The Brazilian Equatorial Margin: A Snapshot in Time of an Oblique Rifted Margin*

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Search and Discovery Article #30325 (2014)
Posted April 14, 2014

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG 2014 Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014,

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Abstract

Cretaceous rifting within Northeast Brazil and the Guinean coast of Africa reactivated Pan-African faults as strike-slip mega-shear zones (Darros de Matos, 1999; Greenroyd et al., 2008; Antobreh et al., 2009). The term oblique rifted margin was used by Yang and Escalona (2011) and shear margin by Bird (2001) to describe the Equatorial South Atlantic. Greenroyd et al. (2008) were the first to describe the segmentation of the margin as a series of rift-dominated and transform-dominated segments, that they named rifted and sheared segments respectively. Antobreh et al. (2009) described similar segmentation in the Guinean coast of Africa and used the same nomenclature. Antobreh et al. (2009) used the term sheared margin to describe segments of the Ghanaian margin that are parallel to the main fracture zone traces, and rifted margins to describe the segments in between. Sheared margins are parallel to major oceanic fracture zones that offset the Mid-Atlantic Ridge up to several hundreds of kilometers. Here we describe the Equatorial margin as a transform margin in the Piauí-Ceará margins and its counterpart Côte d'Ivoire margin, evolving to the north into an oblique margin at the Barreirinhas Pará-Maranhão basins.

Oblique rifts are rifts in which the continent-ocean transition zone (COTZ) is not normal to the direction of seafloor spreading and to the trend of fracture zones. Other examples of oblique rifted margins include the Gulf of California (Lizarralde et al., 2007; Umhoefer et al., 2011), the Gulf of Aden (d'Acremont et al., 2006; Fournier et al., 2007; Autin et al., 2010; Daoud et al., 2011), the East coast of Madagascar and the Dead Sea (Cochran et al., 1983; Bird, 2001). This work focuses in the detail geometries of the rift faults in the Brazilian Equatorial margin. Our study area extends from the Foz do Amazonas to the Piauí-Ceará Basin. We investigate rift-system faults along the Brazilian equatorial margin to better understand the nature of the Continent-To-Ocean Transition Zone (COTZ). The COTZ is that region of attenuated continental crust which lies between the outboard edge of full-thickness continental crust, and the inboard edge of oceanic crust. We mapped the COTZ using seismic and potential field data. We use the continent ocean transition zone (COTZ) defininition from Direen et al. (2012); a region of highly attenuated continental crust on the continental margin that lies between the outboard edge of unequivocal continental crust, and the inboard

edge of unequivocal oceanic crust. Note that this definition is similar, but not identical, to the term ocean–continent transition (OCT) as used by Manatschal (2004) and Reston (2007) for the transition from the distal continental margin to the first oceanic crust.

Basement Geometry and Margin Segmentation

Detailed mapping of the basement using 500,000 km of 2D seismic lines on a 16 km by 8 km grid from the continental shelf to the oceanic basin was used to describe the geometries of the rift faults offshore in the Brazilian Equatorial margin. Four main segments based on fault geometry are described in the study area: (1) Piauí-Ceará, (2) Barreirinhas, (3) Pará-Maranhão-Foz do Amazonas, and (4) Amapá.

Piauí-Ceará Margin

The continental margin is narrow, only 90 kilometers in the segment of the Northeast Brazilian margin occupied by the Piauí-Ceará Basin (Figure 1). The transition from the continental crust to the abyssal basin oceanic crust involves two main east-west-trending basement fault zones, over 200 km long (Figure 2). The basement fault zones trace to the Romanche Fracture Zone on the oceanic crust (Figure 3). The continental oceanic transition zone (COTZ) is narrow, less than 20 km, and involves two main low angle (~15^{o} ±5^{o}) and large displacement (> 4 seconds) east-west-trending basement fault zones, dipping basinward.

Barreirinhas Margin

The Barreirinhas continental margin is narrow (160 kilometers) (Figure 1). Transition between continental and oceanic crust is narrow (~20 kilometers). Basement faults in the Barreirinhas Basin have lengths from 5 to 50 kilometers (Figure 2), low angle (~15^{o}), and large displacement (~3 seconds). Basement faults trend close to east-west in the southern part of the basin, adjacent to the Piauí-Ceará Basin and trend northwest-southeast in rest of the Barreirinhas Basin (Figure 2).

