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INVESTIGAÇÃO GEOFÍSICA DA ELEVAÇÃO DO CEARÁ NA MARGEM EQUATORIAL BRASILEIRA – CROSTA CONTINENTAL OU CROSTA OCEÂNICA?

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Dissertação de Mestrado apresentada ao Programa de Pós-graduação em Geofísica, do Observatório Nacional, como parte dos requisitos necessários à obtenção do título de Mestre em Geofísica.

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"GEOPHYSICAL INVESTIGATION OF THE CEARÁ RISE IN THE BRAZILIAN EQUATORIAL MARGIN – A CONTINENTAL CRUST OR AN OCEANIC CRUST?"

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A classificação da margem equatorial brasileira em relação aos processos de rifteamento, ruptura da litosfera e vulcanismo ainda é controversa. Consequentemente, a origem e a evolução dos platôs oceânicos, das cristas e dorsais oceânicas, dos altos oceânicos localizados nas margens continentais rifteadas, como a Elevação do Ceará na Margem Equatorial Brasileira, são desconhecidas. Os estudos publicados nos últimos 40 anos sugerem dois cenários geológicos para a Elevação do Ceará: crosta continental e crosta oceânica. Interpretamos uma seção transversal vertical 2D que se estende através da área continental até o assoalho oceânico atravessando a Elevação do Ceará utilizando dados sísmicos e de gravidade. Nesta seção transversal, os principais elementos são: água do mar, sedimentos, camadas de crosta e manto, transição crosta continental-crosta oceânica (COT), interface da Moho e a Elevação do Ceará. Presumimos que a água, os sedimentos e as camadas do manto são meios homogêneos com densidades conhecidas. Também presumimos uma variação de densidade lateral dentro da camada de crosta. Com o objetivo de investigar a posição da COT e da densidade crustal da Elevação do Ceará, a geometria da camada sedimentar foi extraída da nossa interpretação de uma imagem de sísmica ultra-profunda. Investigamos a profundidade da Moho ao longo desta seção transversal usando o modelo de compensação isostática Airy e a interpretação sísmica. A modelagem 2D do distúrbio de gravidade calculada usando tanto a Moho isostática como a Moho sísmica permite investigar a COT e a densidade crustal da Elevação do Ceará. A modelagem do distúrbio da gravidade usando a Moho isostática não confirma a Elevação do Ceará como uma enorme acumulação de crosta oceânica e nem uma transição abrupta da crosta continental para a crosta oceânica (COT abrupta) porque este modelo produz um ajuste dos dados do distúrbio de gravidade inaceitável. No entanto, a Moho isostática sobre a crosta oceânica "normal", compreendida no intervalo da COT até a Elevação do Ceará, produz um ajuste dos dados do distúrbio de gravidade aceitável. Sob as hipóteses da crosta continental para a Elevação do Ceará e de um domínio de manto subcontinental exumado, a Moho sísmica produz um ajuste dos dados do distúrbio de gravidade aceitável na região da Elevação do Ceará e na região abrangendo desde a área continental até a COT. No entanto, a Moho sísmica sobre a crosta oceânica "normal" produz um ajuste dos dados do distúrbio de gravidade inaceitável. Propusemos uma modelagem híbrida que junta as Mohos isostática e sísmica sob a hipótese de crosta continental para a Elevação do Ceará. Neste modelo híbrido, a Moho isostática é usada sobre a crosta oceânica "normal" e a Moho sísmica é usada ao longo da Elevação do Ceará e da área continental até a COT. Assim, a modelagem híbrida apoia a hipótese da margem equatorial brasileira como uma margem pobre em magma. Além disso, as hipóteses da Elevação do Ceará como um fragmento continental abandonado e uma COT com exumação do manto devem ser aceitas porque essas hipóteses, juntamente com a modelagem híbrida, produzem um ajuste aceitável dos dados observados do distúrbio de gravidade.

Palavras-chave: [Margem Equatorial do Brasil; Elevação do Ceará; Crosta; Moho; Margem Rifteada; Margem Passiva; Margem Pobre de Magma; Isostasia; Modelagem do Distúrbio da Gravidade; Transição Crosta Continental-Crosta Oceânica]

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GEOPHYSICAL INVESTIGATION OF THE CEARÁ RISE IN THE BRAZILIAN EQUATORIAL MARGIN – A CONTINENTAL CRUST OR AN OCEANIC CRUST?

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The classification of the Brazilian Equatorial Margin concerning rifting, lithosphere breakup and volcanism processes is still controversial. Consequently, the origin and evolution of oceanic plateaus, highs, ridges and rises located on rifted margins such as the Ceará Rise on the Brazilian Equatorial Margin are misunderstood. The studies published over the past 40 years have suggested two geological scenarios for the Ceará Rise: a continental and an oceanic crust. We have interpreted a 2D vertical cross section that extends through the continental area down to the oceanic floor crossing the Ceará Rise by using seismic and gravity data. In this cross section, the main elements are: seawater, sediments, crust and mantle layers, continent-ocean transition (COT), Moho interface and Ceará Rise. We assume that the water, sediments and mantle layers are homogeneous media with known densities. We also assume a lateral density variation within the crustal layer. Aiming at investigating the position of the COT and the crustal density of the Ceará Rise, the geometry of the sedimentary layer is deduced from our interpretation of ultra-deep seismic imaging. We have investigated the Moho depth along this cross section by using Airy isostatic compensation model and seismic interpretation. The 2D gravity disturbance modeling computed by using either the isostatic Moho or the seismic Moho allows investigating the COT and the crustal density of the Ceará Rise. The gravity disturbance modeling from isostatic Moho supports neither the Ceará Rise as a huge oceanic crust accumulation nor an abrupt COT because it produces poor data fitting. However, the isostatic Moho over the "normal" oceanic crust comprehended in the interval from COT to the Ceará Rise yields an acceptable data fitting. Under the hypotheses of continental crust to the Ceará Rise and of an exhumed subcontinental mantle domain, the seismic Moho yields an acceptable data fitting over the Ceará Rise and over the region from the continental area to COT. However, the seismic Moho over the "normal" oceanic crust yields a poor data fitting. We have proposed a hybrid modeling that joins the isostatic and seismic Mohos under the hypothesis of continental crust to the Ceará Rise. In such model, the isostatic Moho is used over the "normal" oceanic crust and the seismic Moho is used over the Ceará Rise and from the continental area to COT. Hence, the hybrid modeling supports the Brazilian Equatorial Margin as a magma-poor rifted margin. Moreover, the hypotheses of the Ceará Rise as an abandoned continental fragment and a COT with mantle exhumation must be accepted because these hypotheses together with a hybrid modeling produce an acceptable fitting of observed gravity disturbance.

