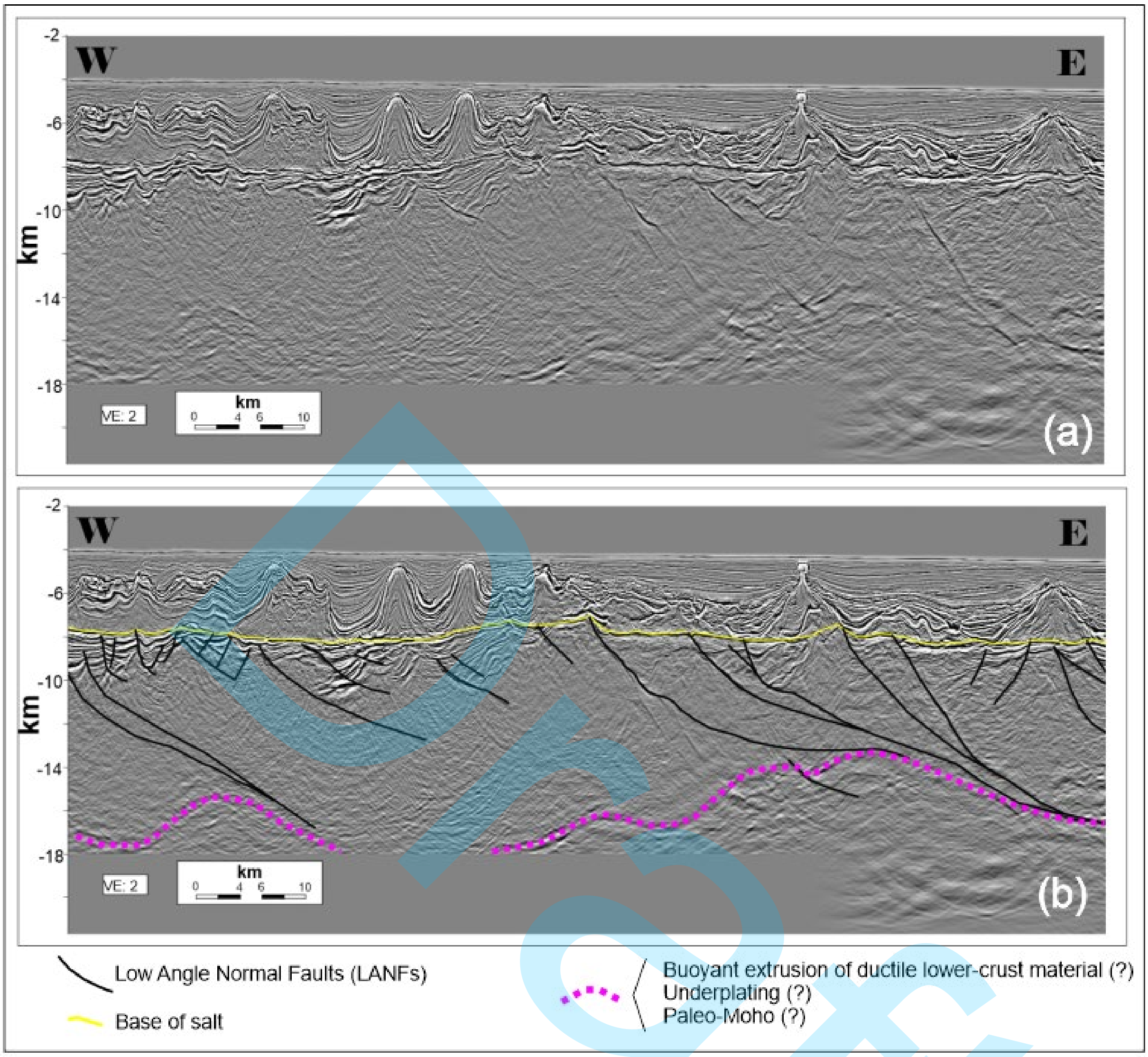


Figure 14.- Uninterpreted (a) and interpreted (b) EW 3D depth seismic line across the eastern part of Libra Block, towards the Saturn block in Santos Basin (regional location in Figure 21), displayed with 2x vertical exaggeration. Source: PPSA (proprietary data from CGG). These low-angle normal faults accommodated a large amount of displacement, and the presence of a domed-shaped structure is probably the result of isostatic uplift during tectonic denudation. The nature of these upward-arcuate intra-crustal reflections is not clear, but the overall geometry resembles the architecture of extensional core complexes. See depth map of the pink reflector in Figure 16.

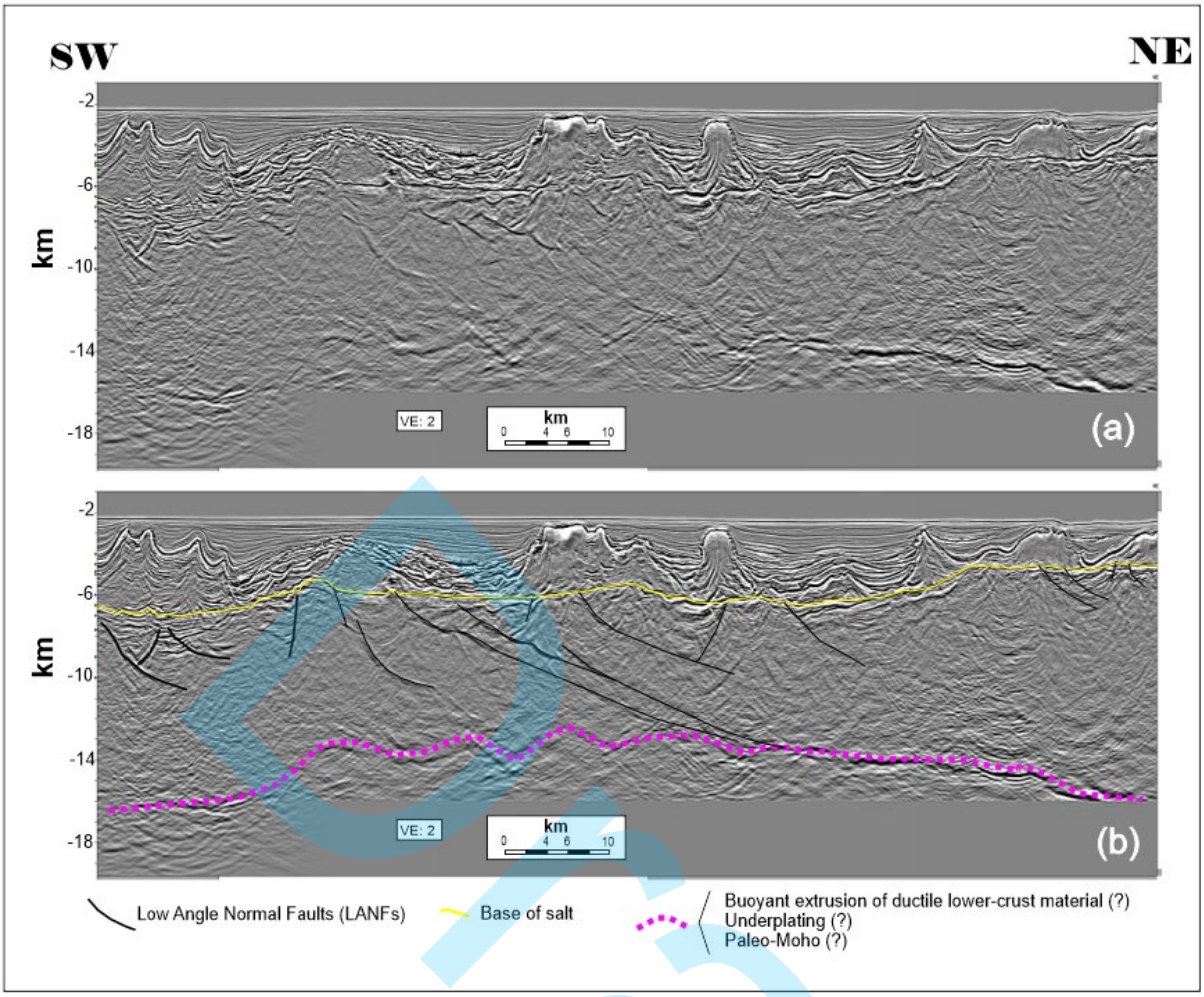


Figure 15. Uninterpreted (a) and interpreted (b) NE-SW 3D depth seismic line south of the Libra Block, in Santos Basin (regional location in Figure 21), displayed with 2x vertical exaggeration. Source: PPSA (proprietary data from CGG). The occurrence of Low-Angle Normal Faults (LANFs) is prevalent, as illustrated in Figure 14 and described by Fetter et al. (2018a, 2018b). See depth map of the pink reflector in Figure 16.

The Seismic Lines of Figures. 14 and 15 are located within the External Rift Domain of Rigoti (2015). The nature of upper-crustal reflections in these hyperextended terrains is not clear. We interpret that these extraordinary reflections from the upper crust could be paleo-Moho, underplating, or possibly the exhumation of the lower crust. The upper crust's thickness varies from 6 to 10 km in the vicinity of these dome-shaped formations.

Evidence of exhumation of the lower crust and isostatic uplift is documented in Figure 16, where dome-shaped intra-crustal bodies were mapped along the area between Libra and Saturno exploration blocks. The geometry suggested the presence of uplifted segments of the upper and lower crust. The existence of elongated domes going NW-SE and divided by small corridors is striking. The image bears a striking resemblance to the Metamorphic Core Complexes of the Basin and Range (USA), in which the direction of extension is parallel to the foliation's folded axis.

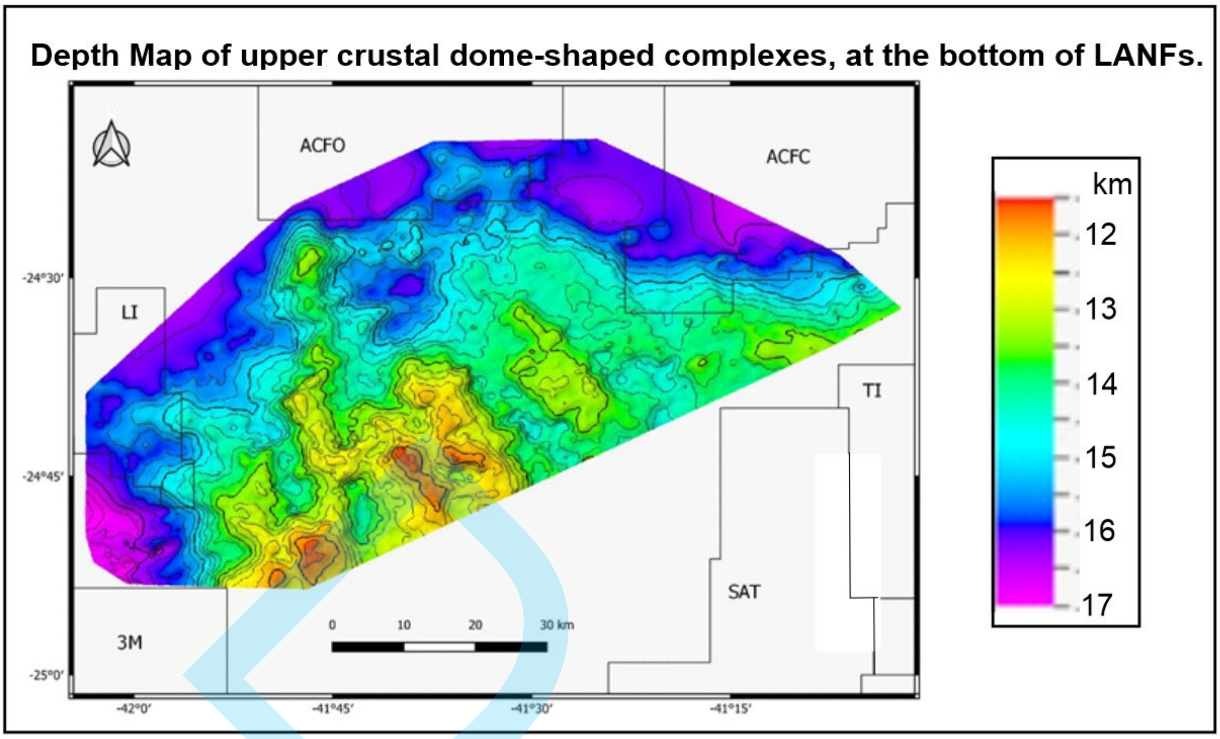


Figure 16. Depth map of the pink reflector illustrated in Figures 14 and 15. Source: PPSA (based on proprietary data from CGG). These intra-crustal bodies are characterized by NW-SE trending elongated domes separated by narrow corridors. The LANFs, displayed in Figures 14 and 15, sole into these dome-shaped structures interpreted as metamorphic core complexes (MCCs), possibly within the ductile middle/upper crust. The NW-SE trend suggests possible buckling caused by strike-slip shortening associated with the regional E-W sinistral deformation. The black lines represent the ring fences of exploration blocks (ACFO – Alto de Cabo Frio Oeste, ACFC – Alto de Cabo Frio Central, LI – Libra, 3M – Três Marias, SAT – Saturno, TI - Titã). Depth scale in km.

