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REGIONAL-RESIDUAL SEPARATION AND ENHANCEMENT METHODS APPLIED TO REGIONAL ANALYSIS OF POTENTIAL DATA: STRUCTURE OF FLORIANÓPOLIS AND RIO DE JANEIRO FRACTURE ZONES IN THE WESTERN SOUTH ATLANTIC

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ABSTRACT. Topographic, gravimetric and magnetic data have been employed to map regional tectonic elements in the South Atlantic presenting major oceanic tectonic structures which had previously lacked continuity when approaching the continental margin. The creation of such contoured maps has proven that numerical transform methods involving regional/residual separation and derivatives of gravity and magnetics can enhance geophysical signatures and unveil hidden structures, especially in the transition from the continental margins to the oceanic basin. In assessing the tectonic trend of the Florianópolis and Rio de Janeiro fracture zones close to the Brazilian continental margin, the fracture zones change direction from E-W in the oceanic region to NE-SW in the continental margin, probably displaced by the Cretaceous hinge line in the northern portion of the Santos Basin. The continental structures associated with possible transcurrent and transfer zones, which gave rise to the fracture zones of Rio de Janeiro and Florianópolis, probably played an essential role in the evolution of both the SE margin of the Santos Basin and the African conjugated margin. Analyses demonstrate that the magnetic and gravimetric signatures of fracture zones can serve as important constraints for reconstructing continental margins in the rift and post-rift.

Keywords: Bouguer gravity anomaly; potential fields; offshore Brazil, continental crust.

INTRODUCTION

The rupture of the Western Gondwana continent in the early Cretaceous opened space for the formation of the South Atlantic Ocean, creating the South American and African lithospheric plates. Earlier plate reconstruction models mainly used isochrones of oceanic magnetic anomalies and tracing of oceanic fracture zones (e.g., Rabinowitz and LaBrecque, 1979; Cande et al., 1988; Eagles, 2007), in addition to structural and volcanic restoration of the conjugate South Atlantic margins and intracontinental rift basins in Africa and South America (e.g., Renne et al., 1992; Mohriak and Rosendahl, 2003; Heine et al., 2013; Quirk et al., 2013; Granot and Dyment, 2015; Darros de Matos, 2021). The relative movement between the plates during the rupture period is still, however, much debated due to a quiet magnetic zone between the crustal ages of 120.6 Ma (M0 anomaly) and 83.9 Ma (C34 anomaly) that adds complexity on the continental crust rupture process.

Yet, the location of fracture zones is essential for deciphering the paleo-reconstructions of the Brazilian and African continental margins. The fracture zones are old transform faults, which strike-slip plate boundaries at the oceanic spreading centers. According to the theory of plate tectonic, the fracture zones follow "small circles" on the Eulerian spherical geometry, which approximately describes the movement of the tectonic plates (e.g., Wilson, 1965; Morgan, 1968).

The mapping of submarine topography, the interpretation of seismic reflection data, the signature of gravity and geoid anomalies, and seafloor magnetic anomalies are usual tools to characterize fracture zones (e.g., Gamboa and Rabinowitz, 1981; Sandwell, 1986; Stanton et al., 2006; Gerya, 2012; Wessel et al., 2015; Hensen et al., 2019). The fracture zones cut the lithosphere in-depth and laterally shifted the oceanic spreading center since the continental margin onset. Therefore, fracture zones/transform faults can be oceanic or continental, depending on the nature of the crust crosscut. Their structure has a strong morphological signature on the ocean floor with narrow valleys and steep walls that can reach more than 2 km of relief and water depths greater than 5 km (e.g., Bonatti et al., 1994; Gomes et al., 2000; Mohriak and Rosendahl, 2003). This morphology continues for thousands of kilometers showing a “scar” on the ocean floor towards the continental margin, beyond the active plate boundary between two mid-ocean ridge segments, the transform fault zone. On the continent, fracture zones may be pre-existing fault zones, such as sutures, and often create broad areas of deformation (e.g., Gerya, 2012; Norris and Toy, 2014; Şengör et al., 2019).

We further investigate two major oceanic fracture zones in the southern South Atlantic and their extension to the Brazilian continental margin and adjacent continental areas. Both Florianópolis and Rio de Janeiro fracture zones are important tectonic features controlling the Santos basin, which had undergone considerable crustal stretching to the east during the continental margin onset (Mohriak et al., 2010; 2022). Our goal is knowing the behavior of these structures under such a tectonic environment.

Gravity and magnetic potential field data are valuable for investigating regional tectonic environments. Here, we applied some numerical transform methods involving regional/residual separation and derivatives on global database grids to enhance gravimetric and magnetic signatures, highlighting tectonic lineaments and domains of interest. Among the tested methods, the tilt derivative applied to magnetic data highlighted quite well features and structures associated with the tectonic evolution of the Santos Basin.

METHODS

This study used topography, gravity and magnetometry data from repositories such as the General Bathymetric Chart of the Oceans (GEBCO) (https://www.gebco.net), Topex/Poseidon project (https://topex.ucsd.edu) and NOAA (National Oceanic and Atmospheric Administration) (https://www.ngdc.noaa.gov/geomag/emag2.html), respectively. All data are public and free of charge and have high resolution, allowing reliable regional studies on structural lineaments (e.g., Maus et al., 2009; Sandwell et al., 2014; Tozer et al., 2019). The topographic data have a resolution of 15 arc seconds (~462.5 meters). The gravimetric data used, gravity model from Cryosat-2 and Jason 1 (Sandwell et al., 2014), have an approximate accuracy of 2 mGal and a resolution of 1 arc minute (~1850 meters). The magnetic data used are part of the EMAG2 (Earth Magnetic Anomaly Grid) database and have a resolution of 2 arc minutes (~3700 meters).

The topographic and gravimetric grids were interpolated on a regular 1 arc minute grid, while the magnetic anomaly grid was interpolated on a regular grid of 2 arc minutes. These grids were produced using the GMT (Generic Mapping Tools) software (https://www.generic-mapping-tools.org). The algorithm used was the minimum curvature with adjustable tension (Smith and Wessel, 1990). We used the tension values of 0.35 and 0.25 for topographic and potential data, respectively. All maps presented were made in the Seequent's Oasis-Montaj software.