Keywords: [Brazilian Equatorial Margin; Ceará Rise; Crust; Moho; Rifted Margin; Passive margin; Magma-Poor Margin; Isostasy; Gravity Disturbance Modeling; Continent-Ocean Transition]

Summary

1 Introduction

The evolution of geophysical studies along time allows the investigation of different layers, physical properties and chemical compositions of the Earth's internal structure. In 1910, Andrija Mohorovičić (1857-1936) interpreted two different pairs of compression and shear waves from a seismogram of Kulpa Valley's region. As a result of this study, it was found that there is a boundary surface at a specific depth which divides two regions with different elastic properties: the crust and the mantle. This crust-mantle interface, also known as Moho discontinuity, is marked by large changes in the velocity of propagation of seismic waves, chemical composition and rheology. Moreover, the Moho's depth is an important parameter in characterizing the crust structure and it is related to the regional geology and tectonic evolution (ZHU e KANAMORI, 2000). The crust-mantle interface can be imaged from seismic methods such as refraction, reflection, teleseismic function receiver analysis and tomography. The estimated depth of the local Moho is observed in seismic reflection through its reflectivity that is highly variable and not necessarily reflective (AITKEN *et al.*, 2013). The most modern seismic imaging restricts hypotheses in the interpretation of continent-ocean transitions by revealing crustal regions which previously could not be interpreted (KUMAR *et al.*, 2012). However, seismic data acquisition is impaired due to the difficult access and high costs operations, resulting in a sparse data coverage. Furthermore, the vast majority of homogeneous seismic data coverage is located in onshore areas in contrast with a poor coverage in offshore regions.

The elastic parameters from seismic methods evidence a huge difference of lithological composition between crust and mantle. Another effective way of characterizing this difference is through density contrasts between the crust and the mantle. The density varies in the internal structure of the Earth through several layers of different physical and chemical properties. For this reason, the gravity force varies along the Earth's surface from one place to another creating equipotential surfaces. These equipotential surfaces have constant gravitational potential, are concentric and the gravity vector in each point is perpendicular to the surface. The component of the gravity acceleration along the vertical can be measured by gravimeters. The measurements of the gravity field vertical component enable a more consistent coverage on offshore areas which provide valuable information about density distribution inside the Earth. The advent of satellite missions dedicated to measuring the Earth's gravity field such as CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) have improved the data accuracy and have provided geophysicists with almost uniform global gravity field models. These models show a global and homogeneous gravity data coverage that can be combined with terrestrial, aerial and radar altimetric data. The difference between the actual Earth's gravity field and the theoretical gravity field results in anomalies and disturbances which are interpreted in geodesy and in geophysics, respectively (HACKNEY e FEATHERSTONE, 2003). The gravity disturbance (HOFMANN-WELLENHOF e MORITZ, 2006) is the difference between the actual Earth's gravity field and the theoretical gravity field in the same observation point. In geophysics, the gravity disturbance is used to investigate anomalous density contrasts distributions from anomalous masses with respect to the assumed normal Earth. Gravity disturbance can be calculated as functionals of the Earth's gravity field from global gravity field models (BARTHELMES, 2013).

The density contrasts and the geometry of the geological layers are important physical parameters to be retrieved from the geophysical modelling. Their application is well described by some authors under different perspectives. TALWANI *et al.* (1959) derived expressions for the vertical and horizontal components of the gravitational attraction and carried out an interactive 2D gravity forward modelling for interpreting free-air anomalies over Mendocino Fracture Zone. To retrieve the Moho depth, TALWANI *et al.* (1959) assume the density contrasts and the geometries for homogeneous crust layer overlain by water and sedimentary layers. OLDENBURG (1974) uses the fast FFT-based gravity forward modelling of PARKER (1973) to estimate the Moho interface by assuming the density contrast between crust and mantle and a mean depth of the Moho interface. Because the gravity inverse problem for the depth-to-Moho estimate is an ill-posed problem, OLDENBURG (1974) uses seismic profiles to reduce inherent ambiguities. FORSBERG (1984) describes the use of known and unknown density contrasts in forward and inverse methods of geophysical modelling, respectively. In this context, the author approaches terrain reductions, spectral analysis and isostasy in the United States. AITKEN *et al*. (2013) applied a gravity inversion method constrained with seismic data to estimate the Australian Moho geometry. HAMAYUN (2014) computed the stripped gravity disturbance and discussed Moho discontinuity geometry and depths in the world through forward modelling and inversion methods. UIEDA e BARBOSA (2017) proposed a fast-satellite gravity inversion in spherical coordinates to retrieve a 3D depth-to-Moho estimate using seismological data with application to the South American Moho.

In this study, we aim to investigate the crustal isostatic state and the anomalous masses of the Brazilian Equatorial Margin by using, respectively, Airy compensation mechanism and gravity disturbance forward modelling. We stress that there is some open questions concerning active or passive rifting mechanisms involved in the separation of South America from Africa in the Aptian approximately 115 Ma. WATTS *et al*. (2009) used seismic and gravity data to determine the structure of sediments, crust and upper mantle of the Amazon continental margin. These authors interpreted the influence of one or more transform faults in the Amazon margin formation and defined the margin that underlies the Amazon fan as “nonvolcanic”. RODGER (2008) interpreted seismic reflection and refraction and gravity data from the Amazon Cone Experiment (ACE) to evaluate the structure of sediments, crust and mantle. RODGER (2008) classifies the Amazon continental margin also as “nonvolcanic”. ZALÁN (2015) interpreted the Brazilian margin from Santos to Camamu-Almada and from Barreirinhas to Foz do Amazonas as magma-poor rifted margins. GORDON *et al*. (2012) advocates that Almada Basin is a non-volcanic rift segment of the South Atlantic passive margin. Otherwise, MENZIES *et al*. (2002) classified the Brazilian continental margin as a volcanic rifted margin beginning with Paraná-Entendeka flood volcanism, intrusive magmatism, extension, uplift and erosion. Considering the most recent compilation for active and passive rifted margins carried out by FRANKE (2013) and PERÓN-PINVIDIC *et al*. (2013), we test two hypotheses about the Brazilian Equatorial Margin to be used in our study as geological reference model. The first one is a magma-poor rifted margin and the second one is a volcanic rifted margin.

We also aim at investigating the nature of a huge oceanic structure located in the Brazilian Equatorial Margin – the so-called Ceará Rise. The Ceará Rise is an opened geological problem to be investigated with two distinct scenarios: (i) an abandoned continental fragment (HENRY et al., 2011) or (ii) an oceanic crust accumulation (DAMUTH e KUMAR, 1975; KUMAR e EMBLEY, 1977; SIBUET e MASCLE, 1978; WATTS *et al.*, 2009; COFFIN *et al*., 2006). Here, these two geological scenarios are addressed and investigated under geophysical and geological perspectives to contribute to the understanding of the origin and evolution of the Ceará Rise as an offshore structure in the context of the Brazilian Equatorial Margin.