Figures 17 and 18 display seismic sections and map views of the base-salt surface, representing the bottom of the Ariri Formation (113 Ma salt layer in Figures 3 and 10) within the Santos Basin. In contrast to other salt basins offshore SE Brazil, where it is mostly smooth, the base-salt surface of the Santos Basin is rather rough (Amarante et al., 2021). The base-salt map (Figure 18) provides a frozen picture of the landscape toward the end of the Aptian in the Santos basin, and the stratigraphic process is characterized by a swift shift between syn-rift successions and salt deposition. It is significant to note that during this period, the entire rift relief was filled in, defining a regional transgressive package.
Like a proxy for the paleo physiography, which was governed by the structural framework at the end of the phase of lithospheric stretching, the base of the salt sequence surface resembles the structural framework at the end of the rift stage and can be used as a guide to identify paleo mountain ranges and their associated structural lineaments. The most prominent structural highs are, in general, supported by basement-resistant terranes, and the depocenters developed in the structural lows present a greater number of clayey sediments, leading to greater compaction throughout the evolution of the basin, in

opposition to what occurs on the active structural highs, where the smaller thickness and the more competent and rigid carbonate facies developed on a basement rock substrate, contributing to a lower compaction coefficient. It can therefore be expected that the topographic amplitude (hundred meters) between the structural highs and lows of the top of the SAG-sequence surface must have been smaller at the time of deposition (Carvalho and Fernandes, 2021).

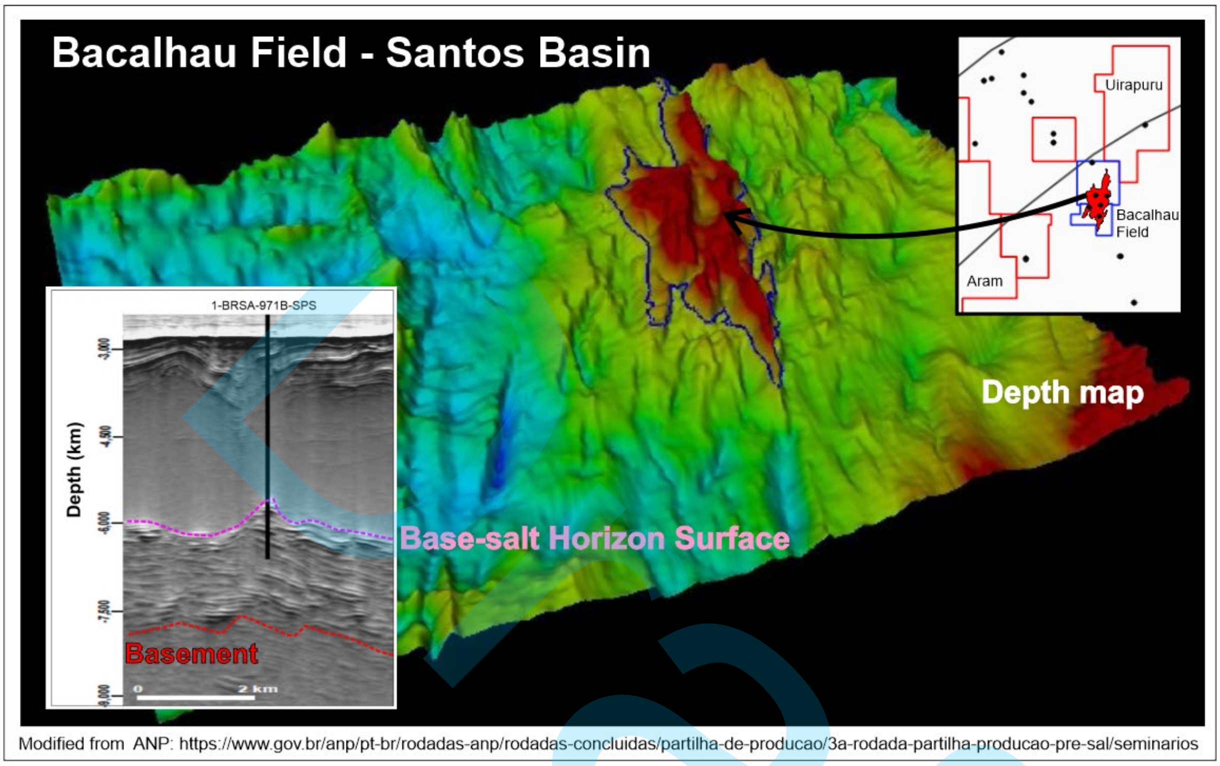
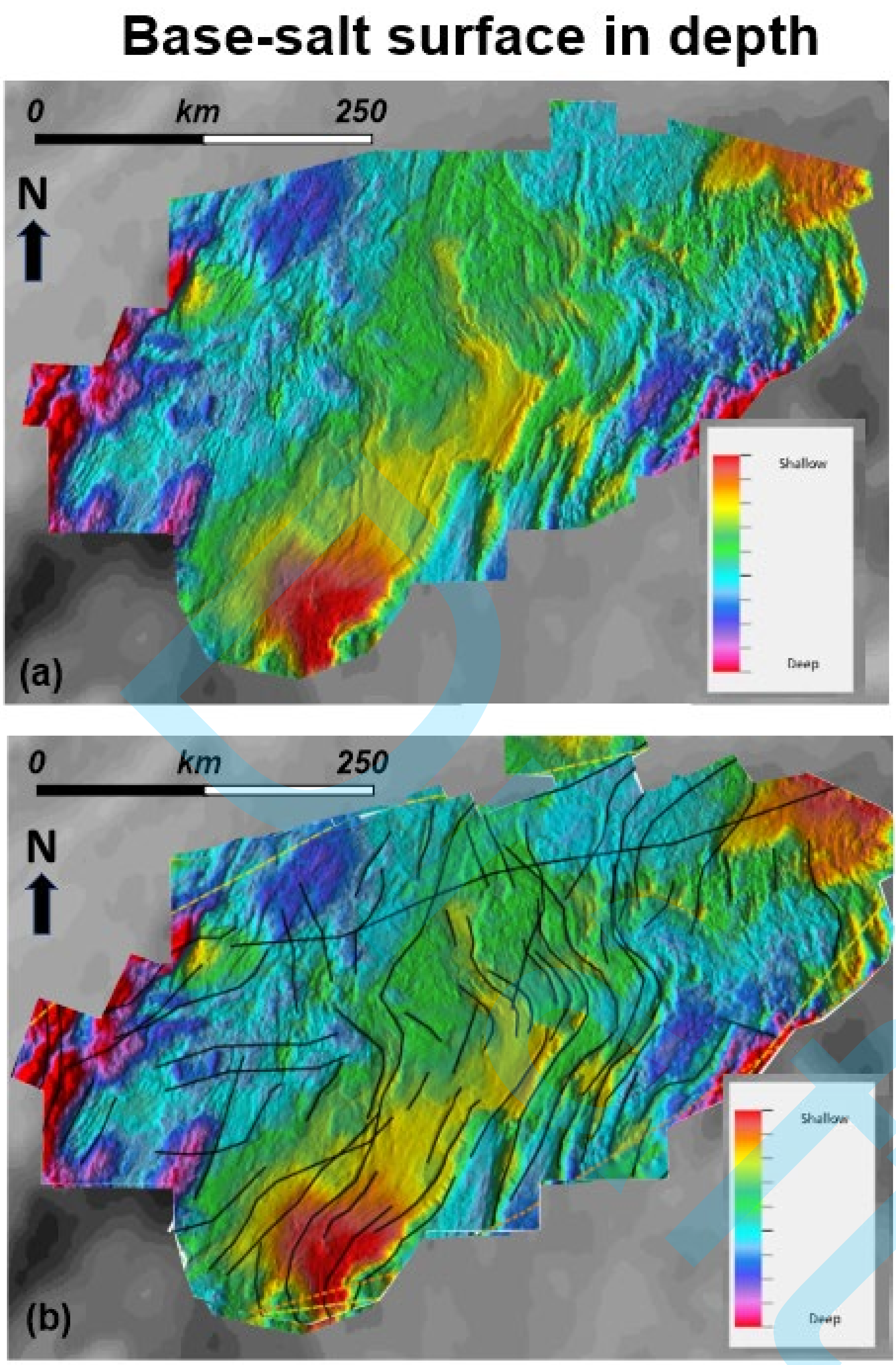


Figure 17. 3D view of the base-salt surface around the Bacalhau Field, Santos Basin. On the right: location map; and on the left: a zoomed seismic view (low frequency attribute, courtesy of CGG). Modified from ANP Bidding Rounds seminars. The base of the salt sequence map displays a clear image of the structural framework at the end of the rift and SAG stage in the Santos Basin. Regional location in Figure 21.

Figure 18 illustrates a high-resolution, shaded relief version of the base of the salt sequence surface. This is a regional base-salt map covering most of the Outer High and the legal Brazilian Pre-Salt Polygon. Sigmoidal shaped structural lineaments are interpreted in Figure 18.b, as well as transversal, roughly E-W striking lineaments. Figure 19 offers a zoomed-in view of the previous figure, with the location of world-class oil and gas fields of the Brazilian Pre-Salt Province. The morphology of the structural highs indicates the presence of strike-slip folded structures with sub-vertical fold axis. These folded lineaments observed in structural seismic maps can be also consistently interpreted in the magnetic anomaly map, reduced to the pole, as illustrated in Figure 20, which is based in the work from Rigoti (2015).



Modified from Carvalho and Fernandes (2021). Based on proprietary data from PGS and CGG.

Figure 18. Base of the salt sequence surface map in depth (a) and the interpreted tectonic lineaments (b) superposed on the vertical gradient map of the free-air gravity anomalies derived from satellite altimetry data (Sandwell et al., 2014). Map boundaries are constrained by the seismic surveys and not by the absence of salt deposition. (b) White lines: interpreted structural lineaments. The map is based on proprietary seismic surveys acquired by PGS and CGG. GIS information was not allowed by the seismic companies.

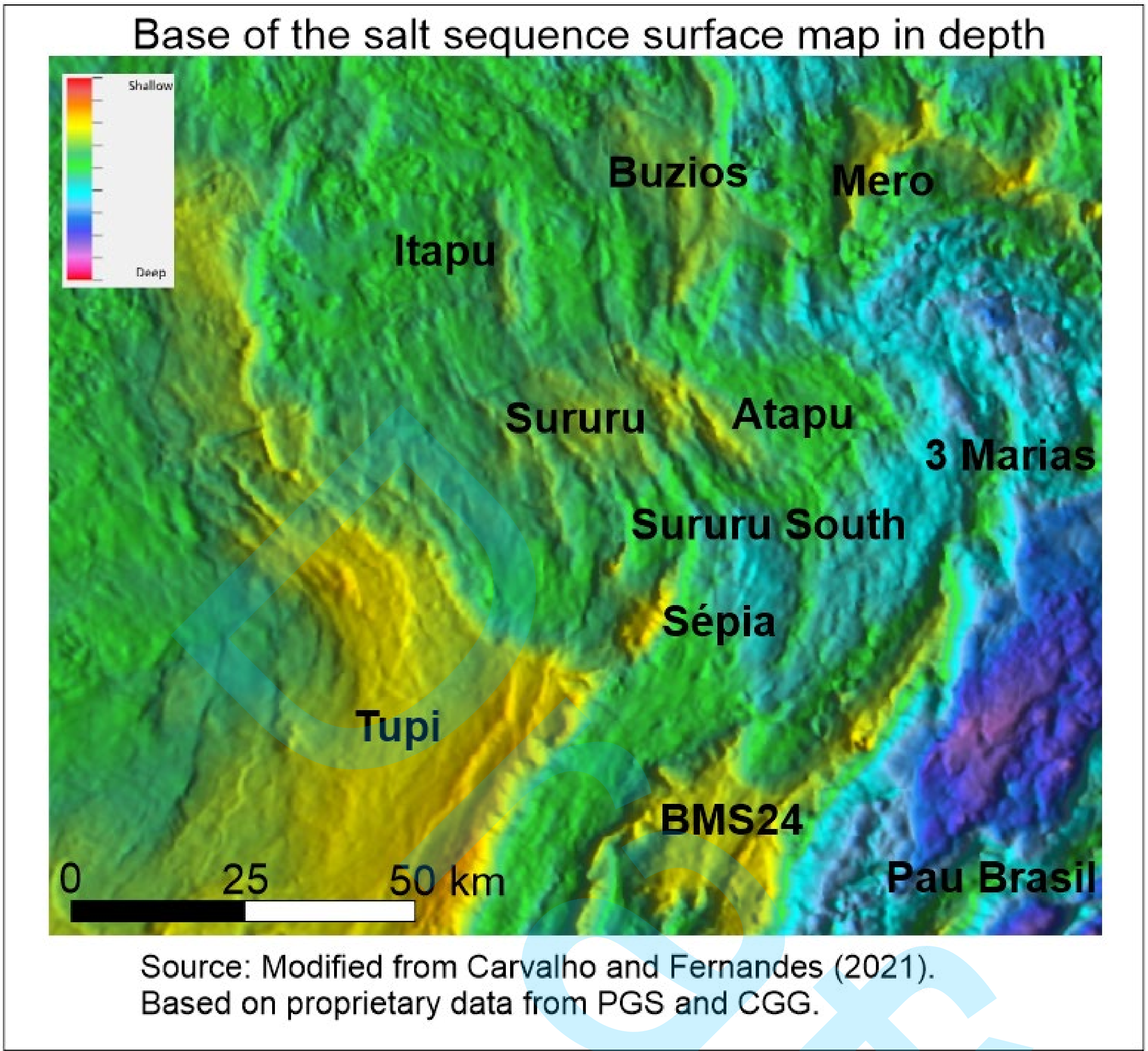


Figure 19. A zoomed-in segment of the base-salt surface map is illustrated in Figure 18. The observed morphology suggested the presence of large-scale basement-involved folded structures with sub-vertical fold axes. The approximate location of some of the giant oil and gas fields of the Santos Basin is displayed in black.