The work maps in Figures 1 and 2 highlight the main tectonic and volcanic features in the South Atlantic, especially fracture zones.

Next, we applied numerical transform methods involving regional/residual separation and derivatives onto the gridded data illustrated by the contoured maps in Figures 1 and 2.

REGIONAL AND RESIDUAL GRAVITY SEPARATION

The gravity residual anomalies are obtained by subtracting regional anomalies from the Bouguer anomaly (Nettleton, 1954).

The Bouguer anomaly is given by the expression:

$$A_B = A_{Free-Air} - C_B, \qquad (1)$$

where, A_B is the Bouguer Anomaly; $A_{Free-Air}$ is the Free-Air gravity anomaly; and C_B is the Bouguer correction. Such correction is given by $2\pi G\rho H$, where G is the Universal Gravitational constant; ρ density; and H the altitude of the observation point. In continental areas, the Bouguer correction removes the gravitational effect of the masses that are above the geoid. In oceanic areas,

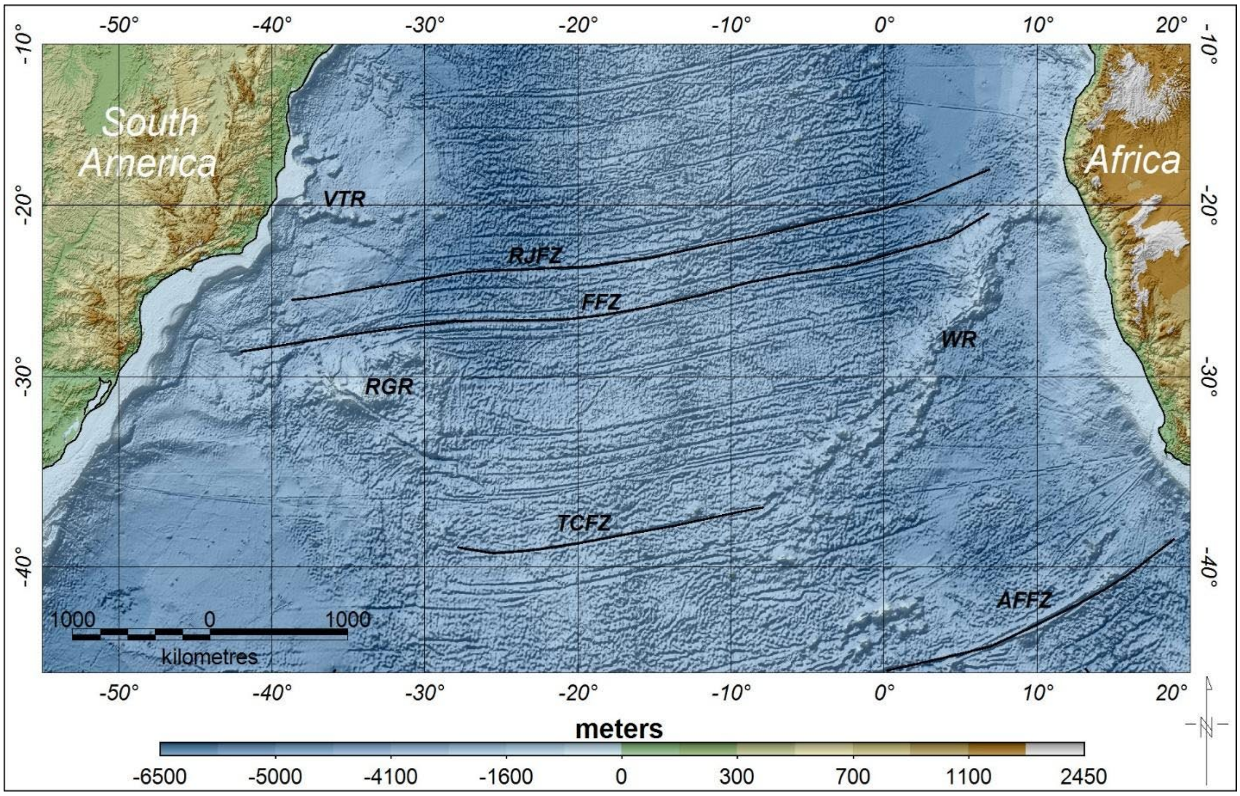

Figure 1: Topographic map of the South Atlantic. The study area is located between latitudes -45º and -10º N and longitudes -55º and 20º. AFFZ (Agulhas-Falkland Fracture Zone), FFZ (Florianópolis Fracture Zone), RGR (Rio Grande Rise), RJFZ (Rio de Janeiro Fracture Zone), WR (Walvis Ridge), TCFZ (Tristão da Cunha Fracture Zone) and VTR (Vitória-Trindade Ridge).

we replaced the seawater by the oceanic crust. Therefore, the Bouguer correction will be added to the value of the Free-Air gravity anomaly. In oceanic areas, the density used to calculate the Bouguer correction is given by:

$$\rho = \rho_{oceanic\_Crust} - \rho_{\text{water}} \tag{2}$$

In this study we used the Parker method that applies the Fourier transform to determine the gravitational anomaly generated between two media of different density, whose interface is not uniform (Parker, 1973). The calculation is performed in the wave number domain:

$$F[\Delta g] = -2\pi\rho G exp(-|\vec{k}|z_0) \sum_{p=1}^{\infty} \frac{|\vec{k}|^{n-1}}{n!} F\,[h^n(\vec{r})] \tag{3}$$

where Δg is the gravity anomaly; ρ the density contrast between the layers; G the Universal gravitation constant; h(r) the interface topography; and k and z_0 are the wave number and average level of the topography, respectively. For this study it was used the density values of 2,67 g/cm³ for continental crust; 2.8 g/cm³ for oceanic crust; and 1.03 g/cm³ for water. The Bouguer anomaly map is shown in Figure 3.