Pará-Maranhão to Foz do Amazonas Margin

The continental margin is wider (~220 kilometers) in the Pará-Maranhão Basin than in the Barreirinhas and the Piauí-Ceará margins (Figure 1). The Pará-Maranhão COTZ corresponds to a series of northwest-southeast direction normal basement fault zones. Basement faults have lengths of 5 to 50 km, displacements of ~1.5 to 2 sec and dip angles of 15^{o} to 20^{o}. The Pará-Maranhão Basin basement is more heavily faulted than the Piauí-Ceará and the Barreirinhas Basins basement (Figure 2). The transition from the continental margin to the abyssal basin (COTZ) is more gradual, being accommodated by many fault sets.

Amapá Margin

The Amapá continental margin is very wide, 330 kilometers (Figure 1). The transition from continental to oceanic crust occurs in ~ 100 kilometers in the strike direction, making it the broadest COTZ on the Brazilian Equatorial margin. The COTZ in the margin corresponds to a series of basinward dipping normal fault zones. Basement faults have lengths of 40 to 180 km and trend northwest-southeast (Figure 2).

Basement slope is the least steep in the Brazilian Equatorial margin, as is accommodated by a series of 15° dip angle and 1 second displacement basement faults.

Relationship Between Basement Fault Geometry and Obliquity of the Rift

Oblique rifts have a strong strike-slip component expressed primarily during the early rift stages and start as a complex pattern of pull-apart basins along strike-slip fault systems that eventually coalesce into through-going systems (Umhoefer et al., 2002). This rifting model was described by Darros de Mattos (1999) for the Central Atlantic. Strike-slip component during rifting in the Central Atlantic has been described in the onshore basins of northeast Brazil (Magnavita, 1992; Darros de Mattos, 1999; Destro et al., 2003), in the South American margin between northeast Brazil and the Guinean coast of Africa (Greenroyd et al., 2008), and in the counterpart Guinean coast of Africa (Antobreh et al., 2009).

Clifton and Schlische (2001), using scaled physical models, demonstrated that there is a geometric upper limit to fault length in oblique rift zones causing fault length to be inversely proportional to obliquity. That relationship is observed in the basement fault geometries of the Brazilian Equatorial margin with a direct correlation between obliquity and strike length basement faults in the Brazilian Equatorial margin. In the Brazilian Equatorial margin, the COTZ forms an oblique angle with the fracture zones, and the angles between COTZ and the fracture zones vary among different segments of the margin. The angle between the continent ocean transition zone (COTZ) and Saint Paul Fracture Zone is 40° in the north branch and 45° in the southern branch (Figure 2). In the oblique-rifted segments of the Barreirinhas and Pará-Maranhão fault strike lengths range from 5 to 50 km (Figure 1). In the Piauí-Ceará margin where the Romanche Fracture Zone is parallel to the COTZ (Figure 2) basement faults strike-lengths are very long from 180 to 210 km (Figure 1). In the Amapá margin, due to the thick sedimentary wedge, fracture zones cannot be mapped near the continental margin, nevertheless the rifting geometry was less oblique (Figure 2), than in the Barreirinhas and Pará-Maranhão segments and basement faults strike lengths are as long as 180 km (Figure 1). Because basement faults formed and grew during the rifting process, their geometries represent the geometry at the time of rifting and an argument can be made that there is an observed upper limit of ~ 50 km to fault length in the oblique-rifted segments of the Brazilian Equatorial margin.

Conclusions

Prior to the emplacement of oceanic crust rift faults grew, then movement ceased as soon as oceanic crust was emplaced. Therefore, the COTZ geometry gives a snapshot in time for the geometry of the fault system at the time of the rifting. Oceanic fracture zones are solely located on oceanic crust and oceanic fracture zone strike direction represents the seafloor spreading direction at that point in time. Strike directions of the oceanic fracture zones immediately adjacent to the COTZ in the Brazilian Equatorial margin therefore represent the seafloor spreading direction at earliest Central Atlantic dift phase. Assuming no change in extension direction from the end of rifting to early drifting, the angle between a normal to the COTZ and the projection of the oceanic fracture zone to the COTZ represents the obliquity of the rift direction in relationship to the main direction of separation between the continents. Comparing the strike directions of the COTZ basement faults, located predominantly on continental crust, with the strike direction of the adjacent oceanic fracture zone was used to classify the Equatorial margin as a transform margin in the Piauí-Ceará portion of the margin, and oblique in the Barreirinhas and Pará-Maranhão.