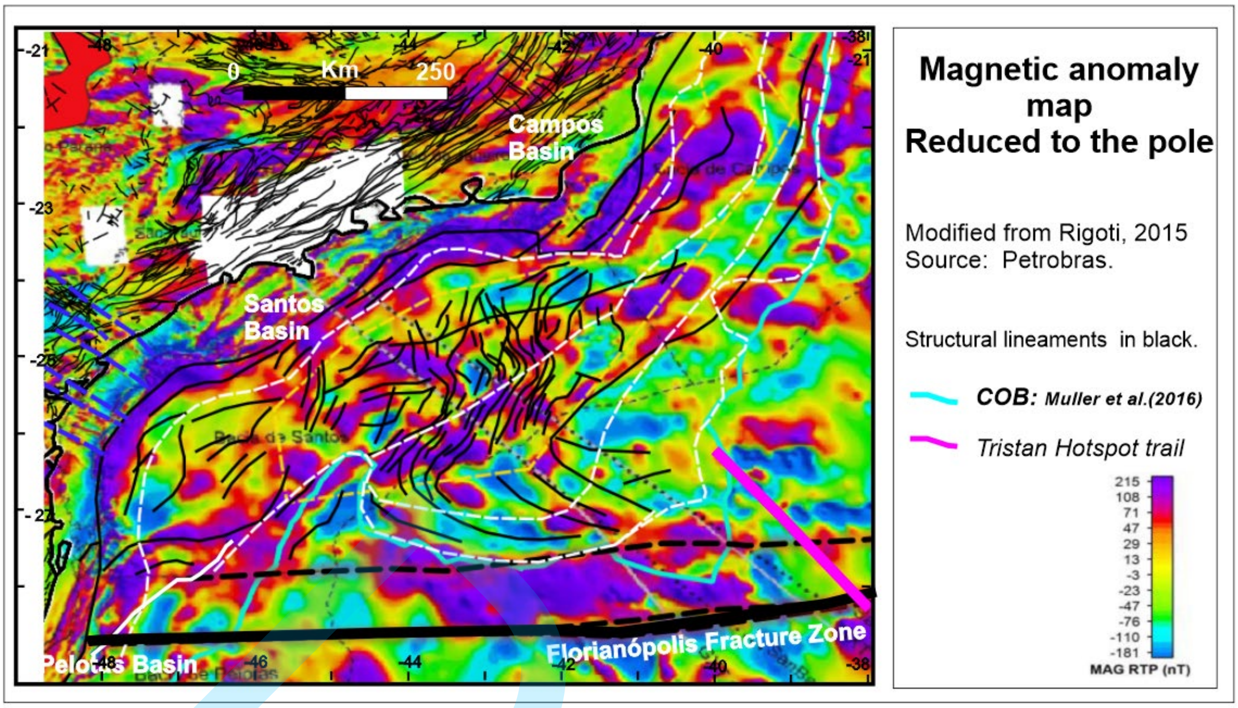


Figure 20. Magnetometric map of SE Brazil, reduced to the pole, was derived from merged airborne and marine geophysical surveys, Petrobras dataset (Modified from Rigoti, 2015). Structural lineaments, in black, partially from Figure 18 b. White dashed lines represent crustal domains, which will be covered later.

Figure 21 illustrates another version of the base-salt surface released by ANP (The Brazilian National Petroleum Agency). The main oil fields and interpreted exploratory leads in the Santos Basin are displayed on top of this surface. Figure 22 offers a zoomed view of the base-salt surface map illustrated in Figure 21, with a remarkable structural bend or fold, where the regional NE-SW basement highs turn to a NW-SW striking direction. This region is the south westernmost tip of the V shape rift geometry described by (Evain et al., 2015 and Rigoti, 2015), illustrated in Figure 3. The ANP´s leads distribution can be used as a useful guideline to identify more paleo mountain ranges, as illustrated in Figures 18, 19, and 20, where our proposed structural framework of the Santos Basin is presented.

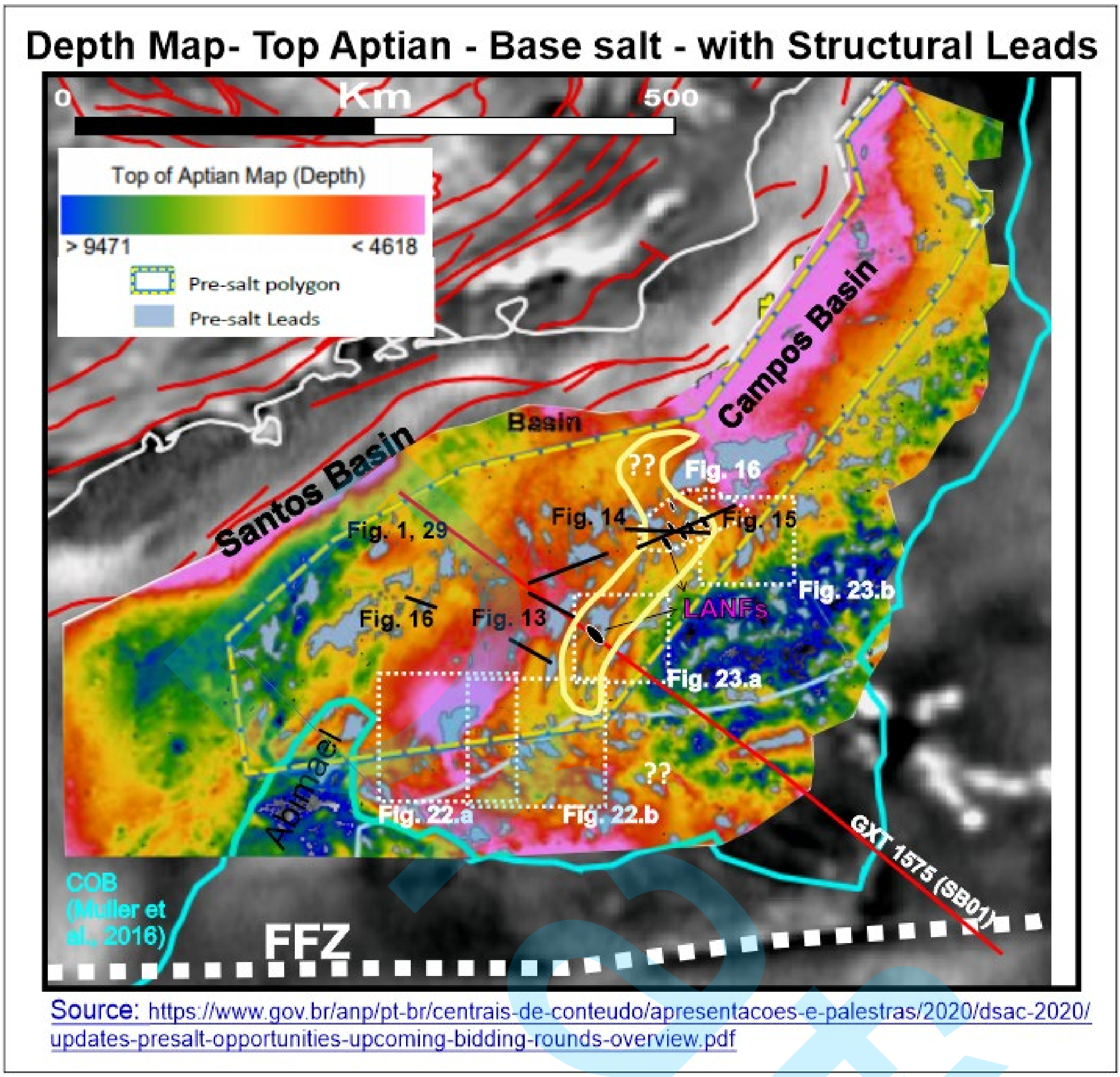


Figure 21. ANP´s version of the base-salt surface map superimposed on the vertical gradient map of the free-air gravity anomalies derived from satellite altimetry data (Sandwell et al., 2014). Dashed yellow line is the legal boundary of the Brazilian Pre-Salt Province. Light green polygons are oil fields and exploration leads from ANP. Red: Structural lineaments in shallow water. Blue line: COB from Müller et al. (2016). Dashed white polygons: Location of Figures 16, 22 and 23. Black lines: Location of seismic lines displayed in figures 1, 13, 14, 15, 17 and 29. Red line: location of Figures 1 and 29. Transparent sinuous white polygon: possible axis of hyperextended terrains dominated by LANFs. Black ellipsoids: dome-shaped core complexes, as illustrated in Figure 16.

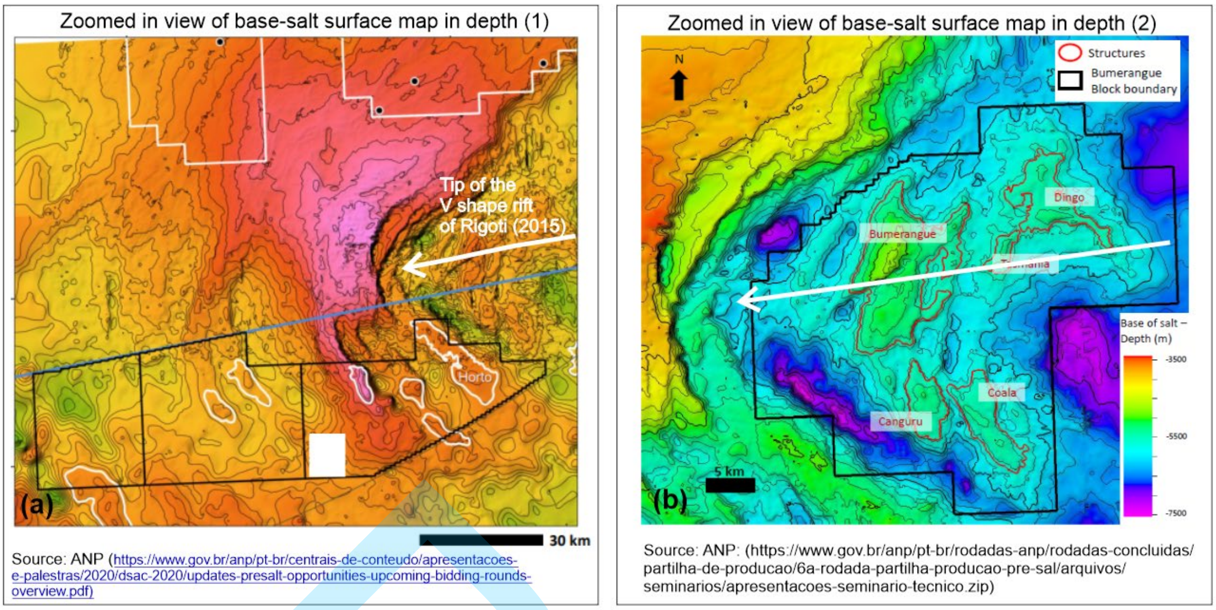


Figure 22. This is a zoomed-in section of the base-salt surface map (two overlapping pictures inside the dashed black polygons) previously shown in Figure 21. There is a pronounced structural bend from NE to NW structural trends. (Rigoti, 2015) defined this bend as a V-shaped fissure. It is a regional fold's sub-vertical axial trace.