The regional-residual separation process was performed by spectral filters, where the gravimetric data are filtered in the Fourier domain. The cutoff wavelength for this process is determined from the power spectrum. The power spectrum of the Bouguer anomaly data showed that the regional anomalies have wavelengths of 500 km or greater (Figure 4). The separation of the small and large wavelength anomalies was performed using the Gaussian Regional/Residual spectral filter (Geosoft, 2021), which is part of the Oasis-Montaj software. The filtering by the Gaussian filter is defined as follows:

$$L_{(k)} = 1 - e^{\frac{-k^2}{2k_0^2}} \tag{4}$$

where k_0 is the cutoff central wavelength of the roll-off.

The residual anomaly map is shown in Figure 5.

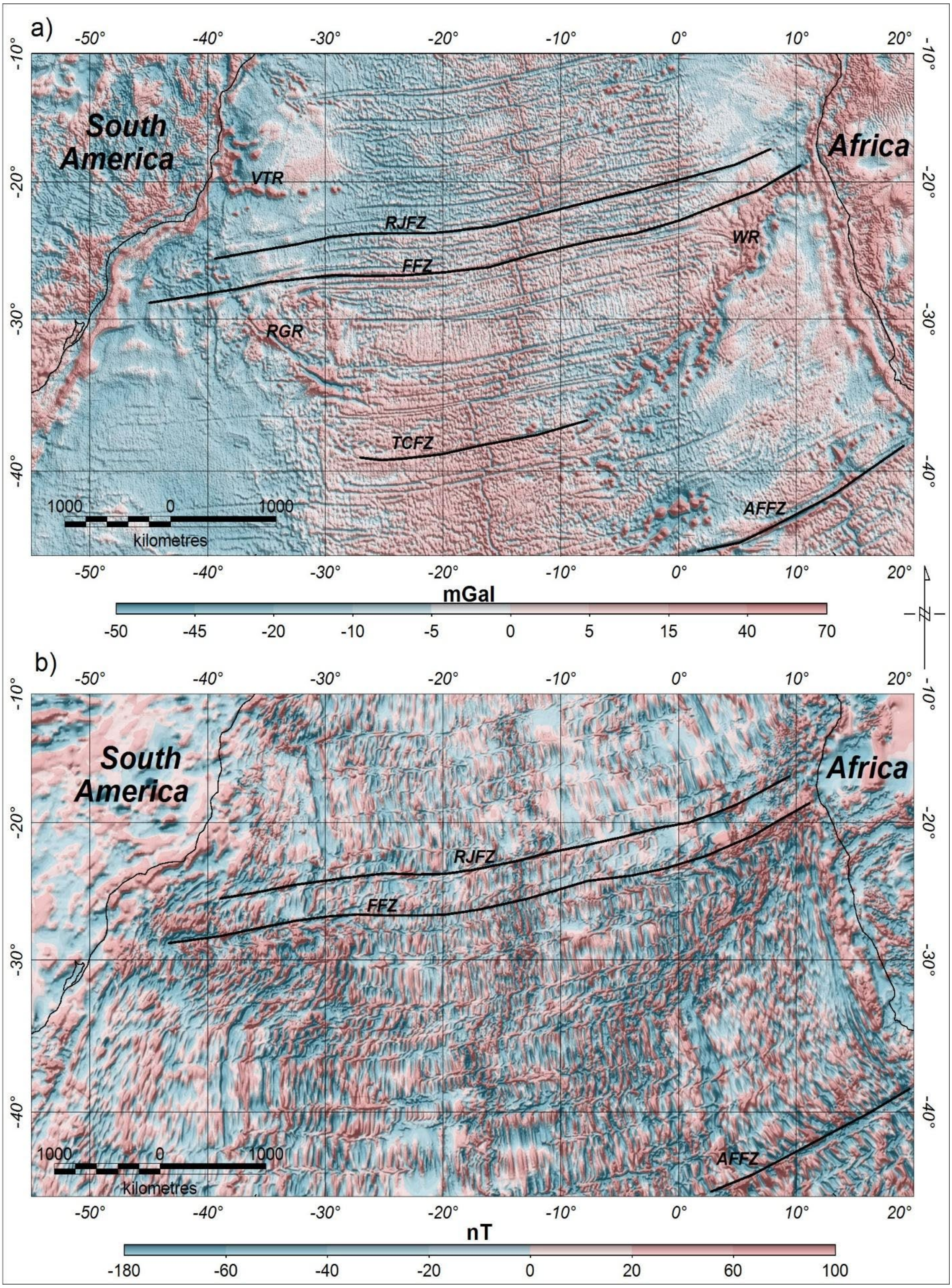

Figure 2: (a) Free-air gravity anomaly map and (b) Total magnetic intensity (TMI) anomaly map. AFFZ (Agulhas-Falkland Fracture Zone), FFZ (Florianópolis Fracture Zone), RGR (Rio Grande Rise), RJFZ (Rio de Janeiro Fracture Zone), WR (Walvis Ridge), TCFZ (Tristão da Cunha Fracture Zone) and VTR (Vitória-Trindade Ridge).