In the Piauí-Ceará margin, east-west striking basement faults are predominant and are parallel to the Romanche fracture zone segments, therefore in the Piauí-Ceará margin the COTZ is parallel to the Early Cretaceous spreading direction and that makes it a transform margin. Along the Barreirinhas and Pará- Maranhão basins the COTZ and the basement faults have a northwest strike. The COTZ forms an angle of 35 to 40 degrees with the Saint Paul fracture zone and that makes it an oblique margin. North of the Foz do Amazonas along the Amapá margin, oceanic fracture zones could not be traced all the way to the COTZ, but a change to a north-south strike direction on the basement faults on the COTZ suggests a more orthogonal rifting direction. Where the continental margin is oblique, basement fault lengths are shorter with a limit of 50 km which is in agreement with physical models (Clifton and Schlische, 2001). The observed basement fault geometries through the margin require a strike-slip component during the early rift stages. We infer north-striking segments to be dominantly extensional while east-west striking segments would primarily accommodate strike-slip motion and northwest-striking segments accommodate oblique motion. Therefore, the most likely model of evolution for the Central Atlantic rift is a complex pattern of pull-apart basins along strike-slip fault systems that eventually coalesce into through-going systems, as described by Darros de Mattos (1999) for the central Atlantic.

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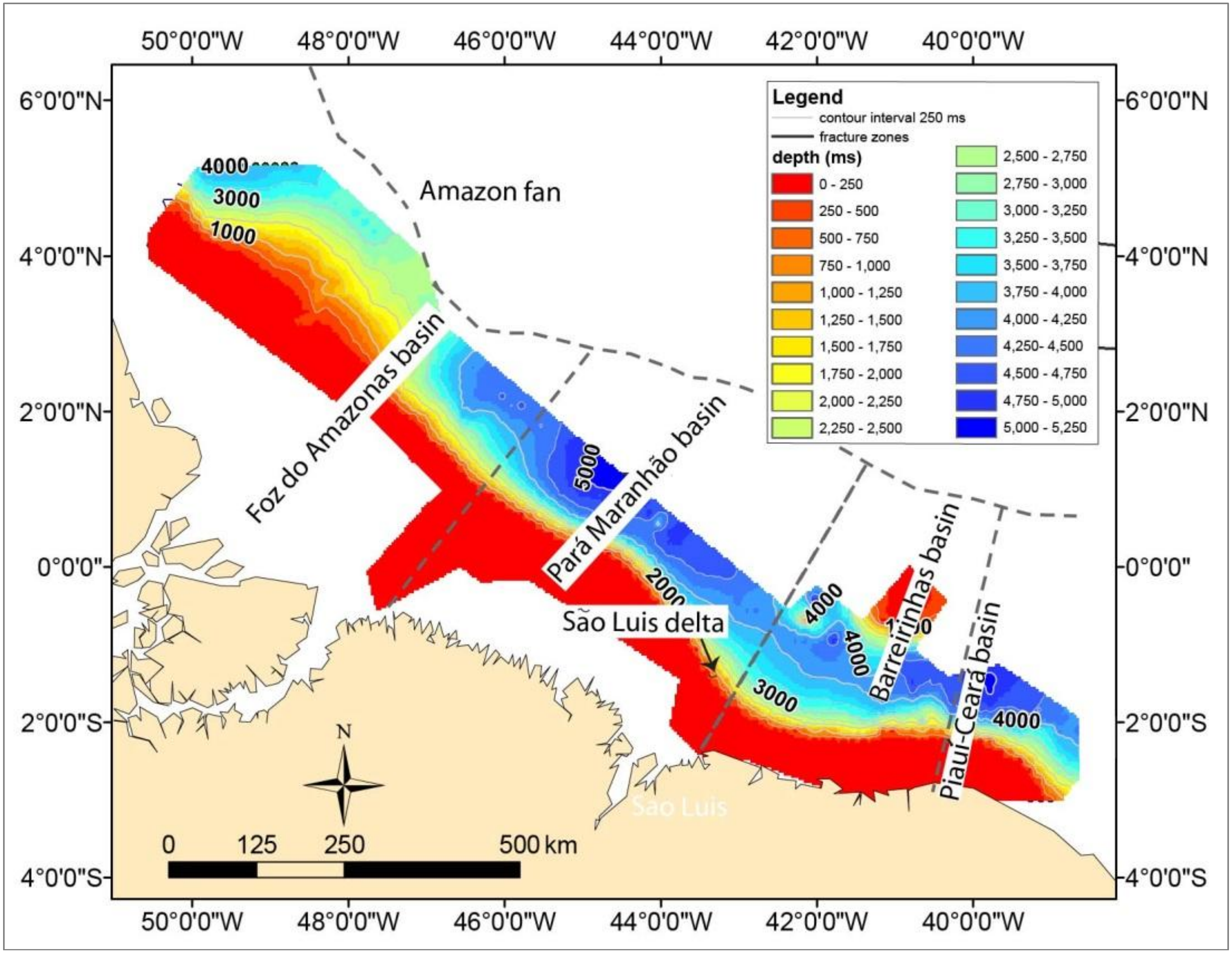