To achieve these goals, we take the local Airy isostatic model modified for considering a lateral density distribution and a sedimentary layer as primordial to the isostatic compensation mechanism of the Brazilian Equatorial Margin. The Airy compensation mechanism stablishes that all geological loads are locally supported by Moho undulations (TURCOTTE e SCHUBERT, 2002; WATTS, 2001). Thus, we assume density contrasts and geometries for all geological entities from a rifted-type margin model. For this reason, we follow three steps: (i) calculating the isostatic Moho and validating the isostatic model from the conception of lithostatic stress, (ii) performing an interactive gravity field forward modelling by assuming density contrasts and (iii) building a hybrid model using Moho depth models resulting from the seismic and the isostatic model. We interpret one ultra-deep seismic reflection profile from the Brazilian Equatorial Margin and use its seismic horizons as a prior information to constrain the gravity disturbance forward modelling. Earth gravity data from global gravity field models (ICGEM – International Center for Global Earth Models) and bathymetry from ETOPO1 are also used.

In our study, the seismic interpretation highlights that the continental crust is separated from the oceanic crust by an exhumed subcontinental mantle domain which is a key aspect of a magma-poor rifted margin. Assuming oceanic crust density (2.84 g/cm^3) for the normal Earth density distribution, we calculate density contrasts for a crustal layer overlain by water (- 1.81 g/cm^3) and sediments (-0.74 g/cm^3), and underlain by mantle (0.43 g/cm^3). The gravity disturbance forward modelling using the isostatic Moho produces an acceptable data fitting over most of the oceanic crust layer. The lithostatic stress computed using the isostatic Moho confirms that this region is isostatically balanced. The gravity disturbance forward modelling using the seismic Moho produces an acceptable data fitting over the platform breakup, Ceará Rise and the exhumed mantle. This modelling supports the assumption that the Ceará Rise is an abandoned continent fragment surrounded by oceanic crust (PERON-PINVIDIC e MANATSCHAL, 2010; ABERA *et al.*, 2016). Besides, the lithostatic stress calculated from the seismic model shows that the Moho undulations does not support the crust. Lower values of lithostatic stress are found over most of the oceanic crust; however, over the exhumed mantle and Ceará Rise higher values are found. Finally, we have combined parts of the isostatic Moho with parts of seismic Moho to produce a single geophysical model called hybrid model. These parts are chosen only in the intervals where the gravity data fitting is acceptable. This hybrid modelling supports the Brazilian Equatorial Margin as a magma-poor rifted margin under the hypothesis of continental crust to the Ceará Rise and of mantle exhumation. Besides, the lithostatic stress calculated from the hybrid model reflects two main disturbed regions: one interval from the continental area to the COT and another one over the Ceará Rise and eastern regions adjacent to the Ceará Rise. Rather, it supports the balanced isostatic state over the "normal" oceanic crust.

2 Geology

2.1 Overview of the Brazilian Equatorial Margin

The geographical area of this study is placed on the Brazilian Equatorial Margin and comprises the following structural provinces: the Amazon cone, the Pará-Maranhão shelf, adjacent oceanic basins and the Ceará Rise. The Ceará Rise is bounded to the west by the Amazon Cone, east and south by the Ceará Abyssal Plain and north by the Demerara Abyssal Plain. The EW9209 expedition, carried out by the Ocean Drilling Program (ODP) during the 70s along the Brazilian Equatorial Margin, acquired topographic, seismic and drilling data. From this data, it is important to note that the Ceará Rise is an anomalous elevation located on ultra-deep seawater layer and present bathymetric levels between -4315 e -3065 meters (Figure 1). In order to investigate the nature of the Ceará Rise is essential to clarify some aspects involving passive rifting processes and the tectonic evolution of the Brazilian Equatorial Margin.

The morphology of the Brazilian Equatorial Margin comprises a shelf, a slope and a rise that constitute a typical Atlantic-type passive continental margin. The continental margin of north-eastern Brazil is formed as a consequence of the separation of South America from Africa in the Aptian approximately 115 Ma. The Amazon Delta and its associated deep-sea fan constitute one of the world’s largest sedimentary systems. For this reason, it is easy to note by a simple visual inspection in the Amazon delta that the slope and the rise locally widen and bathymetric contours vary up to a few hundred km (Figure 1). WATTS *et al.* (2009) studied the Amazon margin through seismic data and interpreted a sedimentary layer thicker than 9 km.

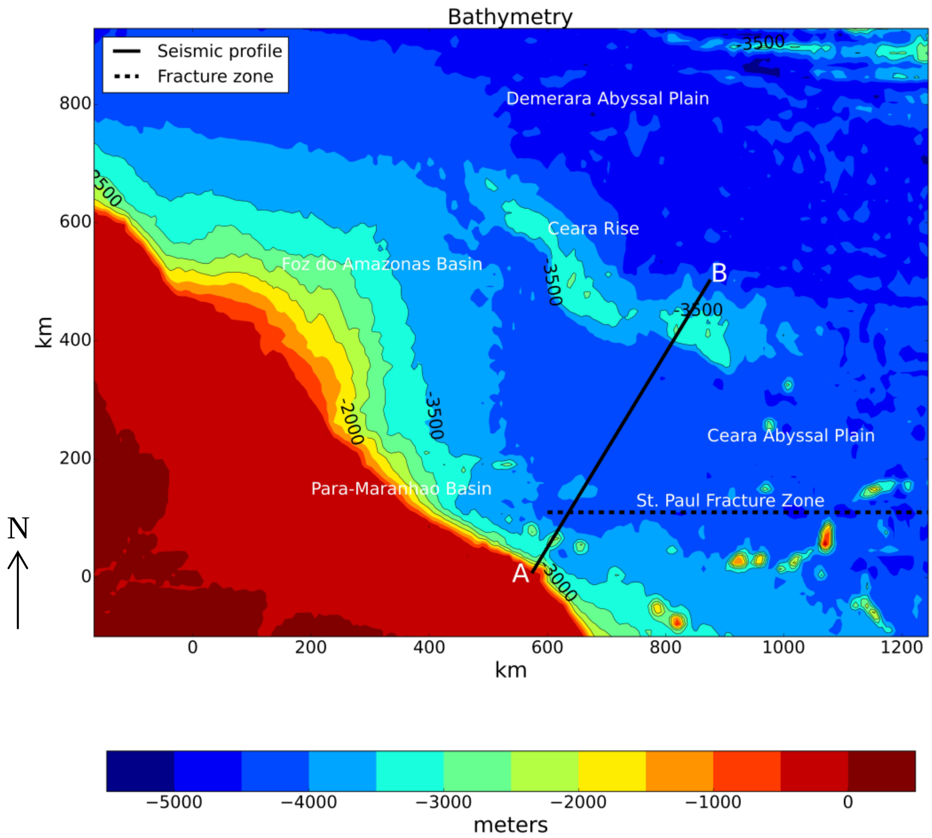

Figure 1. Regional bathymetric map of the Brazilian Equatorial Margin. The geomorphology of the Ceará Rise has bathymetric levels between -4315 and -3065 meters. The Amazon Fan is one of the biggest submarine fans in the world and can be observed as the major geologic feature in the Foz do Amazonas Basin. The bathymetric data were acquired by the NOAA. Line segment AB stablishes the location of seismic and gravity profile.