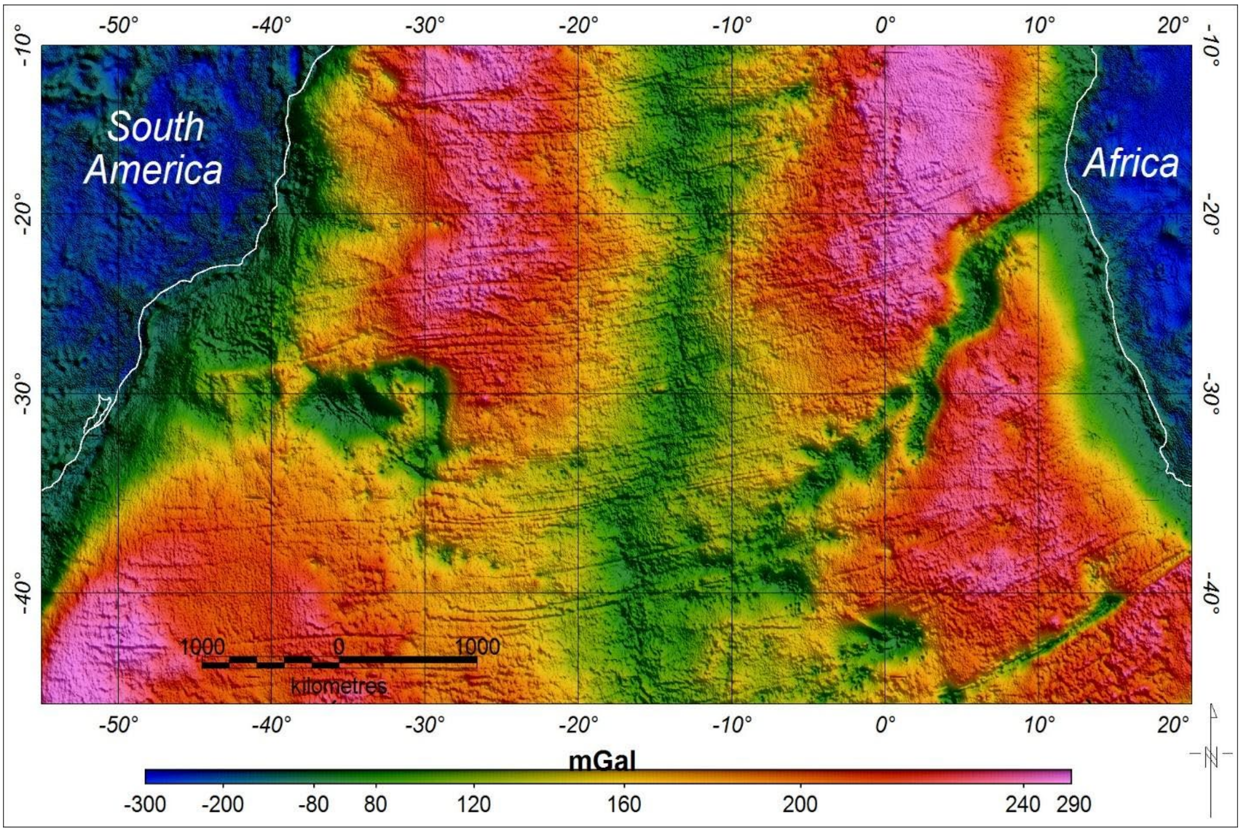

Figure 3: Bouguer anomaly map of the South Atlantic.

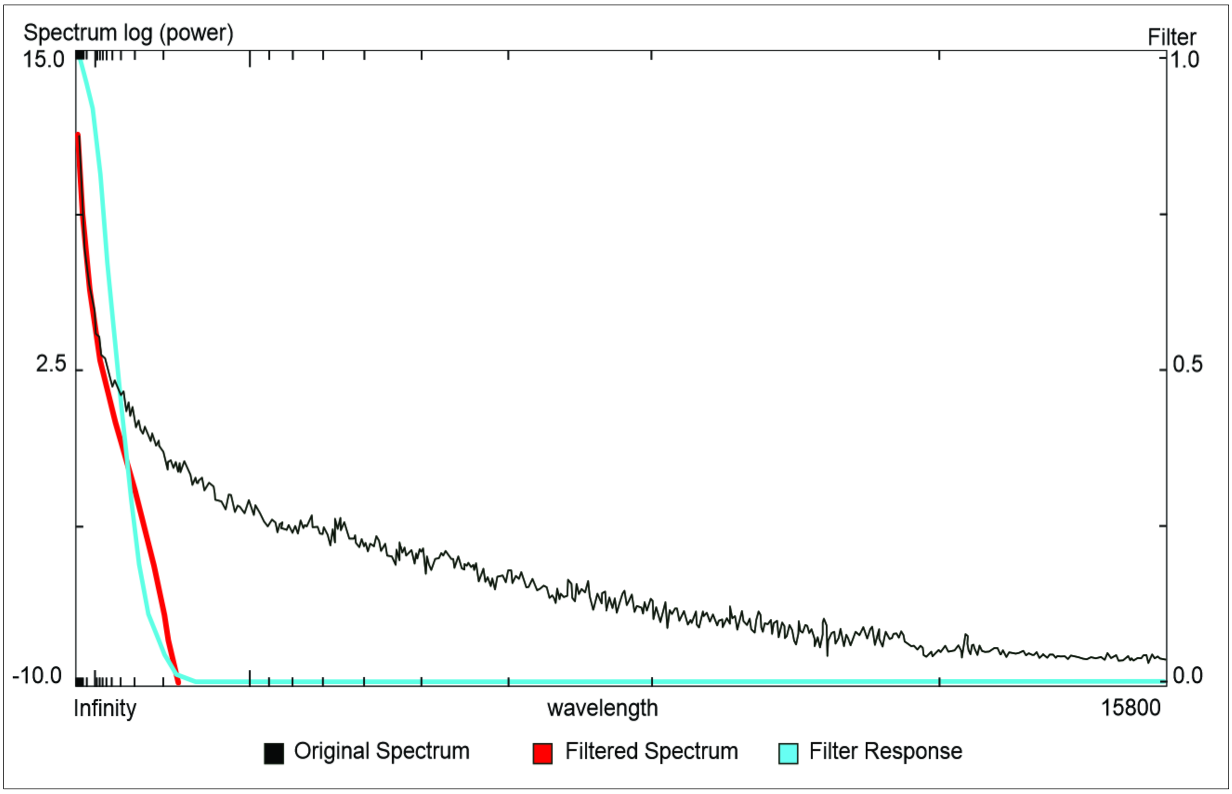

Figure 4: Power spectrum of the Bouguer anomaly map. The cutoff wavelength is 500 km.