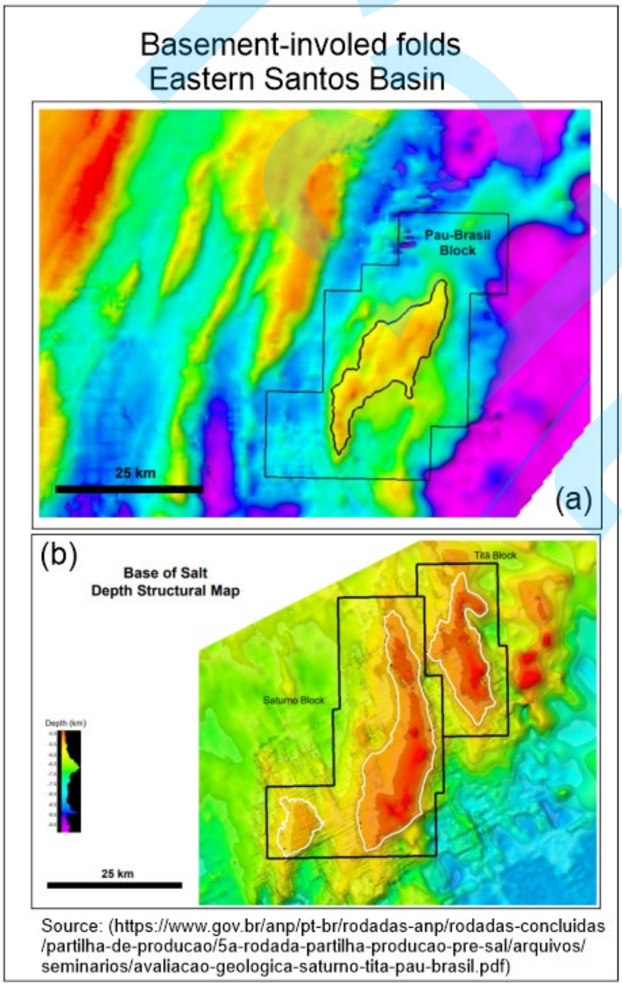


Figure 23. Zoomed-in segment of the base-salt surface map illustrated in Figure 21, displaying the eastern limb of a large-scale folded structure, originally described as a V shape rift (Rigoti, 2015).

Data from multiple sources are combined in Figure 24, which provides a new tectonic framework for the Santos Basin. A regional map of the top of the Barra Velha Formation, or the base of the salt, shows the geometry of folded structures involved in basement, which is the dominant feature (Figures. 15, 17, 18, 21 and 22). This observation is highlighted by the pink polygon in Figure 24, which was previously presented in Figure 21 and has a characteristic "double S" shaped curve or double sigmoidal geometry, suggesting overall shortening. Evidence of Lower Cretaceous shortening and inversion structures along the Santos Basin rift were suggested before by Alves et al. (2017). This topic will be covered further in this work.

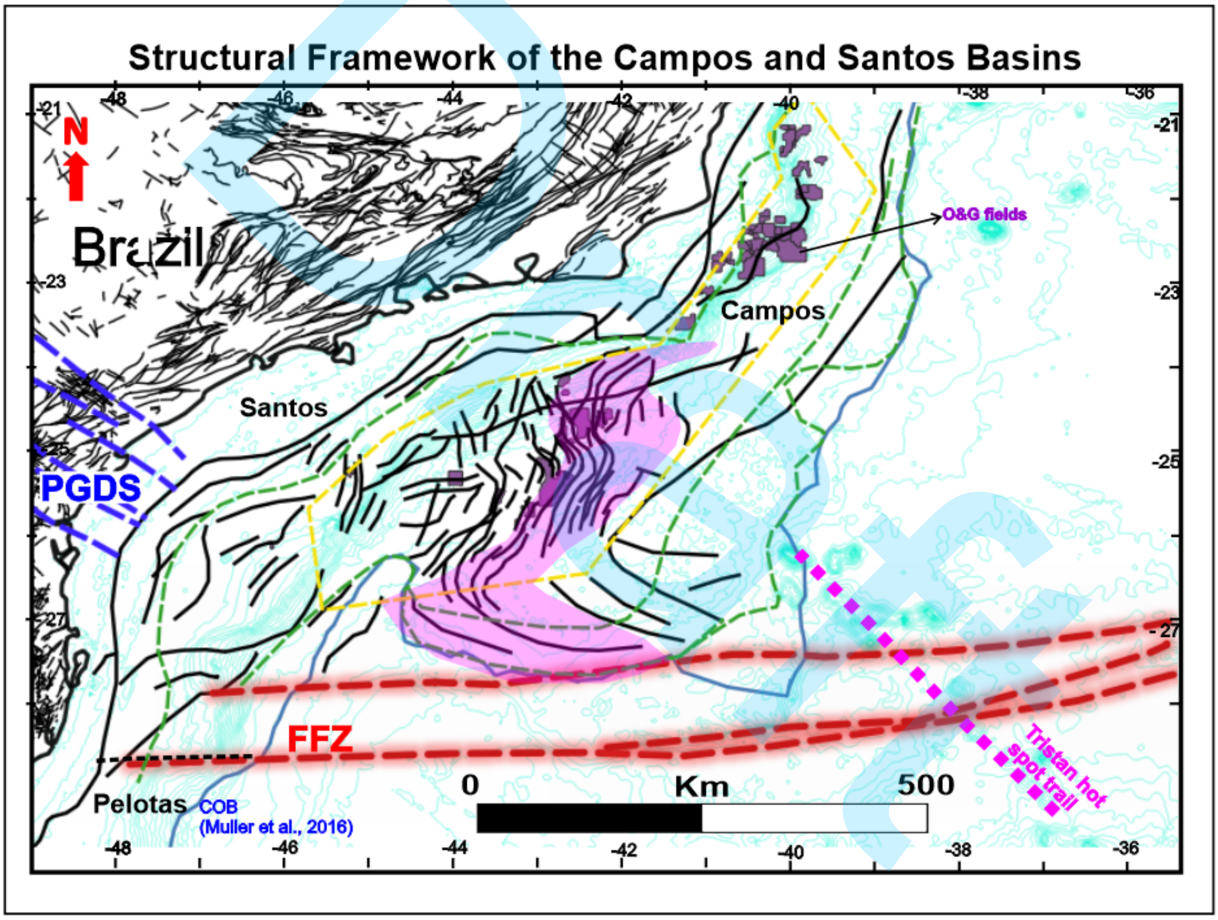


Figure 24. Based on interpreted structural lineaments from high-resolution base of the salt maps (Figure 18, Source PPSA), mapped structural leads (Figure 21) and Giro et al. (2021), the new structural framework of the Santos basin is represented by black lines. Tectonic lineaments onshore are likewise shown as black lines. Thin blue lines representing bathymetry The Florianópolis Fracture Zone is indicated by dashed red lines. Oil fields are shown as pink polygons. The light-pink translucent polygon has a double sigmoid curved shape that clearly shows pre-salt mountain range bends. This suggests syn-rift folding that is connected to the regional strike-slip kinematics' shortening tendency. Boundaries indicated by dashed green lines will be covered later.

THE SANTOS-NAMIBE BASINS RELAY ZONE AND THE SOUTH AMERICA ROTATION ABOVE THE TRISTAN-GOUGH PLUME HEAD

As previously mentioned, the Santos-Namibe conjugate margin is the meeting point of two conflicting spreading centers (Figures 2, 5 and 9). During the 133–113 Ma interval, the development of SRDs within the volcanically filled Pelotas/Walvis conjugate basins coincided with the wide extended COT, in the Santos-Namibe conjugate margin, becoming progressively a magmatic crust eastward (Figures 2, 3, 5 and 9). Following the huge magma eruption of the PEMP-LIP at approximately 133.6 Ma (Rocha et al., 2020) or between 135 and 132.2 Ma (Gomes et al., 2021), the Proto Florianópolis Fracture Zone was born at about 130 Ma, defining the boundary or transition zone between these two simultaneous contending rift/spreading centers (Rocha et al., 2020). According to Moulin et al. (2010), Collier et al. (2017), and Stica et al. (2014), the M10-M0 geomagnetic anomalies series from the magmatic crust became younger consistently northward, as seen in Figures 3, 5, and 9.

Figures 25 and 26 show the kinematics and strain partitioning of the Santos-Namibe conjugate margins. As initially described by Macedo (1990) and subsequently confirmed by Meisling et al. (2001), Mohriak et al. (2010), Rigoti (2015), and Dehler et al. (2016), strain partitioning is explained by an oblique-sinistral extensional system rather than by a complex model with multiple internal structures, as proposed by Moulin et al. (2013).

Snapshots of the positions of South America and Africa and their respective movements in response to the widening of this Aptian Large-Scale Relay Zone are displayed in Figures 25 and 26. South America is fixed in these figures, and the African plate is restored after precise reconstructions supplied by the PLATES Project, honoring the database of the entire South Atlantic (Matos et al.,2021). The fragmentation of Gondwana is shown in four time-slice reconstructions at 134–130, 126, 120, and 114 Ma. The rotation poles shown in Table 2 determine how South America and Africa move relative to one another during the clockwise rotation. In Figures 25 and 26, local divergent flow motions are depicted by dashed black arrows at each individual reconstruction. These flow lines have an overall stretching tendency around an E-W/ESE-WNW axis, which is compatible with the plate kinematic reconstructions shown in Figure 12. The instantaneous strain ellipses in Figures 25 and 26 show strain partitioning. The Santos Basin's highest elongation direction is primarily NW-SE, which is frequently mistakenly misinterpreted as the direction of extension.

Considering the South American plate's clockwise rotation during the 113/114-130 Ma interval, as seen in Figures 9, 25, and 26, Matos (2021) suggested that the plume's trail follows an track with respect to a fixed reference setting. The TG plume head left behind a NW-SE crooked trail, connecting the Ponta Grossa dike swarm with the first expression of the hotspot track on the oceanic crust (Figure 24). The TG plume head's interpreted positions in space and time are depicted by the red stars in Figures 25 and 26.