The tectonic evolution of the African and Brazilian Equatorial Margins is still controversial and needs a better comprehension about rifting mechanisms. An open question is whether the Brazilian Equatorial Margin is associated with the active or passive hypothesis for continental rifting. The genesis of the Brazilian Equatorial Margin is directly related to two major elements: Gondwana Supercontinent breakup and the seafloor spreading in the Mesozoic. Contrary to the Brazilian Eastern Margin basins, the Brazilian Equatorial Margin basins had their structural framework controlled by transtensional and transpressional stresses due to east-west continental drifting. According to MOHRIAK e TALWANI (2000), the Potiguar Basin and Benue Trough (Africa) are an example of triple junction during the breakup of South Atlantic implying in an active type model of basin development. Besides, the rifting process is diachronous and voluminous magmatism clearly post-dates the opening of the Equatorial Atlantic. However, it is important to note that there were some pre- and syn-extension dyke intrusions in the Potiguar Basin before the Equatorial Atlantic opening. When the extensional deformation started in Benue, the Potiguar Basin and other intracontinental rift basins, such as Cariri-Potiguar rift valley, were already aborted. The rifting along the E-W portion of the Pará-Maranhão Basin was predominantly transcurrent and controlled its structural framework (BRAGA, 1991). MOHRIAK e TALWANI (2000) refuted the idea proposed by O'CONNOR and DUNCAN (1990) that the St Helena hotspot trigged the onset of rifting in the Equatorial Atlantic. It occurs because the true evidence for an active hotspot in this region comes from the Tertiary record. Thus, the hotspot is not related to the rifting process. MOHRIAK e TALWANI (2000) also refuted later studies that corroborated the active plume system from magmatic data in distant basins under the argument that the datasets used were related to basins about 500 km away from the Potiguar-Benue triple junction which would need a very broad zone of diffuse volcanism.

Plate tectonic forces originated large-scale lateral movements and triggered transform movements in the region. Consequently, this process originated arrays of regional complex structures different from those found in regions dominated by classic orthogonal movements. Ultimately, the transform motions strongly controlled the equatorial fragmentation which led to the origin of onshore and offshore basins. For this reason, traditional models of sedimentary basin formation such as passive and active rifting cannot be immediately associated to the Brazilian and African Equatorial Margin basins. According to MOHRIAK e TALWANI (2000), the biggest challenge to understand transform margins is the quantification of stretching prior to breakup and the deformation rate during the syn-transform stage. These authors defined the tectonic evolution of the Equatorial Atlantic in three stages: pre-, syn- and post-transform movements. Furthermore, it was recognized a multi-stage basin development: a rift stage in the Early Aptian and a shear-dominated stage in the Early Albian-Cenomanian. The Brazilian equatorial offshore basins had their origin in Neocomian-Barremian or Aptian. According to CAMPOS *et al*. (1974), the tectonic framework of the Brazilian Equatorial Margin was set in the Early Cretaceous and magmatic events related to the St Paul's and Romanche Fracture Zones followed the rifting process. WATTS *et al.* (2009) recognized that the Amazon Margin was originated following the rifting apart of South America and Africa during the Neocomian-Barremian approximately 130 Ma. Furthermore, these authors interpreted the influence of one or more transform faults in the Amazon margin formation.

2.2 Ceará Rise

The Ceará Rise is considered an aseismic rise of the ocean floor located on the Western Equatorial Atlantic and is adjacent to the Brazilian margin. The term "aseismic" refers to the lack of seismic activity in long and linear elevations or ridges. In the eastern Equatorial Atlantic, adjacent to the African margin, there is a huge structure in the ocean floor named Sierra Leone Rise. The Ceará Rise is located in the African conjugate margin of the Sierra Leone Rise in the West Africa. Both rises, as well several other features, have been studied since the 60s, but the processes involved in the origin and evolution of these structures are still unknown. Some authors as KUMAR e EMBLEY (1977), from reflection seismic and drilling data collected by the Ocean Drilling Program (ODP), considered the Ceará Rise a huge accumulation of oceanic crust originated in the Mid-Atlantic Ridge 80 Ma ago. The Sierra Leone Rise was studied by MAXWELL *et al.* (1970) and EMERY *et al.* (1975), who observed the existence of an underlying anomalous oceanic crust to the rise. In these investigations, the Sierra Leone Rise was interpreted as a typical structure of the oceanic basement from propagation velocity of seismic data between 4.5 and 6.1 km/s. Besides, KUMAR e EMBLEY (1977) interpreted both rises as “twins” under the claim that they were limited by the same oceanic fracture zones (Doldrums and 4ºN fracture zones) and, approximately, equidistant from the Mid-Atlantic Ridge. Contrary, SIBUET e MASCLE (1978) proposed the Ceará and Sierra Leone Rises had their origin 127-110 Ma, during the Bullard Gap (BULLARD *et al*., 1965), in their current geographical position with respect to South America and Africa. This initial phase of the North Atlantic was described by BULLARD *et al.* (1965) through numerical methods in order to characterize the geometrical fit of the continents around the Atlantic Ocean. More recently, COFFIN *et al*. (2006) interpreted the Ceará and the Sierra Leone Rises as two transient hotspots in the LIPs (Large Igneous Provinces) context. The term LIP is assigned to a large accumulation of intrusive or extrusive igneous rocks caused by a mantle process different from the one that occurs in the oceanic spreading centers. This term was created by COFFIN e ELDHOM (1994) and can be associated to the following global phenomena: underwater mountain ridges, passive volcanic margins, oceanic plateaus and seamounts. According to COFFIN *et al*. (2006), the Ceará Rise, as well the Rio Grande Rise, the Walvis Ridge and the Sierra Leone Rise, were created by a similar mantle process. WATTS *et al*. (2009) interpreted seismic and gravity data of the Amazon fan and adjacent areas and identified lateral changes in the subcrustal mantle density. These lateral changes are supposed to be related to the thermal structure of the Ceará Rise which in turn is classified as an oceanic plateau. Alternatively to the geological context above, HENRY *et al*. (2011) suggested from ultra-deep seismic imaging (named PSDM or Pre-stack Depth Migrated) that the Ceará Rise is a possible continental fragment abandoned due to a ridge jump of the Monrovia oceanic fracture zone.