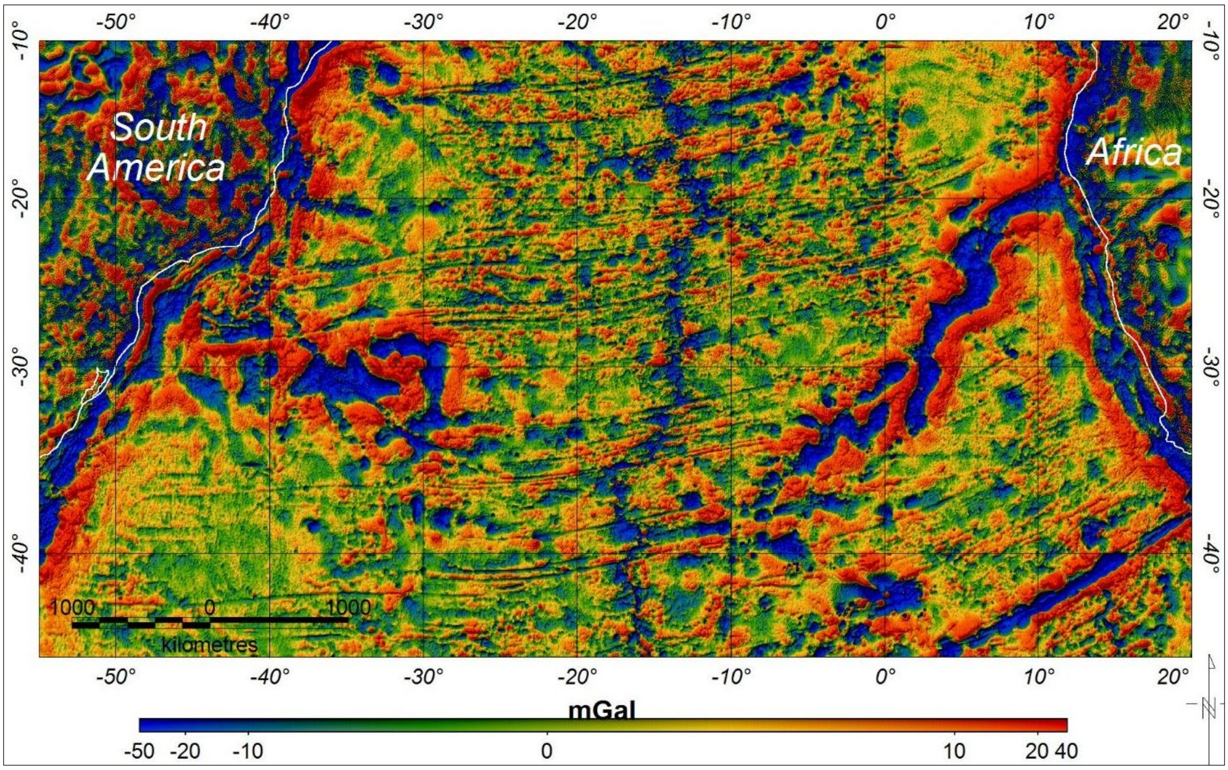

Figure 5: Residual anomaly map of the South Atlantic.

ANALYTIC SIGNAL AMPLITUDE

Magnetic anomalies are dipolar. The shapes and amplitudes of these anomalies vary according to their geographical location, because the measured signal is the sum of the source magnetization and the Earth's geomagnetic field. Therefore, it is necessary to use techniques that simplify the interpretation of the magnetic data. The analytical signal amplitude (Nabighian, 1972) is widely used in magnetics, as it weakly depends on the direction of magnetization of the geomagnetic field. The ASA is given by the expression (Roest et al., 1992):

$$|A(x,y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2} \qquad (5)$$

where $\frac{\partial M}{\partial x}; \frac{\partial M}{\partial y}$; and $\frac{\partial M}{\partial z}$ are the partial derivatives of the Total Magnetic Intensity (TMI) field. The ASA is widely used to determine the boundaries of gravimetric and magnetic anomaly sources (Figure 6). In shallow bodies, the maximum ASA amplitudes are located near the edges. As the depth of the body increases, the greatest amplitude values move away from the edges (Li, 2006).

TILT DERIVATIVE

The Tilt Derivative is a filter that enhances magnetic anomalies from shallower sources. It is given by: $TDR = tan^{-1}\left[\frac{VDR}{THDR}\right]$, where VDR is the vertical derivative and THDR is the total horizontal derivative (Verduzco et al., 2004). The TDR values fall within the range of $-\frac{\pi}{2} < TDR < \frac{\pi}{2}$. To highlight the fracture zones of approximate E-W direction, we applied the directional cosine filter to remove geological structures with azimuth of zero degrees (Figure 7).

DATA INTERPRETATION

The magnetic and gravimetric maps generated from the methodology described above allowed a particular emphasis on the lineaments associated with oceanic fracture zones (FZs). A comparative analysis of the maps in Figures 6 and 7 showed that the tilt derivative method (with the application of the directional cosine filter) enhanced the tracing of the FZs, as it removed the complex magnetic fabric effect oceanic crust spreading. Thus, it is possible to verify the existence of systems formed by multiple lineaments (with widths of hundreds of kilometers) that include the FZs (Figure 7). Among these systems, the Florianópolis and Rio de Janeiro fracture zones originated in the SE segment of the Brazilian are highlighted in Figure 8.