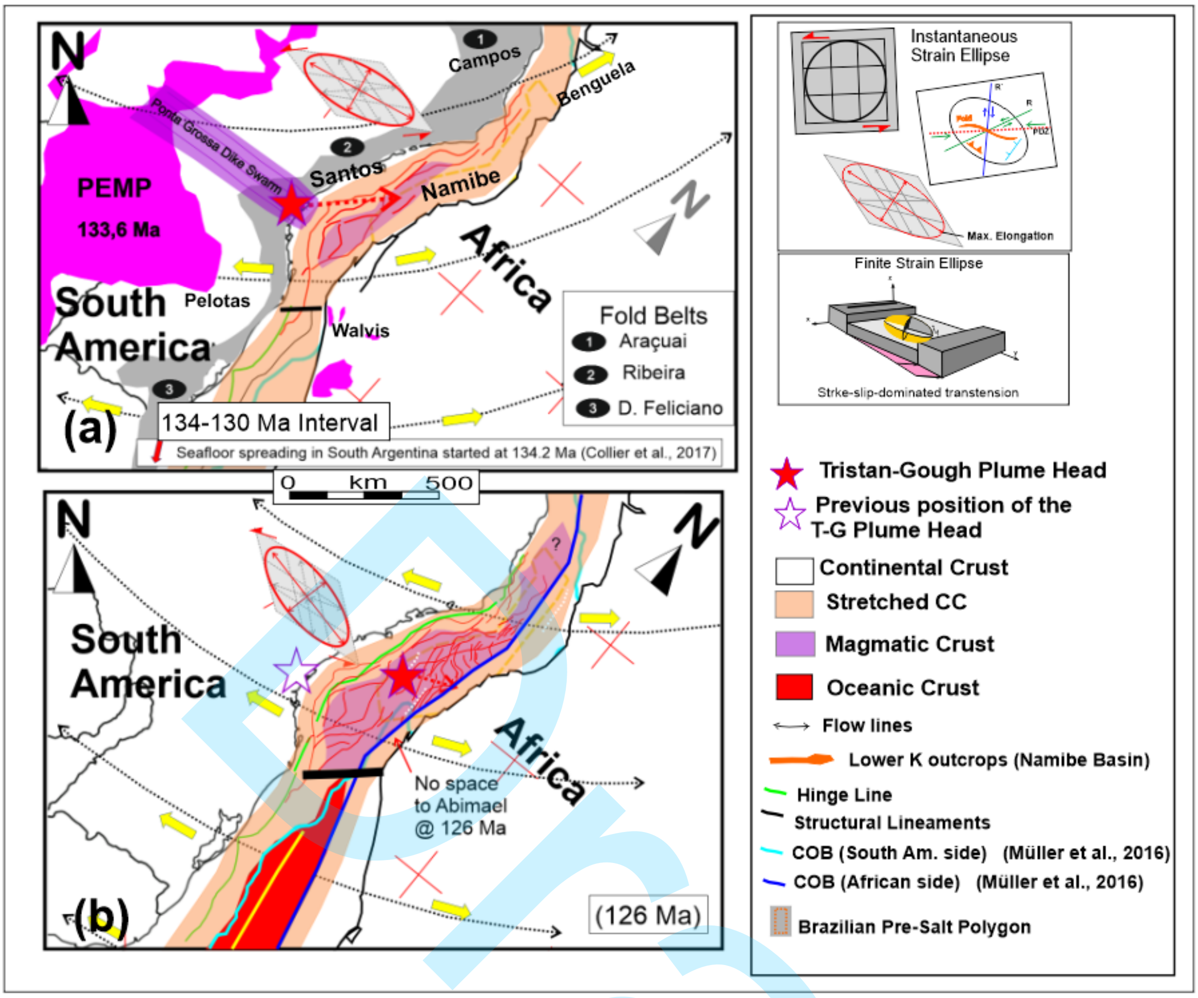


Figure 25. Time-slice reconstructions of the fragmentation of Gondwana at 134-130 Ma and 126 Ma (based on the UTIG PLATES Project global-scale reconstructions). South America fixed (black "compass rose" in Brazil). The light gray "compass rose" in Africa illustrates the relative rotation at each time interval. Global-scale reconstructions explain the South America clockwise rotation with respect to Africa. The dashed black arrows indicate local divergent flow movements. (a) Plate reconstruction during the development of the Paraná-Etendeka Magmatic Province, while South America rotated clockwise around a rotation pole located in North Brazil (b) Rotation pole moved to Northeast Brazil, while oceanic or proto-oceanic crust was created south of the future site of the Florianópolis Fracture Zone. The COBs (Müller et al., 2016) from the South America side (light blue continuous line) and the African side (dark blue line) are used as reference frame to illustrate the process of migration of extensional deformation, widening and hyperextending the continental crust within the Santos-Namibe conjugate basins.

Mohriak (2001), followed by Gomes et al. (2002, 2009), Mohriak et al., (2010), and Scotchman et al. (2010), interpreted gravity and magnetic anomalies observed between the Pelotas and Santos Basin, as reminiscent of an aborted oceanic rift, named as the Abimael extinct ridge (Figure 8). Pichel et al. (2021) interpreted the Merluza graben (Figure 4) as the northern continuation of the Abimael aborted spreading center and suggested that its controlling faults were active during and immediately after salt deposition.

The evolution of the Abimael extinct ridge over time and space is somewhat demonstrated by Figures 23 and 26. The 126 and 120 Ma reconstructions suggest that the Abimael magmatic center propagated northward between these two-time intervals. It is not around the time of salt deposition, as proposed by Mohriak et al. (2010), and suggests a late Aptian age for the Merluza graben.

The superposition of the COBs from South America and Africa, shown as light and dark blue lines (Figure 26.b), respectively, indicates a clear overlap of the easternmost magmatic crust from the Santos Basin over the African continental crust at 114 Ma. Comparing Figures 4 and 26 b using Müller et al. (2016)'s COB as a framework, we find that the COBs that has been presented and interpreted for the Santos basin is protruding into the African continental crust (dark blue line in Figure 26 b). The crustal domain represented in the hatched area of Figure 26 b displays a unique magmatic crust, including continental crust ribbons and/or sheared slivers of continental crust, proto-oceanic crust ribbons, possibly highly intruded by magmatic bodies and eventually covered by salt, as described by Dehler et al., 2016; Galvão & Castro, 2017; Altenbernd et al., 2019, and illustrated in Figures 20, 26 d , and 27.

The 114 Ma plate reconstruction shown in Figure 26 b provides a potential tectonic portrait before salt deposition, during a time when the Santos Basin was the meeting point of two rival spreading centers. Late Aptian oceanic crust would make up the gap between Africa and South America (dark and light blue lines in the upper right-hand side of Figure 26 b, respectively). This supports the interpretation of a Transform Marginal Plateau (TMP) for the São Paulo Plateau, as suggested by Loncke et al. (2020), in which oceanic and magmatic crust have been produced simultaneously during the breakup process.

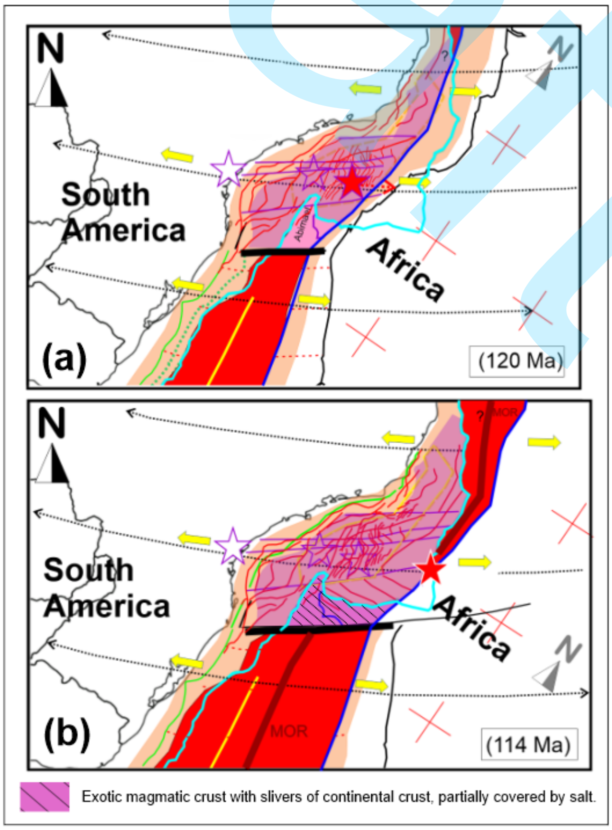


Figure 26. Time-slice reconstructions of the fragmentation of Gondwana at 120 Ma and 114 Ma (based on the UTIG PLATES Project global-scale reconstructions). Legends as in Figure 25. While oceanic to proto-oceanic crust was continually formed south of the future location of the Florianópolis Fracture Zone, the rotating pole shifted to North America. The Abimael rift propagated northwards around 120 Ma. According to Stica et al. (2014), the COB on the Brazilian side is represented by the light pink continuous line in the Austral Branch. The easternmost Santos Basin is clearly overlapped by the African side at 113-114 Ma (Figure 25.b), which may indicate that the southeasternmost tip of the Santos Basin is not likely made of continental crust. The dashed pink line illustrates the interpreted path of the TG plume head (dark red star) beneath the Santos Basin during the main rift stage (130 – 114 Ma). The interpreted path it is not a straight line. The crooked pattern is a consequence of the dynamic clockwise rotation of South America, changes in the flow lines and far-field stresses.

Rotation poles for South America to Africa				
Age (Ma)	**Lat.**	**Long.**	**Angle**	**Comment**
145	45.368	-32.191	57.085	Onset Rifting
135	45.368	-32.191	56.835	Onset SDRs
128.78	47.525	-34.485	55.2313	Chron M9
120,8	51.077	-32.505	52.6024	Chron M0
102	54.131	-34.549	45.5	Interpolated
83	62.29	-34.78	33.58	Chron 34
Stage poles calculated from above				
Age Range(Ma)	**Lat.**	**Long.**	**Angle**	**Tectonic Stage**
145-135	45.378	-32.1	0.25	I and II
135-128.78	-0.131	6.541	2.592	II
128.78-120.8	6.202	2.201	4.318	III and IV a
120.8-102	34.284	-24.564	7.538	VI b and V
102--83	34.285	-24.565	13.11	V to Campanian

Table 2. Rotation poles for South America to Africa used for large-scale plate modelling. Source: UTIG PLATES Project.

Figure 27 displays the new structural framework of the Santos Basin on top of the free-air gravity anomaly map of SE Brazil. A completely new structural framework for the Santos Basin is revealed in Figures 18, 20, 24, and 27, which show abrupt shifts in the structural trends and substantial alterations with structural lineaments never described before. These structural lineaments can be described as a Double Sigmoid Curved Shape (DSCS), as seen in Figure 24 in shaded pink. These mountain range bends imply large-scale, syn-rift folding, including basements with the generation of exhumed noncylindrical domes.

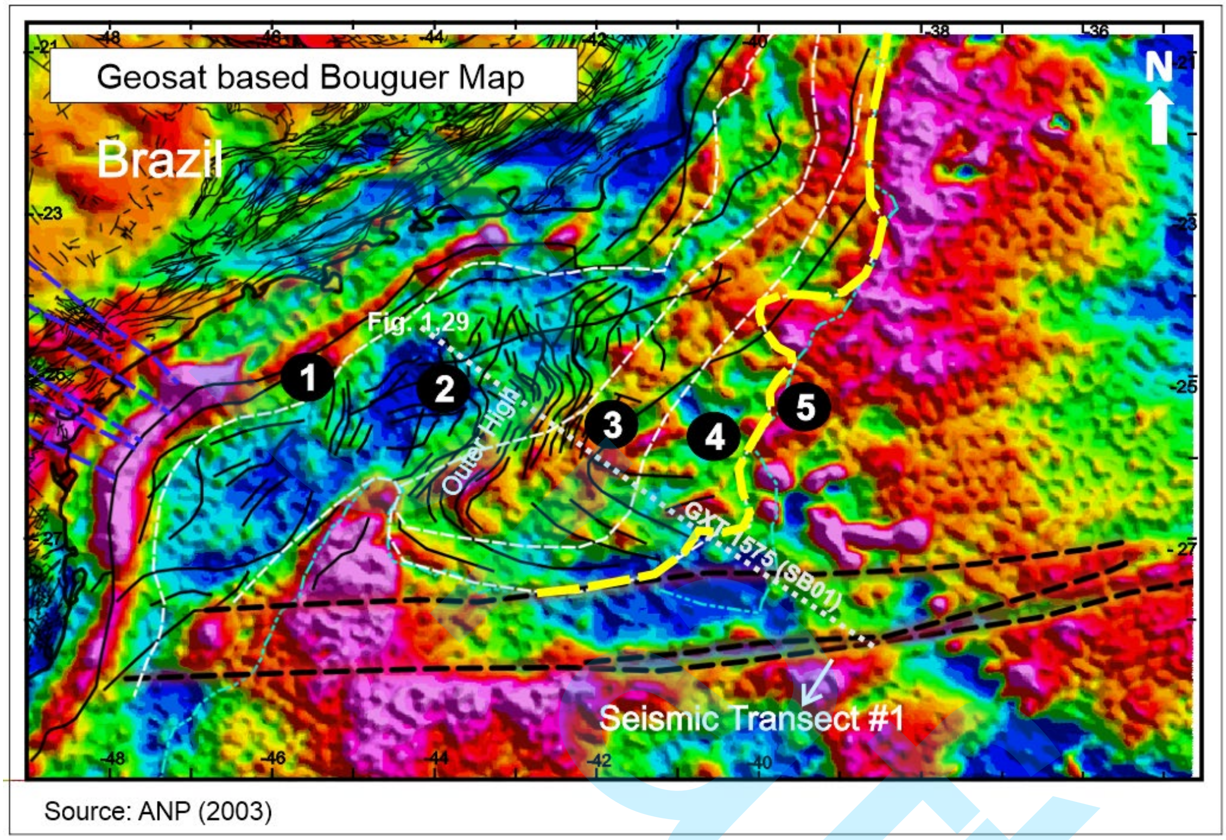


Figure 27. GEOSAT-based Bouguer anomaly map of the Southeastern Brazilian Margin, with the interpreted structural lineaments from Figures 20 and 24. Dashed black lines are the interpreted landward projection of the Florianópolis Fracture Zone. Continuous light blue line: COB from Müller et al. (2016). Gray dashed line is the location of the seismic transect #1, displayed in Figure 29. The border between crustal domains is delineated by dashed white lines, with numbers 1 through 5 indicated in the black circles. Dashed thick yellow line: True oceanic crust boundary, also displayed in Figure 31.

ANALOGUES OF MOUNTAIN RANGE EXHUMATION ASSOCIATED WITH CORE-COMPLEX TYPE DETACHMENT SYSTEMS

In the central Basin and Range province (USA), significant flexural bends of mountain ranges adjacent to shear zones have been described. These bends are associated with the left-lateral Lake Mead strike-slip system and with the 120-km-long Las Vegas Valley Shear Zone (LVVSZ), a right-lateral NW strike-slip fault (Langenheim et al. 2001). Paleomagnetic data confirmed the flexural bending of these Cenozoic sedimentary rocks (Nelson and Jones, 1987). The morphology of these folded mountain ranges near Las Vegas, Nevada, USA, and connected with the LVVSZ is illustrated in Figure 28.