To sum up the studies published over the past 40 years, we suggest two geological scenarios for the Ceará Rise. In the first one, the Ceará Rise has an oceanic origin (DAMUTH e KUMAR, 1975; KUMAR e EMBLEY, 1977; SIBUET e MASCLE, 1978; WATTS *et al*., 2009; COFFIN *et al*., 2006). In the second scenario, the Ceará Rise is an abandoned continent fragment (HENRY *et al*., 2011).

3 Geological Reference Model

The present study was developed in the Western Equatorial Margin and its classification concerning the rifting mechanisms is not clear yet. Because our study requires the definition of a geological model for the geophysical modelling, we reviewed some geological aspects and thus adopted a geological reference model. A continental margin is defined as the boundary between two geographical provinces that divides the Earth's surface: the continents and the oceans. Due to the dynamic of global plate motions, these boundaries expose a diversified interaction. The continental margins were initially classified by SEUSS (1904) as 'Atlantic-type' and 'Pacific-type'. The 'Atlantic-type' or passive margin is characterized by its low relief, coastal plains and greater sediment accumulation. The 'Pacific-type' or active margin presents distinct features such as mountain chains, island arcs and volcanism. The passive margins are originated through extension and breakup of the continental crust followed by continuous ocean floor spreading. For this reason, marginal sedimentation processes occur above an ancient rift which is limited by a transitional lithosphere. The rifting processes can also be divided into two subtypes: active and passive. The active rifts are developed in response to thermal upwelling of asthenosphere. On the other hand, the passive rifts occur due to lithospheric extension directed by stresses created in far-field regions (FRANKE, 2013). By considering the volume and the extension of the magmatism is possible to define basically two subtypes of passive margins: volcanic and magma-poor. Based on the development of rifting and breakup models, FRANKE (2013) believes the differentiation of passive margins in volcanic and magma-poor is more convenient than the use of "nonvolcanic margin". This is due to the fact that there is no passive margin with total absence of intrusive and extrusive magmatic rocks. The key aspects responsible for characterizing the volcanic and magma-poor rifted margins are related to the mantle, stratigraphic response to rifting and continental breakup (FRANKE, 2013). Briefly, the volcanic rifted margin is developed by extension and wide extrusive magmatism during the breakup in short time periods. These thick wedges of volcanic flows are easily interpreted in reflection seismic data as seaward-dipping reflectors (SDR) (MOHRIAK *et al*., 2002) and high-velocity (Vp > 7.3 km/s) lower crust seaward. Besides, volcanic margins are commonly associated to mantle plumes and consequently to LIPs (COFFIN e ELDHOLM, 1994). The magma-poor margin is characterized by limited magmatism and wide domains of extended crust with rotated faults blocks and detachment surfaces. Furthermore, this margin is characterized by a polyphase deformation that results in exhumed mantle rocks and extensional allochthons carried due to top-basement detachment faults (FRANKE, 2013). FRANKE (2013) discussed three types of rifts and passive margins: the active Laptev Rift in the Siberian Arctic, a magma-poor rifting process in the South China Sea and an Atlantic-type rift in South Atlantic Ocean. To understand the active and passive rifted margins, FRANKE (2013) created a basic conceptual model that proposes a two-domain separation: proximal and distal. Considering the magma-poor margin, the proximal domain is interpreted by high-angle listric faults related to fault-bounded rift basins. In the same domain, a detachment between the brittle upper crust and the mantle is commonly interpreted. The distal domain is characterized by extremely thinned continental crust potentially separated from oceanic crust by exhumed mantle rocks. The exhumed subcontinental mantle was initially studied by PERON-PINVIDIC e MANATSCHAL (2009) who interpreted the transitional area from continental to oceanic crust in the combined continental margins of Iberia-Newfoundland. The volcanic margin shows a narrow proximal margin with noticeable crustal thinning comparably to the magma-poor margin. Volcanic flows are interpreted as SDRs in seismic reflection datasets followed by wide high-velocity lower-crust seaboard.

To understand and discriminate the rifted margins is primordial to comprehend the relation between the distinct structural entities. According to PERON-PINVIDIC *et al*. (2013), from the continent to the ocean, we have a proximal domain (a), a necking domain (b), a distal domain (c), an outer domain (d) and an oceanic domain (e). Figures 2 and 3 show these domains and illustrate key sections of, respectively, magma-poor and volcanic rifted margins. The proximal region is called platform and corresponds to the continental crust which was slightly stretched during the extension process. The top basement presents an array of high-angle listric faults related either to fault-bounded rift basins and a detachment between an upper crust and a mantle. Furthermore, normal faults affect the brittle upper crust, the crustal thinning is moderate and the major faults setting does not affect the Moho (PERON-PINVIDIC *et al.*, 2013). The necking domain is the zone where the crust thinning is expressive and can be observed through seismic interpretation of the Moho discontinuity. The distal domain is characterized by a crustal thinning that is potentially separated from the oceanic crust by an exhumed subcontinental mantle or a hyper-extended domain. The brittle upper crust and the upper mantle are separated by only a thin lower continental crust layer or are juxtaposed. The decoupling associated with the detachment of the crust-mantle boundary implies the mantle exhumation. The outer domain is not well stablished and depends on the evolution of the margin. According to PERON-PINVIDIC *et al*. (2013), at the mid-Norwegian margin the breakup related magmatic sequences are well interpreted and the volume of magma exposes a significant magmatic activity. Otherwise, Iberia-Newfoundland margins does not evidence extrusive rocks. Geologically and geophysically, the oceanic domain is poorly defined due to the difficulty in characterizing the internal structure of the oceanic crust. Basically, two patterns of seismic reflectivity are deployed: three-layer and transparent pattern. The geological domains interpreted by PERON-PINVIDIC *et al*. (2013) are related to the following specific phases of deformation: the stretching phase (a), the thinning phase (b), the hyperextension and/or exhumation phase (c), the magmatic phase (d), and the oceanization (e). Initially, the rifting and breakup models were mainly based on the comprehension of proximal regions due to the acquisition of numerous geophysical data in continental rifts and in offshore rift basins. Seismic, potential field and deep sea drilling data acquisition in distal regions of rifted margins led to the discovery of different structural settings as exhumed subcontinental mantle and hyperextended continental crust (PERON-PINVIDIC *et al*., 2013). Analogously, PERON-PINVIDIC *et al.* (2013) reviewed three Atlantic rifted conjugate margin systems (Iberia-Newfoundland, East Greenland-Norway and Brazil-Angola) referring to them as ‘end-members’ or ‘archetypes’ of magma-poor, magma-rich and sediment-rich margins, respectively. In this study, we adopted the ‘volcanic’ and ‘magma-poor’ margins nomenclatures from FRANKE (2013) because of the discrimination between the two subtypes is mainly based on magmatic volume.