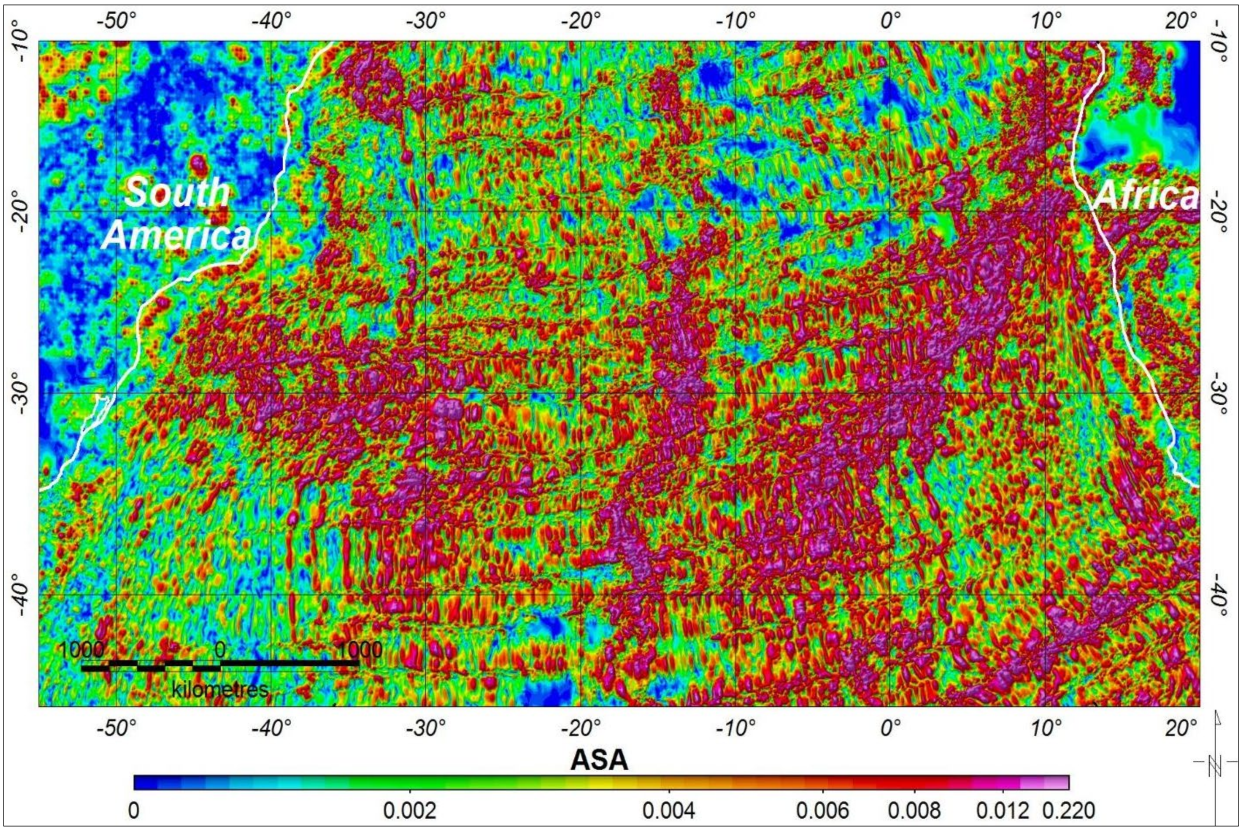

Figure 6: Analytic signal amplitude map of the South Atlantic.

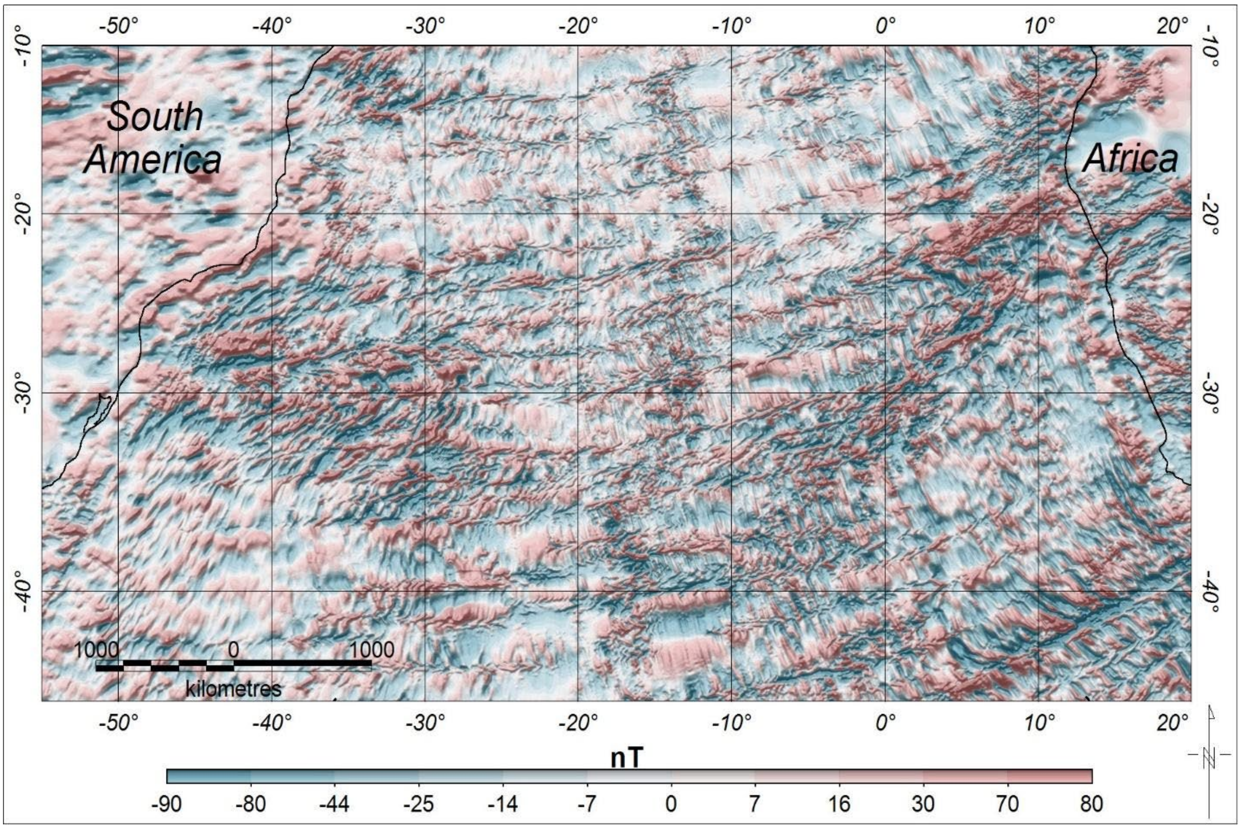

Figure 7: Tilt derivative map of the South Atlantic with N-S directional cosine filter.