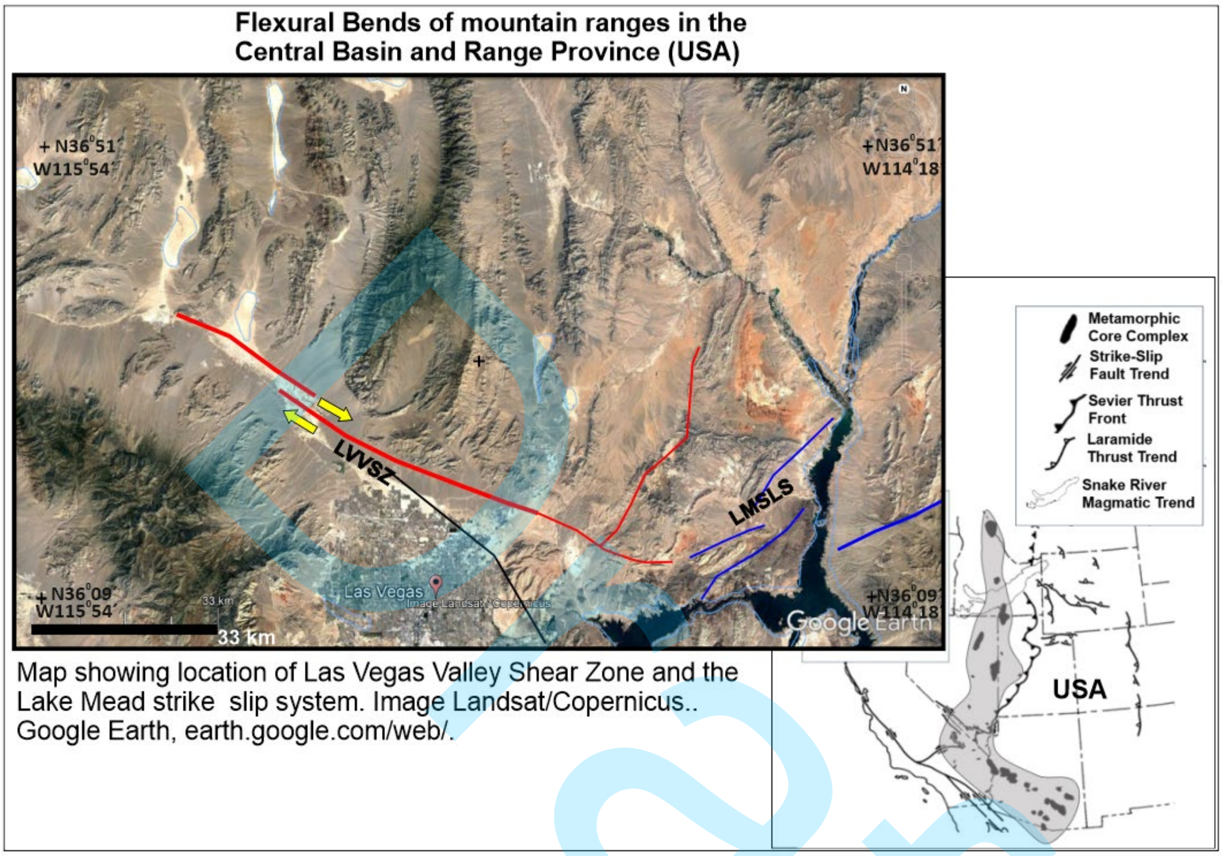


Figure 28. Basin and Range crustal deformation. Upper left - Analog of flexural bends of mountain ranges obtained using Landsat data on Google Earth Engine. The Las Vegas Valley Shear Zone (LVVSZ) is a NW-SE striking right-lateral shear zone, genetically associated with the Miocene Lake Mead strike-slip left-lateral system (LMSLS). The LVVSZ is 150 km long, with 23 to 69 km right-lateral offset. Faut traces based on Langenheim et al. (2001) and Campagna and Aydin (1994). Lower right – Regional belt of LANFs and MCCs (modified from Coney, 1980). Yellow arrows represent the right-lateral movement of the LVVSZ.

These strike-slip faults (LVVSZ and LMSLS) were interpreted as transfer structures by Duebendorfer et al. (1998), Guth (1981), and Wernicke et al. (1982). These faults were generated as part of a complex three-dimensional strain field throughout the Cenozoic extension, rooted in regional-scale detachment faults. These detachment faults are a key characteristic of Metamorphic Core Complexes (MCCs; Coney, 1980; Figure 28). Tectonic denudation occurs along low-angle normal faults (LANFs) and the dome-shaped structure is found in areas with syn extensional magmatism.

The LANFs separate the mylonitic fabrics of the lower plate from the unmetamorphosed uppermost crust (and its sedimentary cover). According to Martinez et al. (2001), MCCs accommodate extension through the mechanism of buoyant extrusion of ductile lower-crust material, as the result of a volcanic-related thermal expansion and the consequent decrease in crustal density.

Through 3D thermomechanical modeling, Pourhiet et al. (2012) explored the impact of 3D kinematically controlled deformation on the shape of metamorphic core complexes. The authors show that it is possible to form folds in response to local constriction within extensional step-over between strike-slip faults. Pourhiet et al. (2012) applied their models to the North Cyclades Detachment System in Greece (Jolivet et al., 2010) and interpreted that the formation of domes elongated normal and parallel to the stretching direction are associated with horsetail splay fault kinematics.

Pourhiet et al. (2012) investigated the effect of 3D kinematically controlled deformation on the geometry of metamorphic core complexes using 3D thermomechanical modeling. According to the authors, folds can develop because of local constriction between strike-slip faults. After applying their models to the North Cyclades Detachment System in Greece (Jolivet et al., 2010), Pourhiet et al. (2012) concluded that the kinematics of the horsetail splay fault are related to the production of domes that are elongated normal and parallel to the stretching direction.

VOLCANIC OR MAGMATIC MARGIN IN THE SANTOS-NAMIBE CONJUGATE BASINS

The understanding of rift and magmatism in the Santos Basin has changed since the discovery of world-class oil reserves in deep-water. Voluminous syn-rift magmatism has been imaged and drilled in the Santos Basin, while many authors have attempted to consider it as a magma-poor margin (Zalán et al, 2011; Zalán, 2013; Ros et al., 2017 and references therein) or as magma-rich margin (Gladczenko et al., 1997; Kumar et al., 2012 and references therein). Large late Aptian magmatic bodies are imaged in the deep-water Santos Basin (Zalán et al., 2011).

Oceanward and beyond hyperextended terrains, it is expected that the Continent-Ocean Transitions (COTs) would register thin continental blocks, anomalously thin oceanic crust, and narrow exhumed mantle, as described by Davy et al. (2016) in the Deep Galicia rifted margin. The Santos-Namibe segment seems to be a remarkable exception. Based on wide-angle inversion models of velocities and densities, it has been interpreted as an anomalously thick crust, regardless of its nature, throughout the Santos Basin (Zalán et al, 2011, 2012; Klingelhoefer et al., 2014; Evain et al., 2015; Schnürle et al., 2019).

The resolution of wide-angle seismic cannot clearly distinguish between granite/gneiss and basalt/gabbros (Karner et al., 2021). Notwithstanding the uncertainties surrounding the interpretation of seismic data, the Santos Basin is a magma-rich margin, either because of an early lithospheric breakup (Karner et al., 2021) or as a result of the region's crustal/lithospheric stretching phase occurring concurrently with the Tristan-Gough plume head's path beneath the Santos Basin in both space and time (Matos, 2021). According to Whitney et al. (2012), developing core-complexes, driven by lithospheric extension, is the main process of heat and mass transfer in the Earth.

TECTONIC AND CRUSTAL DOMAINS IN THE SANTOS BASIN

The regional seismic transect across the entire Santos Basin presented in Figure 29, from the BrazilSPAN Salt Study Survey (ION-GXT, Zalán et al., 2011 and 2013), is particularly helpful to discuss alternative interpretations for the nature of the crust in the Santos Basin. The line coincides with wide-angle SanBa profiles presented by Evain et al. (2015). Different crustal domains, between the true continental crust and the oceanic crust, designated N, A, B, C, and D were identified by the authors (Figures 4 and 29).: Domain N: Continental crust no less than 25 km thick; Domain A: 11 to 15 km thick upper continental crust, with a 20 km thick continental crust and sedimentary cover; Domain B: heterogeneous thin crust, either continental or oceanic. If continental, the upper crust was intruded by mafic intrusions or recorded exhumed lower crust; Domain C: Salt is absent and the crust is characterized by high positive magnetic anomalies and low gravity anomalies; Domain D: a triangular shape region in the southeastern part of the Santos Basin, characterized by a 5 km atypical thick crust, interpreted by Klingelhoefer et al.(2014) as a proto-oceanic crust. While Evain et al. (2015) argued that the high upper mantle velocities are indicative of peridotites and inconsistent with the hypothesized exhumed mantle at this region of Zalán et al. (2011, 2013)

In our analysis of the tectonic and crustal domains of the Santos Basin, we consider that the addition of magmatic material during the major rift stage (130–114 Ma) occurred under the effect of the TG plume head, which resulted in the thickening of the continental crust (Figure 26), leading to the development of a magmatic crust. Furthermore, plate reconstruction during the 120–114 Ma period shows that the Santos Basin's OMBH and OSDB compartments clearly overlap the African side. Therefore, it is unlikely that this section is composed of continental lithosphere (Figures 4, 26 and 29). Our interpretation of the crustal domains, together with the findings of Evain et al. (2015), are shown in Figure 29d. The interpreted basement (in red) and the base of the salt layer (in pink) are taken from Zalán et al. (2011 and 2013). At the top of Figure 29d, the red, blue, and black small colored ellipsoids illustrate: (1_red) the crustal domains interpreted by Evain et al.(2015); (2_blue) Tectonic compartments (this work); and (3_black) crustal domains proposed by Rigoti (2015). The black circles with numbers ranging from 1 to 5 represent the tectonic domains and crustal types of the Santos basin. The spatial distribution of the domains is illustrated in Figure 27.

- Tectonic domain (1) or Necking zone (Evain et al., 2015). is defined as where the continental crust thins abruptly towards the IBL (Inner Basin Low); See Figure 27.
- Tectonic domain (2) combines the A and A′ crustal domain of Evain et al. (2015), which is distinguished by a broad positive magnetic anomaly and a wide low gravity anomaly. Magmatic underplating and mid-to-lower crust magma intrusion were responsible for isostatically maintaining the Outer High (OH) as the most prominent basement high in the Santos basin. Karner et al. (2021) have interpreted this thick crust as a MC, indicating magma-intrusion into the mid-to-lower continental crust.

- Tectonic domain (3), also known as Evain et al. (2015)'s B and B′ crustal domain, has significant variations in crustal thickness and Moho depth, low magnetic and high gravitational anomalies. Basement rises, and Mono deepens eastwards. (Evain at al., 2015). These areas of major crustal thinning were more susceptive to suffering magmatic injections intruded into the upper continental crust from continental refertilized mantle derived material (CRM, Figure 29d).
- The border between crustal domains 3 and 4 (Figure 27 in map view and as a thick dashed black vertical rectangle in Figure 29d) would represent the boundary between the obliquely hyperextended continental lithosphere and a late-Aptian born magmatic crust supplied by an oceanic lithosphere mantle (OLM, Figure 29d). This interpretation honors plate tectonics reconstructions regarding the nature of the crust eastward of this boundary. Tectonic domain (4) or roughly the C crustal domain of Evain et al. (2015). is characterized by high magnetic anomalies and low gravimetric anomalies. Our interpretation is that this is no longer a continental-originally born crustal domain, but it is rather an over-thickened new proto-oceanic crust, or magmatic crust, intruded with associated syntectonic basalts, and supplied from oceanic lithospheric mantle. Karner et al. (2021) interpreted part of this segment as a slow spreading oceanic crust or exhumed mantle.
- Tectonic Domain (5) is the oceanic crust. The D domain of Evain et al., (2015) was interpreted as a POC by Klingelhoefer et al. (2014) and as exhumed mantle by Zalán et al. (2011). The contrast between the D domain and OC domain (Figure 29d) is the nature of the crust. The D domain, have seismic velocities compatible with serpentinized and exhumed mantle, developed while there was not yet any organized and stable mid-ocean ridge. The breakup process is completed by the emplacement of Penrose oceanic crust (OC domain in Figure 29d).

The black ellipsoid with number 3 in Figure 29d illustrates the space distribution of the crustal domains proposed by Rigoti (2015). They recognized the presence of large-scale detachment systems and low-angle normal faults developed during the exhumation phase of the Santos Basin.