In our study, we employed two schematic sections of a typical magma-poor (Figure 2) and a volcanic (Figure 3) rifted margins. These geological reference sections were based in the two models described above: PERON-PINVIDIC *et al*. (2013) and FRANKE (2013). PERON-PINVIDIC *et al*. (2013) used a set of distinct domains of rifted margins which are strictly associated to distinct stages in the evolution of this type of margin. We stress that, according to PERON-PINVIDIC *et al*. (2013) the distinct domains as well the distinct stages are independent if the margin is classified as magma-poor or magma-rich margins. FRANKE (2013) discussed rifting, lithosphere breakup and volcanism through the comparison between magma-poor and volcanic rifted margins. It is important to note that the outer domain preconized by PERON-PINVIDIC *et al*. (2013) was not included in this sketch for two reasons. The first one is that both the continentward and the oceanward limits are difficult to define. For instance, at many margins, the outer domain is related to the seaward termination of allochthonous salt. The seismic imaging of such structures is often impaired and hard to be interpreted. The second reason is that the composition of the outer domain basement is not clearly determined. In our study, the key features schematically shown in Figures 2 and 3 are used in the seismic reinterpretation and the gravity modelling, as will be shown later.

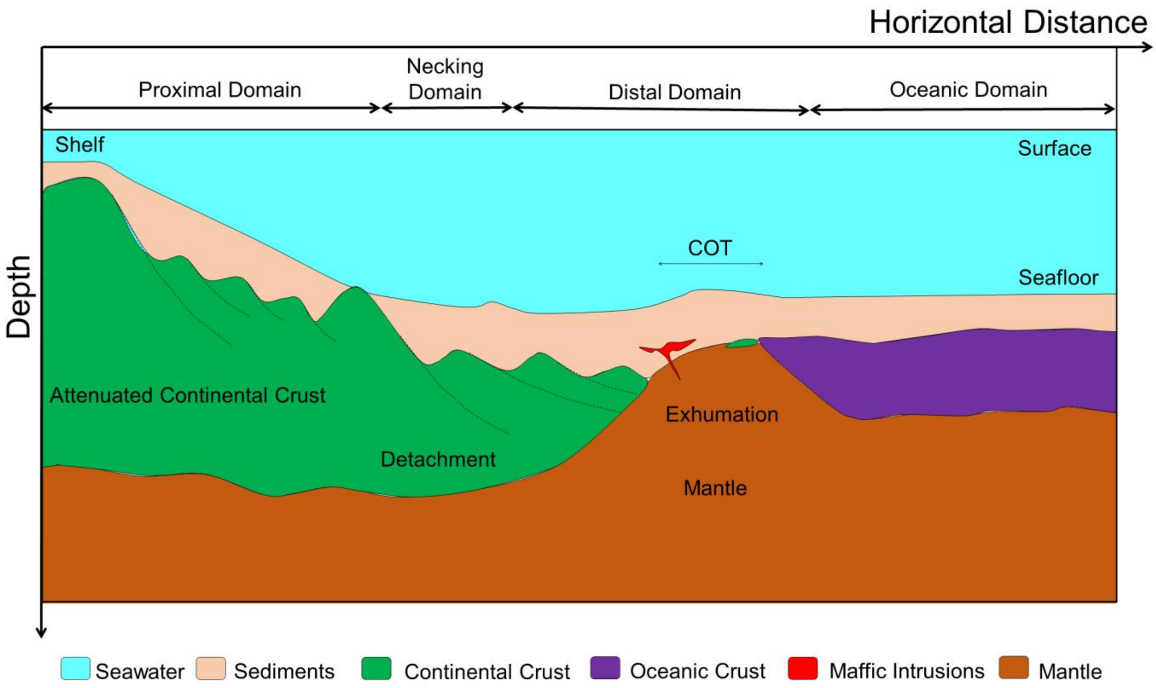

Figure 2. Schematic illustration (not to scale) of the adopted geological reference model in this study for testing the hypothesis of magma-poor passive continental margin. This geological model is based on FRANKE (2013) and PERON-PINVIDIC *et al*. (2013).

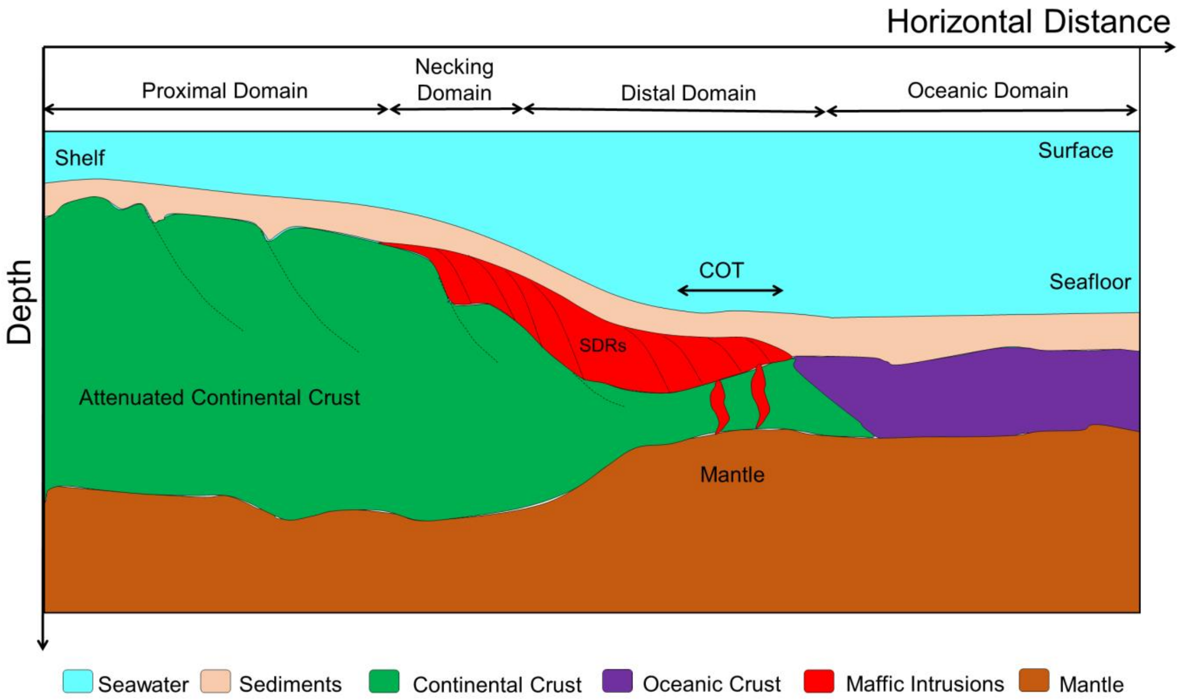

Figure 3. Schematic illustration (not to scale) of the adopted geological reference model in this study for testing the hypothesis of volcanic passive continental margin. This geological model is based on FRANKE (2013) and PERON-PINVIDIC *et al*. (2013).