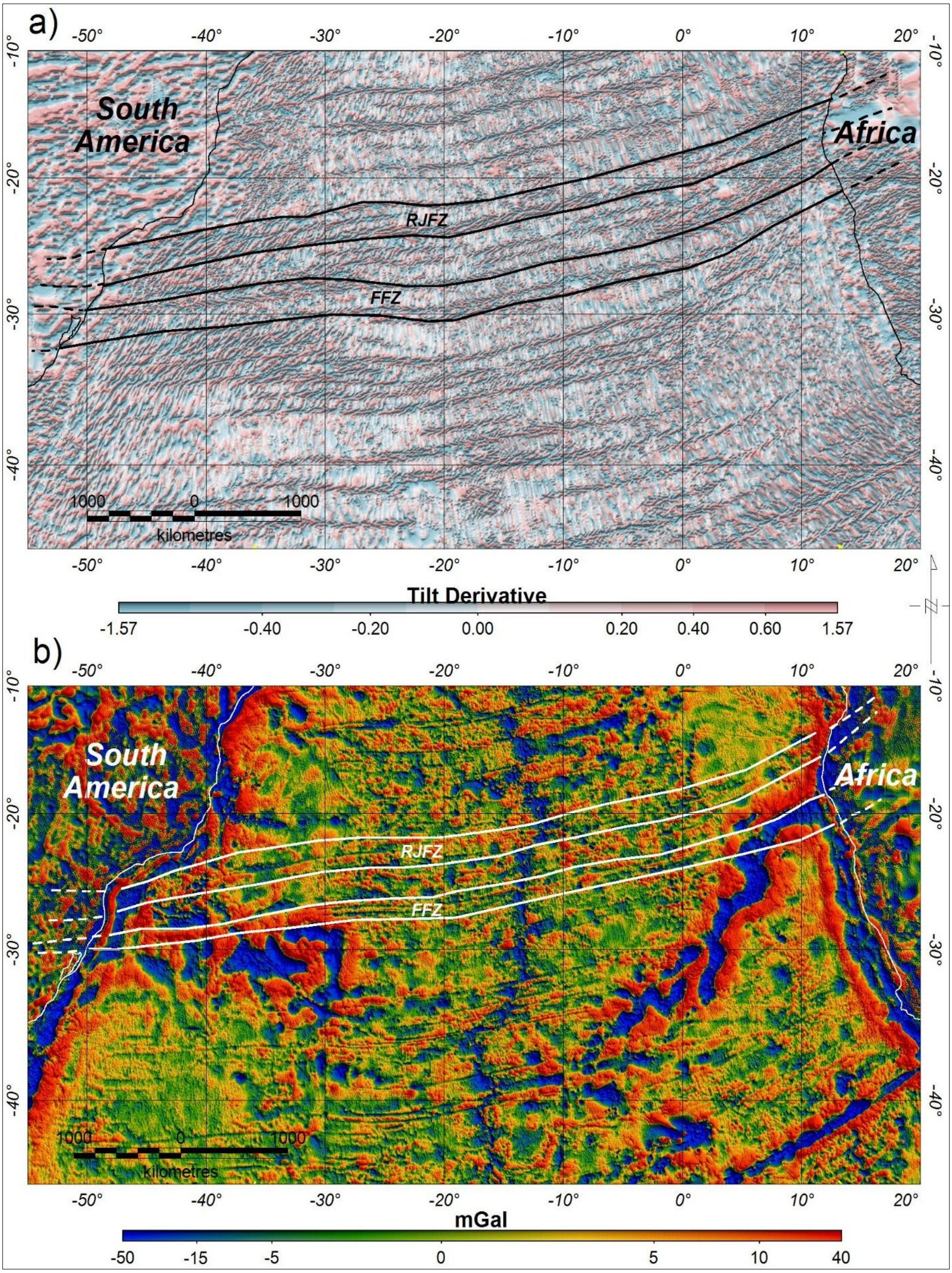

Figure 8: (a) Tilt derivative magnetic anomaly map showing the fracture zones of Rio de Janeiro (RJFZ) and Florianópolis (FFZ); (b) Residual Bouguer gravity anomaly map showing the same elements as above. Note the good correlation between the magnetic and gravimetric lineaments observed in both maps.

Figure 9 shows the magnetic map (tilt derivative) and the residual Bouguer gravity anomaly map, focusing on the Brazilian SE margin. There is an evident change in the behavior of the FZs in Rio de Janeiro (RJFZ) and Florianópolis (FFZ) as they approach the continent (highlighted in the interpretation). When compared to the other FZs in the south (Pelotas Basin) and north (Vitória-Trindade Ridge), both fracture zone directions deflect from E-W (in the oceanic area) to NE-SW as they approach the continent. In contrast, the others remain constant in the E-W direction approximately.

The distal area of the SB basin (Figure 9), between the RJFZ and the FFZ, is called the São Paulo Plateau and large volumes of hydrocarbons were recently discovered in this area. Ferraz et al. (2019), Gamboa et al. (2019) and Gamboa et al. (2021) interpreted the nature of its crust as attenuated continental crust and propose a mechanism for the arrival of the large existing concentrations of CO_2 in the calcareous reservoirs that exist under a thick evaporitic layer.

As the maps in Figure 9 suggest, the Rio de Janeiro system (RJFZ) originates from NE-SW lineaments on the continent that cross the Santos Basin and reach the oceanic crust near the latitude of Rio de Janeiro (RJ) where they assume the condition of the oceanic fracture zone. The Florianópolis system (FFZ), further south, would also have its origins on the continent, evolving to the Florianópolis (Fl) fracture zone that limits the southern portion of the Santos Basin (used in Figure 9).

When observing the continuity of these FZ systems to the African margin (Figure 8), it is also possible to verify their continuity in NE-SW lineaments entering the continent, suggesting that they were part of the same lineament system (established in the continental crust), integrating the rifted Gondwana that gave rise to Africa and South America.

In the Santos Basin context, there is a system of NW-SE lineaments, also relevant, which are present mainly in the northern portion of the basin, displacing the basin's hinge line (Figure 9). There is a connection of these lineaments with the RJFZ system, as the interpretation in the figure suggests. Also noteworthy is the observed parallelism of these lineaments with the Vitória-Trindade Ridge (VTR) which is highlighted on the residual Bouguer map as a low-gravimetric lineament that extends as an oceanic FZ to the east.