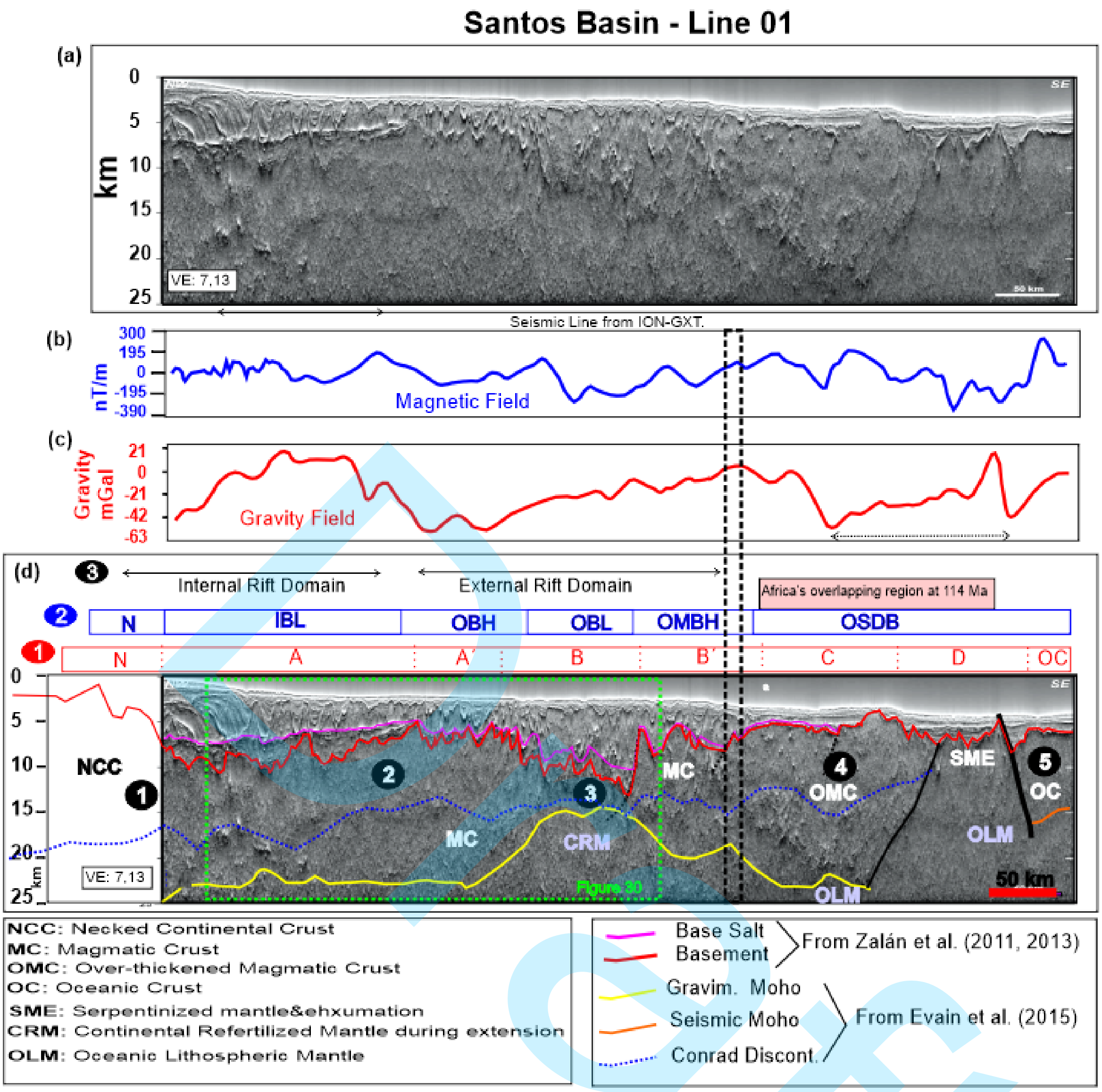


Figure 29. (a) Uninterpreted 2D seismic transect through Santos Basin as introduced in Fig 1b; (b) and (c) Gravity and magnetic anomalies throughout the transect. (d) Interpreted section with the superposition of the seismic interpretation from Zalán et al. (2011 and 2013), Evain et al., (2015) and this work. In red (1) is displayed the crustal domains interpreted by Evain et al. (2015). In blue (2) outer basin compartments, where N is the Necking Zone, IBL is the Inner Basin Low, OH is Outer High, OBL is the Outer Basin Low, OMBH is the Outermost Basin High, and OSDB is the Outer Santos Basin Deep Basin. In black (3) are displayed the crustal domains proposed by Rigoti (2015). The thick dashed black vertical rectangle (b to d) represents the boundary between the obliquely hyperextended continental lithosphere (domains A and B) and a magmatic crust supplied by an oceanic lithosphere (domains C and D). Green dotted rectangle indicates the position of Figure 30.

FINAL REMARKS

Low-angle normal faults and detachment systems have been interpreted in the Santos Basin (Rigoti, 2015; Fetter et al., 2018a, 2018b). Using a proper vertical exaggeration, Figure 30 presents a zoomed view of Figure 29, illustrating detachment systems around the Outer High (OH). There is a long wavelength crustal curvature through the Inner Basin Low, Outer High and Outer Basin Low (OBL) where the low-angle normal faults are easily interpreted. Despite being atop a thick crust, the western side (OBL) has a secondary neck.

Tectonic denudation along low-angle normal faults is clearly visible, most likely related to magmatic thermal weakening. Fetter et al. (2017) state that strain weakening is a crucial geomechanical driver for initiating and spreading of LANFs. We interpret this area as a metamorphic core complex (MCC) analog. Howlett et al. (2021) claim that MCCs can deplete rocks as far down as the middle crust at 10–30 km depths. Typically, they occur in thick crust that is gravitationally unstable and has syn-extensional magmatism. The origin of the Proterozoic transpressional (dextral) shear zones of the Ribeira fold belt, the cradle of the Santos Basin, coincided with the over thickening of the original continental crust of the basin, resulted from the oblique continent-continent collision between the Congo and the São Francisco cratons (Silva et al. 2005).

Yin (1991) states that the lower plate folds during the development of MCCs, with the minor axis typically developing perpendicular to the regional extension field and the major axis parallel to the regional extension. The clear bends of pre-salt mountain ranges displayed in Figure 24 documented ENE-WSW syn-stretching folding parallel to the regional extension field.

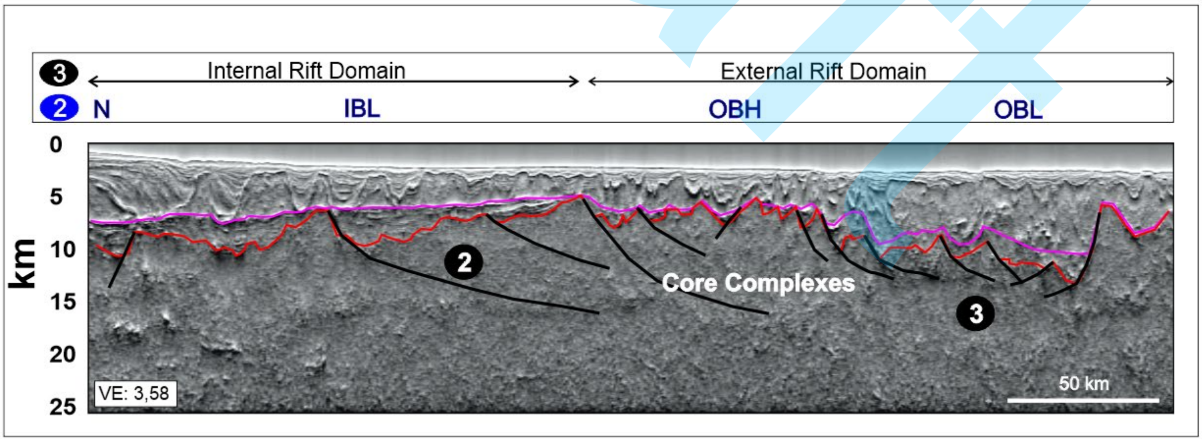


Figure 30. A zoomed-in segment of the seismic transect in Figure 29, displayed in small vertical exaggeration, focusing on the internal and external rift domains (Rigoti, 2015) and the predominance of low-angle normal faults. Location in Figure 29. In blue (2), N - Necking Zone, IBL - Inner Basin Low, OH - Outer High, OBL - Outer Basin Low.

The North Cyclades Detachment System in Greece is a possible analog to the Santos Basin. Pourhiet et al. (2012) interpreted in the area the formation of doming and along strike bending as the result of horsetail splay fault kinematics in a core complex type detachment system.

Dome-shaped structures and abundant syn extensional magmatism are seen in the Santos Basin, combined with signs of tectonic denudation along low-angle normal faults. The Tristan-Gough plume head's passage beneath the basin may have sped up this denudation process. Before the development of hyperextended terrains by thermal weakening, Matos (2021) suggests that the arrival of a sub-lithospheric mantle plume head beneath the Santos Basin during the main stretching phase may have also significantly altered the magma budget, resulting in the production of magmatic rocks that both intruded and erupted onto the continental crust (Figures 14 and 15), as accurately described by Zalán et al (2011); Zalán, (2013); Quirk et al (2013) and Gamboa et al. (2019).

Through an integrated regional interpretation using Figure 29 as a template, and plate reconstruction boundary conditions (Figures 25 and 26), we are providing an alternative geodynamic model to unravel an obliquely sheared active magmatic core-complex type detachment systems associated with large-scale extensional relay zones and strike-slip faults. A sinistral oblique rift system gave rise to the denudation process that was established in the internal and external hyperextended rift domains. Meanwhile, two competing stretching fronts that are 600 km apart from one another are propagating through a large-scale relay zone across the Santos-Namibe corridor. We infer that syn-rift folding and the clear bends of mountain ranges are circumscribed around the core-complex detachment system and its associated low-angle normal faults (double sigmoidal geometry in Figures 24 and 30). The style, magnitude, and distribution of exhumed terrains may have been determined by anomalous temperature, the occurrence of melt, and inherited rheology, as Whitney et al. (2012) discussed.

The Santos-Namibe margin's magma budget changed because of the unique 3D kinematic extensional boundary conditions, which were defined by an obliquely sheared active core complex type detachment system concurrently influenced by the thermal influence of a mantle plume head. This likely accelerated crustal denudation through thermally induced uplift and mechanical weakening. The doming process might have been caused by magmatic underplating. The subcontinental lithosphere provided molten material towards the new magmatic crust, regardless of when the continental crust was fully stretched or when the lithospheric reached the breakup point. The formation of the Jean Charcot Seamounts was initiated by the TG plume head after salt deposition, marking the emplacement of an unambiguous oceanic crust.

Even though there are remarkable geometrical similarities between the MCCs of Basin and Range with the core-complexes of the Santos Basin, the mechanisms of advection of heat and metamorphosed rocks from deep to shallow crustal levels are probably not similar. We call the above-described core complex structures of Santos Basin as a magmatic, shear-driven TMP core complex (MSD-TMP-CC). The new tectonic framework for the Santos Basin, illustrated in Figures 24, 27 and 31, unravels the presence of basement-involved flexural-flow folds within the hyperextended domain of the basin. The

Proterozoic dextral transpressional Ribeira Belt, which was inverted during the Early Cretaceous, gave birth to an east-west left-lateral extensional shear zone that governed the entire basin's establishment.

During each progressive shear deformation, the NE trending normal faults, the E-W strike-slip faults, their related transfer faults, and flexural folds were kinematically linked, creating a complex three-dimensional strain field. The infinitesimal strain ellipse of Figure 31 illustrates the direction of maximum elongation during left-lateral shearing.