4 Methodology

4.1 Interpretation model for a rifted margin

Let us assume the geophysical reference model for a magma-poor rifted margin (Figure 4). We consider a 2D vertical cross section that extends through the continental area and the continental shelf down to the oceanic floor crossing the Ceará Rise. In this cross section, we include water and sedimentary layers in the physiographic provinces comprising the continental shelf, the continental slope, and the oceanic floor. In this magma-poor rifted margin which is rich in sediments, the main structural and stratigraphic elements are: 1) crust layer, 2) mantle, 3) sedimentary layer, 4) continent–ocean boundary (COT), 5) Moho discontinuity, and 6) Ceará Rise.

In this model, we assume that the mantle, sedimentary and water layers are homogeneous media with known densities equal to ρ_m, ρ_s and ρ_w, respectively. We also assume that the crust layer consists of homogeneous and laterally adjacent compartments with two densities: 1) the continental crustal density (ρ_{cc}) and 2) the oceanic crustal density (ρ_{oc}). The horizontal coordinate of the COT along a profile is known approximately. Then, this assumption allows a lateral density variation within the crust layer consisting of continental (ρ_{cc}) and oceanic (ρ_{oc}) crusts.

In our study, the objective of introducing the hypothesis of a lateral density variation within the crust layer is twofold. First, we interpret the positions of the COT. Second, we investigate the Ceará Rise crustal density by assuming the knowledge of the continentward and oceanward extremes of the Ceará Rise.

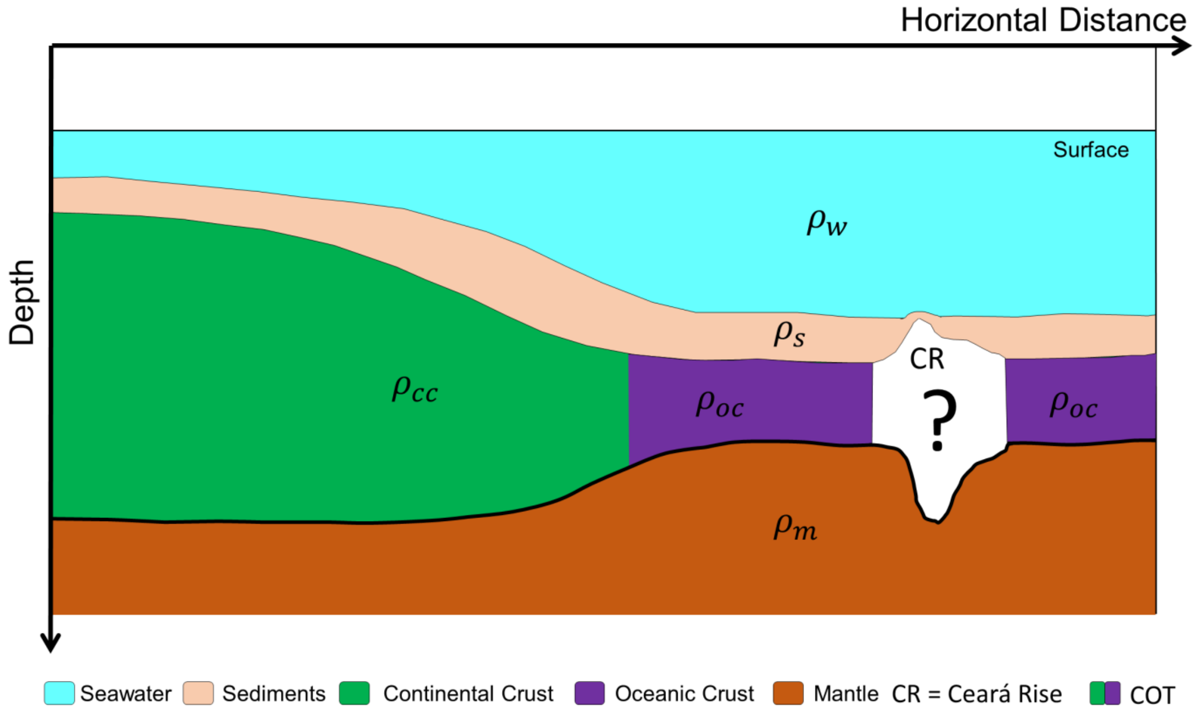

Figure 4. Interpretation model for a rifted margin composed by: 1) crust layer, 2) mantle, 3) sedimentary layer, 4) continent–ocean boundary (COT), 5) Moho discontinuity (thick black line), and 6) Ceará Rise (CR). The mantle, sedimentary and water layers are homogeneous media with known densities equal to ρ_m, ρ_s and ρ_w, respectively. The crust layer can be assigned two densities: the continental crustal density (ρ_{cc}) or the oceanic crustal density (ρ_{oc}). The Ceará Rise (CR) has an unknown density to be investigated.

4.2 The depth of Moho

We determine the Moho depth by using seismic interpretation (henceforth referred to as the seismic Moho) or the Airy isostatic compensation model which is based on local compensation mechanisms (henceforth referred to as the isostatic Moho).

Let S_o be the isostatic compensation depth. We define the set of L fixed and known horizontal coordinates $\mathbf{x} \equiv (x_1, x_{2,} \dots, x_L)^{\mathrm{T}}$ as shown in Figure 5. Let $\mathbf{S} \equiv (S_1, S_{2,} \dots, S_L)^{\mathrm{T}}$ be a set of L depths to the unknown Moho discontinuity, where S_i is the unknown depth to the Moho at the ith horizontal coordinate x_i. Let $\mathbf{t_w} \equiv (t_{w_1}, t_{w_2}, \dots, t_{w_L})^{\mathrm{T}}$ be a set of L thicknesses of the water layer, where t_{w_i} is the known thickness of the water layer at the ith horizontal coordinate x_i. We assume the knowledge of L thicknesses of the sedimentary layer $\mathbf{t_s} \equiv (t_{s_1}, t_{s_2}, \dots, t_{s_L})^{\mathrm{T}}$, where t_{s_i} is the thickness of the sedimentary layer at the ith horizontal coordinate x_i.

Under the hypothesis of a lateral density variation within the crust aiming at investigating the position of the COT and an adequate crustal density for the Ceará Rise, the prior information about three horizontal coordinates are required (Figure 5). These x −coordinates are: 1) the interpreted position of the COT (x_{cot}) and; 2) the known continentward x_a and seaward x_b extremes of the Ceará Rise.