Figure 1. Bathymetry of the Brazilian Equatorial margin, mapped on the water bottom signal of ~ 500,000 km of 2D seismic reflection profiles. Offshore basin outlines are from Agência Nacional de Petróleo (www.anp.gov.br).

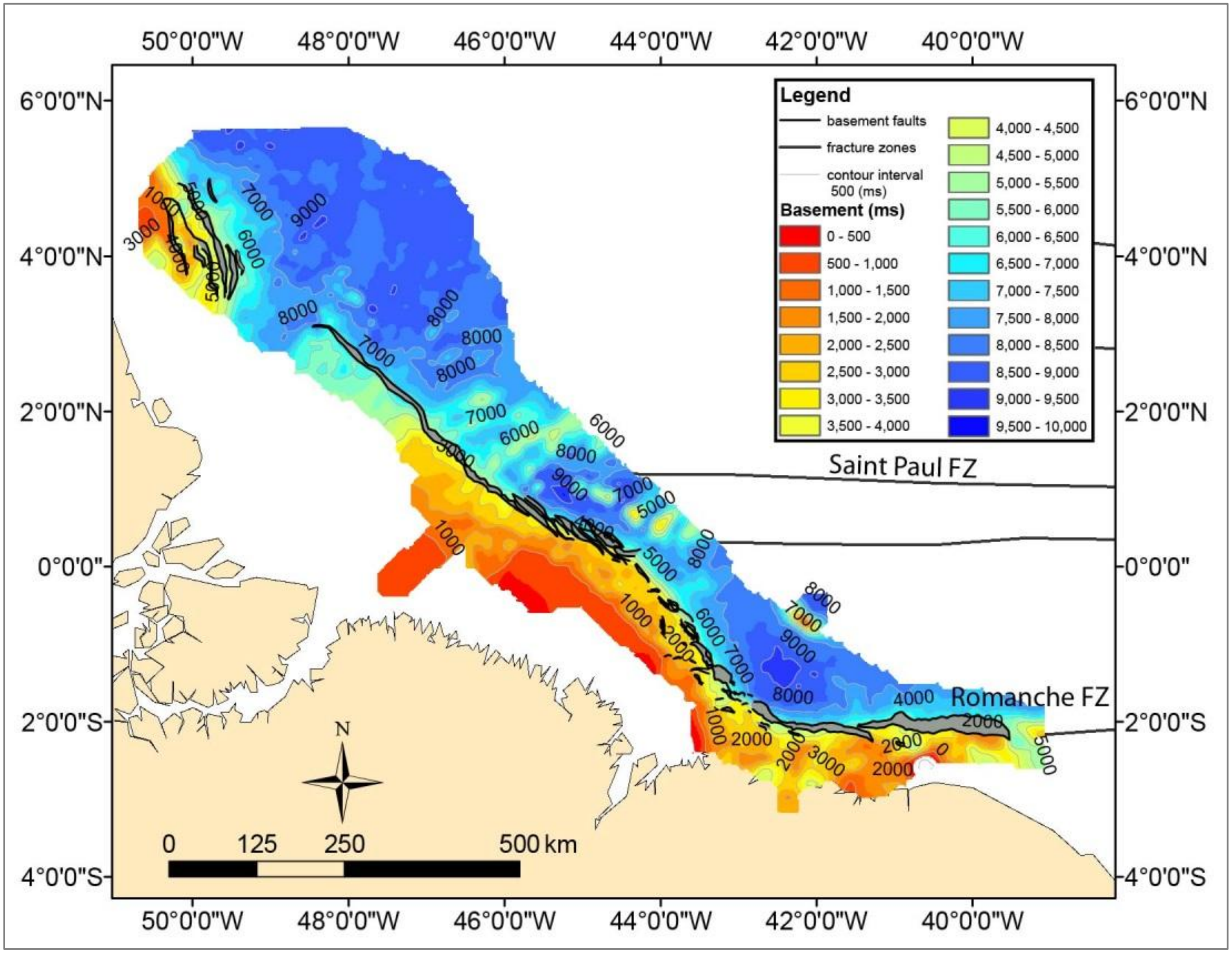

Figure 2. Depth to basement in milliseconds. Basement faults and fracture zones mapped are part of this study. The basement faults mapped are preferentially located around the COTZ and the most seaward fault zones mapped mark the contact with oceanic crust in the hanging wall. Faults shown in the map are in the basement which is now