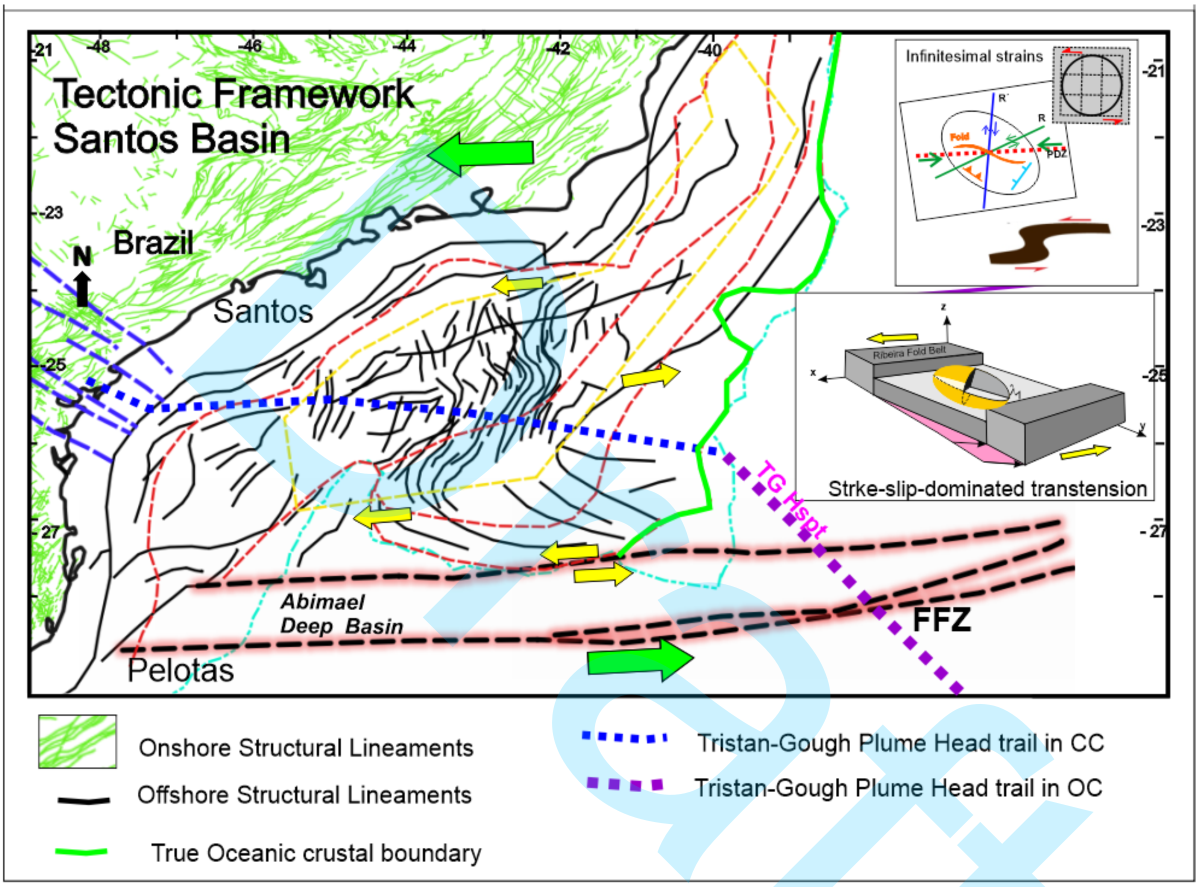


Figure 31. Tectonic framework of the Santos Basin with the interpreted structural lineaments consolidated from Figures 20, 24 and 27. Structurally, the basin is dominated by a system of North to NE normal faults, E-W strike-slip faults and secondary transfer faults that separate regions of contrasting extension rooted in core-complex detachment faults. Remarkable features are the flexural folds, represented by a double sigmoidal geometry, highlighted in Figure 24. Dashed black lines are the trace of fracture zones. Inside figure in the upper right illustrates the infinitesimal and finite strain ellipses developed during the oblique-left-lateral extension of the basin. The basin became broader in the NW-SE direction, the direction of maximum elongation at each incremental shear step, often mistakenly misinterpreted as the extension direction in the Santos basin. The trail of the Tristan-Gough hotspot (TG Hspt) within the continental (CC) and oceanic crust (OC) is displayed in blue and purple dashed thick lines, respectively. Yellow arrows represent major left-lateral offsets, within this large-scale relay zone.

The dynamics of these large-scale processes, with the development of core-complex type detachment systems, coupled with the exhumation of a hyperextended continental and newly formed magmatic crust, occurred during the deposition of the lacustrine rocks of the Itapema Formation, followed by the deposits of the Barra Velha Formation, which is correlated with Petrobras´ SAG section (Figure 10). Andersonian normal faults, strike-slip faults, and LANFs, rooted in the basement, produced basement-controlled active structural highs, defining the paleogeographic relief close to the lake base level, where many platforms sustained catch-up carbonate factories that produced hundreds of meters of high-quality reservoirs (Fetter et al., 2018a; Wright, 2020).

Figure 32 shows a schematic three-dimensional perspective of the Santos Basin, viewed from the Pelotas Basin, which illustrates the significance of a double sigmoidal folded geometry in the central portion of the Santos Basin, as shown by our novel structural framework (Figures 21, 22, 23 and 27). The complex three-dimensional strain field suggested by our geodynamic model has direct impact on the prediction of reservoir properties of the world-class oil and gas giant reserves of the Brazilian Pre-Salt Province. Soft-sediment deformation may be misinterpreted as tectonic folds and faults (Alsop et al., 2020), while early syn-depositional fractures may have an impact on reservoir permeability.

Early and late diagenesis, silicification, fluid movement, and porosity development may have been significantly impacted by syn sedimentary tectonic folding. The Santos Basin's double sigmoidal folded geometry serves as an example of how along-strike folding may alter the distribution and intensity of fractures inside the oil fields. The relationship among folding, fracturing, and fluid movement during the evolution of these core-complex detachment systems also had a direct impact on the world-class oil accumulations of the Santos Basin.

The Santos Basin is the spot where a magmatic tip of a rift branch arriving from the North competed, in time and space, with a propagating volcanic rift branch coming from the South as illustrated in Figure 32.

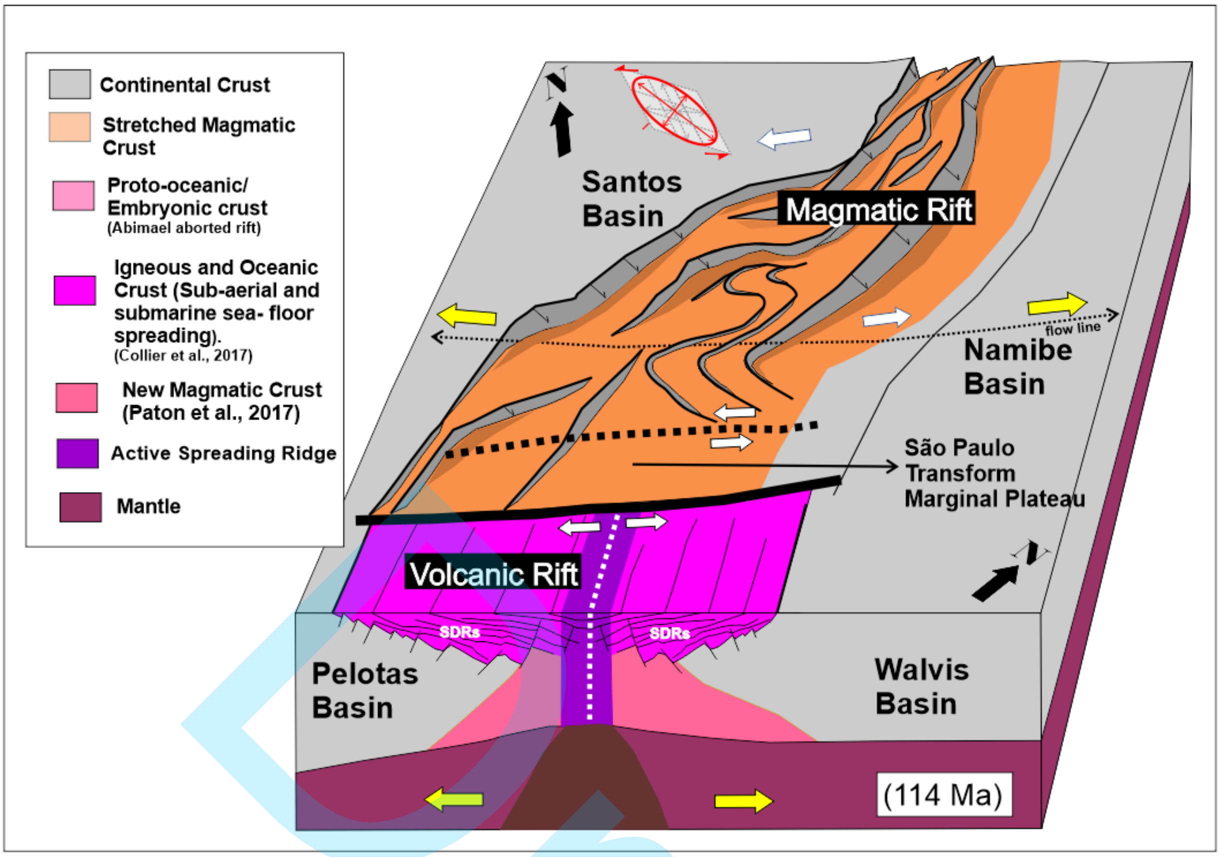


Figure 32. 3D schematic model of the regional structure of the Santos-Namibe Basins, illustrating the "double sigmoid curved shape" of an active core complex type detachment system at the center of the basin, obliqued sheared and folded during the development of a 600 km long strike-slip rift propagator, linking a spreading branch and a rift branch, arriving simultaneously from South and North, respectively. Pelotas and Walvis basin architecture was inspired by the work of Collier et al. (2017), Stica et al. (2014), and Paton et al. (2017). The Pelotas and Santos basins are examples of a volcanic and a magmatic rift, respectively.

CONCLUSIONS

Dynamic changes in the poles of rotation during the clockwise rotation of South America, Proterozoic inheritance, and far-field stresses-controlled strain partitioning between the volcanic margins of Campos/Benguela basins and Pelotas/Walvis basins during the Early Cretaceous breakup of southern Gondwana. Located in the center of this area, the Santos-Namibe basins evolved as a large-scale relay zone, developing an oblique-sinistral extensional system during the Aptian, balancing mechanically extensional deformation through a 600 km wide accommodation zone between a spreading branch arriving from the South and a rift branch incoming from the North.

Following the onset of seafloor spreading around the Malvinas/Falkland trend, the increase in the clockwise rotational momentum of the southernmost portion of the South American plate triggered the intrusion of transversal dike swarms along the Ponta Grossa Arch. This continental-scale feature is interpreted as a fissural-type magmatic event with NW-SE trending dikes emplaced into an opening mode (Type I) fracture system.

The obliquely extended Santos-Namibe conjugate margin became wider in the NW-SE direction, the direction of maximum elongation at each incremental shear step. The NW-SE elongation direction is often misinterpreted as the regional extension direction in the Santos Basin, which was mainly E-W, as indicated by plate kinematic transport direction from the PLATES Project´s reconstructions.

We present a new structural framework for the Santos Basin, clearly indicating the presence of basement-involved large-scale folding within the internal and external hyperextended domains of the basin. Our plate reconstructions shed light on how the strain was partitioned in the Santos-Namibe mega relay zone, where oblique core-complex type detachment systems are associated with large-scale half-graben systems and strike-slip zones, in order to accommodate the regional deformation between the two competing spreading centers.

The Santos Basin, acting as a large-scale relay zone, hosted a 600 km wide strike-slip rift propagator, slicing the continental crust by successive oblique shearing deformation episodes and leading the way for magmatic loading through the emplacement of extrusive volcanic rocks and possible magmatic underplating. Proterozoic inheritance is a primary factor controlling deformation partitioning in Santos Basin. Slices of continental crust previously stacked during a diachronic oblique continent-continent collision between the margins of the Congo and the São Francisco cratons were reactivated and inverted during the Early Cretaceous regional extension. Conventional stretching models do not apply to the conjugate basins of Campos-Benguela, Santos-Namibe and Pelotas-Walvis.

The final basin architecture has resulted from unique 3D kinematic extensional boundary conditions. Obliquely sheared active core complex type detachment systems were strongly influenced by the thermal anomaly of the Tristan-Gough plume, responsible for mechanical weakening and thermal-induced uplift. Magmatic underplating may have helped the doming process.

The Santos Basin, considering Karner et al. (2021) working hypothesis, and our work, matches the definition of a Transform Marginal Plateaus as specified by Loncke et al. (2020). We recognized the occurrence of core-complex structures within the Santos Basin and named them Magmatic Shear-Driven TMP core complexes (MSD-TMP-CC). An oblique-sinistral kinematic regime fragmented the crust, vertically slicing, horizontally thinning, and magmatically loading the former transpressional Proterozoic Ribeira fold belt under the influence of the Tristan-Gough plume. The Florianópolis Transform Fault acted as a buffer zone between Santos-Namibe and Pelotas-Walvis basins.

Our research and our geodynamic model have a series of scientific implications, mainly on basin modelling and reservoir quality prediction in the search for the remaining potential of the world-class oil and gas giant reserves of the Brazilian Pre-Salt Province. Eventually, such implications may also lead the way for future hypothesis-testing scientific research.

ACKNOWLEDGMENTS

The authors thank Pré-Sal Petróleo S.A. (PPSA) and the PLATES Project for supporting this work. We specially thank Veridian and TGS for permission to publish a full, high-resolution map of the base of the salt; Veridien for permission to illustrate the presence of low-angle normal faults and detachment systems in the Santos Basin. ION-GXT for a previously published seismic transect across the Santos Basin. We also thank ANP for the public images of exploratory Pre-Salt opportunities.

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