CONCLUSIONS

The present study demonstrated the applicability of numerical transform methods to potential data to highlight regional tectonic features. The maps obtained were helpful for the comparison of tectonic features through different data views, such as topographic, gravimetric, and magnetic.

Among the tested methods, the tilt derivative allowed better focus on systems of fracture zones crossing the ocean and connecting the margins of South America and Africa. Compared with the regional/residual gravity, the tilt derivative method map showed a high correlation with residual gravity map, supporting the conclusions on the Florianópolis and Rio de Janeiro fracture zone inflection at the Brazilian continental margin.

The analysis of maps highlights the trend of the Florianópolis and Rio de Janeiro fracture zones at the Brazilian continental margin, bringing into focus their different behavior compared to the other systems observed both to the North and South. Both fracture zones change direction (from E-W in the ocean to NE-SW) as they approach their origin in the continental areas. Also, they find a new opposite direction system (NW-SE) that displaces the Cretaceous hinge line in the northern portion of the Santos Basin.

The present study suggests a generic relationship between oceanic fracture zones and continental lineaments (in both South America and Africa), demonstrating that the magnetic and gravimetric expression of these structures can serve as important constraints for reconstructions of continental margins in the rift and post-rift.

Also, this study demonstrates that the continental structures associated with possible transcurrent and transfer zones, which gave rise to the fracture zones of Rio de Janeiro and Florianópolis, played an essential role in the tectonic evolution of the SE margin not only in the Santos Basin but also in the African conjugated margin in a similar way.

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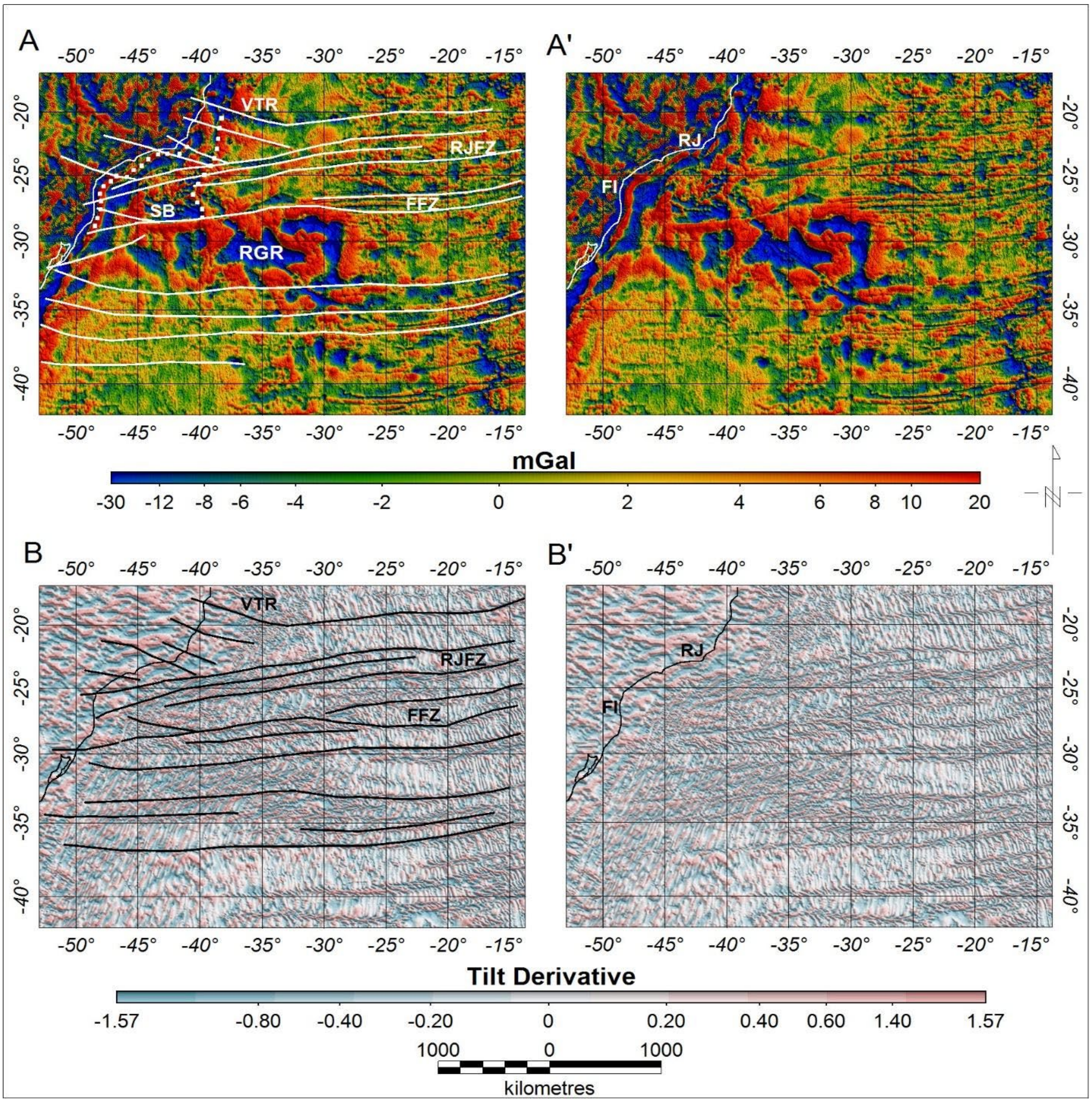

Figure 9: (A) Residual Bouguer gravity anomaly map showing detail of the SE Brazil margin with interpretation of the lineaments associated with the fracture zones of Rio de Janeiro (RJFZ) and Florianópolis (FFZ), indicating its continental origin from structures that depart from the continent and cross the Santos Basin (SB). The dotted lines represent the SB hinge line to the west and the COB to the east. RGR = Rio Grande Rise and VTR = Vitória-Trindade Ridge. (B) Tilt derivative magnetic map showing the same lineaments as above. Note the agreement between the magnetic and gravimetric lineaments and the deflection to NW of the RJFZ and FFZ when approaching the continent. A' and B' correspond respectively to the same maps without interpretation for comparison purposes.

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