overlain by 1 to 5 seconds of sediments. Basement faults under the Amazon fan are not mapped, as they are deeper than the seismic record.

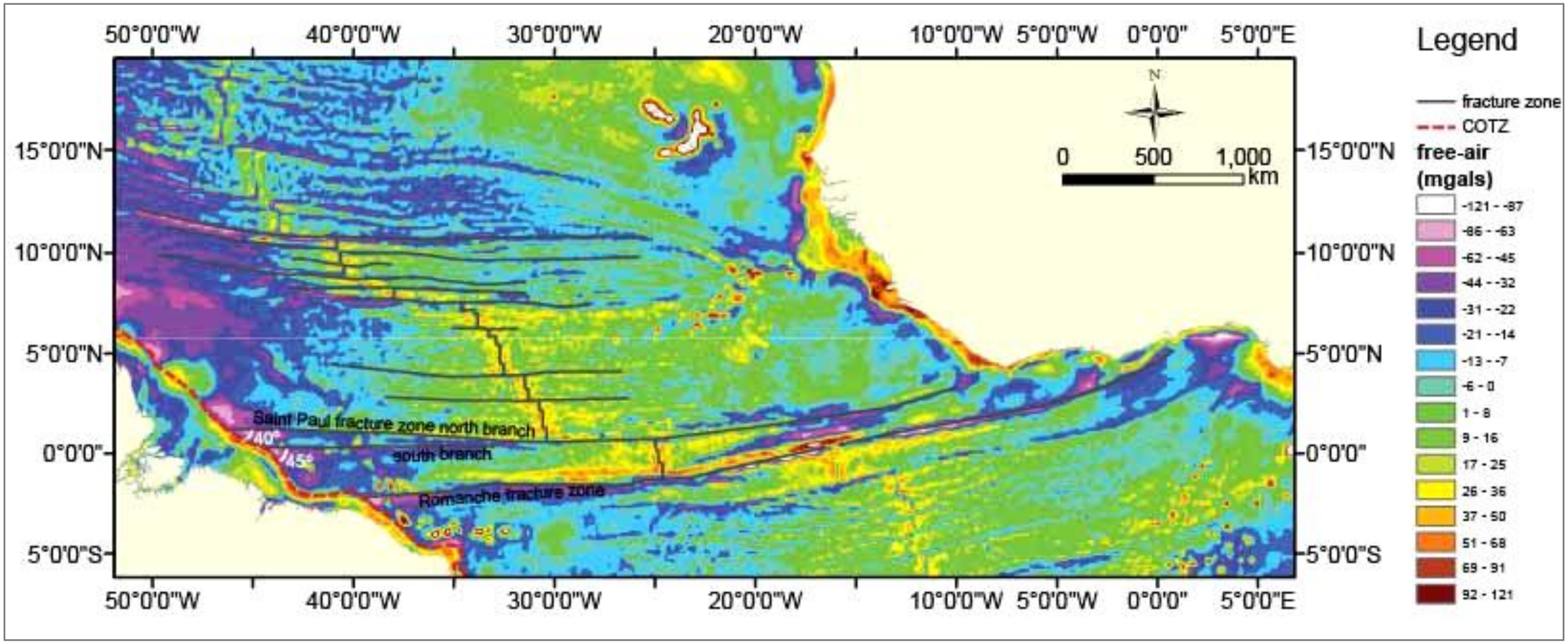

Figure 3. Geometric relationship between COTZ and Free-air gravity map of the Equatorial South Atlantic. Free-Air data obtained from the SATELLITE GEODESY gravity data (Sandwell and Smith, 2009). Fracture zones and mid-ocean ridge displacements are interpreted based on the free-air gravity anomalies. COTZ is represented in the map in red dashed lines and was interpreted using free-air gravity data combined with seismic data.