The isostatic Moho depth $S_i \equiv S(x_i)$ computed at the ith horizontal coordinate x_i can be written as:

$$S_i = t_{s_i}\frac{(\rho_s-\rho_i)}{(\rho_m-\rho_i)} + t_{w_i}\frac{(\rho_w-\rho_i)}{(\rho_m-\rho_i)} + S_o\frac{(\rho_m-\rho_c)}{(\rho_m-\rho_i)}, \qquad i = 1, \dots, L \qquad (1)$$

where $\rho_i \equiv \rho(x_i)$ is the presumed density for the crust at the ith horizontal coordinate x_i. If the coordinate x_i lies inside the continental region, in the x-interval $[x_1,\ x_{cob}]$, we set $\rho_i = \rho_{cc}$ in order to consider a continental crust. If the coordinate x_i lies inside the ocean regions, in the x-intervals $[\ x_{cot},\ x_a]$ and in the x-coordinates greater than x_b ($x_i > x_b$), we set $\rho_i = \rho_{oc}$.

By using equation 1, we can investigate the horizontal position of the COT (x_{cot}) and test the two hypotheses about the Ceará Rise. In the first, the Ceará Rise is a huge accumulation of oceanic crust (if $\rho_i = \rho_{oc}$), whereas in the second hypothesis, it is an abandoned continental fragment (if $\rho_i = \rho_{cc}$).

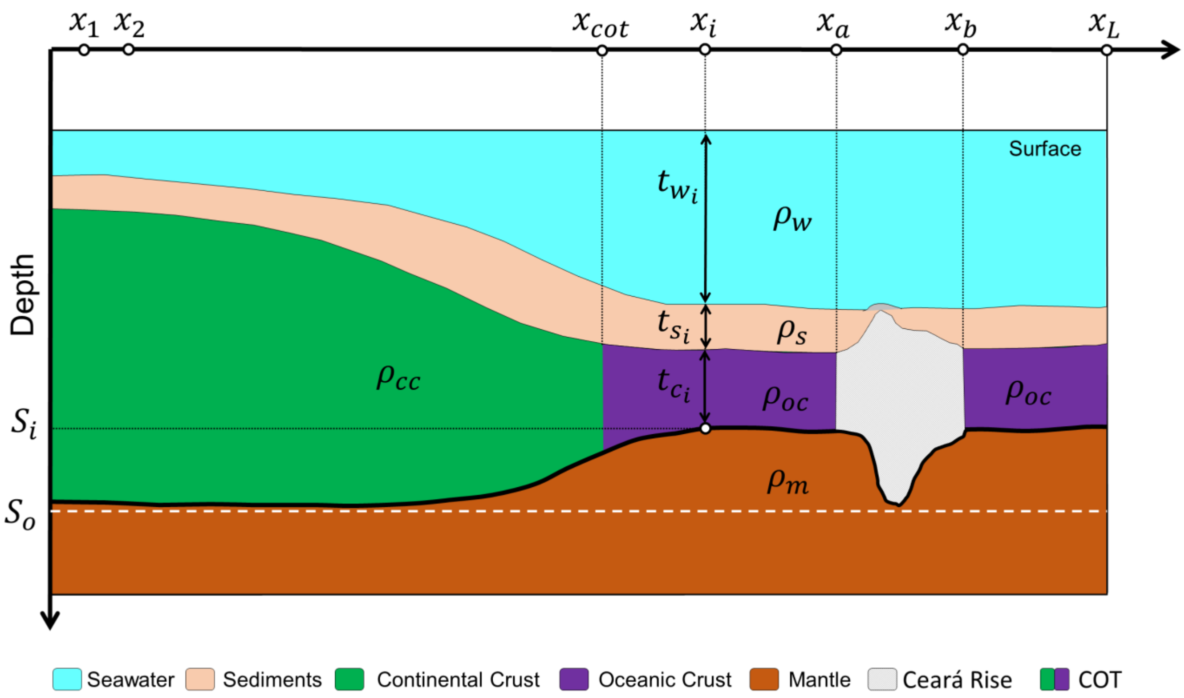

Figure 5. Sketch of the isostatic model for a rifted margin. The seawater and the sedimentary layers are approximated by an interpretation model consisting of L vertical 2D prisms (not shown) whose thicknesses at the ith horizontal coordinate x_i are t_{w_i} and t_{s_i}, respectively. The density distribution consists of $\rho_{\rm w}$, $\rho_{\rm s}$, $\rho_{\rm cc}$, $\rho_{\rm oc}$ and $\rho_{\rm m}$ which represent the water, sediment, continental crust, oceanic crust and mantle densities. The thick black line represents the unknown isostatic Moho interface whose depth $S_i \equiv S(x_i)$ (calculated by equation 1) represents the isostatic Moho depth at the ith horizontal coordinate x_i. The x-coordinates x_a and x_b represent the continentward and seaward extremes of the Ceará Rise. The x-coordinate x_{cot} is the interpreted horizontal position of the COT. The depth S_0 is the isostatic compensation depth (dashed white line).

4.3 Lithostatic Stress

To comprehend the isostatic balance of the region, we calculate the lithostatic stress at the base of the model. To do this let us assume for a moment that our model (Figure 5) is formed by laterally adjacent columns which, in turn, are formed by vertically superposed blocks having constant density. Then we assume that no vertical forces are acting on the lateral surfaces of the columns forming the model and that gravity is constant along each column. In this case, the surface force per unit area acting perpendicularly to the horizontal surface located at the isostatic compensation depth is due to the weight of the overlying rocks or overburden. This normal force is called pressure or lithostatic stress (TURCOTTE e SCHUBERT, 2002).

Let γ be the gravitational constant and $\boldsymbol{\sigma} \equiv (\sigma_1, \sigma_2, \ldots, \sigma_L)^{\mathrm{T}}$ be a set of L unknown lithostatic stress, where σ_i is the unknown lithostatic stress exerted by the i^{th} vertical column of the model (Figure 5) on the isostatic compensation depth. Let $\mathbf{t}_{\boldsymbol{c}} \equiv (t_{c_1}, t_{c_2}, \ldots, t_{c_L})^{\mathrm{T}}$ be a set of L thicknesses of the crust column, where t_{c_i} is the known thickness of the crust column at the ith horizontal coordinate x_i.

The lithostatic stress $\sigma_i \equiv \sigma(x_i)$ computed at the ith horizontal coordinate x_i can be written as:

$$\sigma_i = t_{w_i}(\rho_w \gamma) + t_{s_i}(\rho_s \gamma) + t_{c_i}(\rho_{c_i} \gamma) + (S_o - S_i)(\rho_m \gamma), \qquad i = 1, \ldots, L, \tag{2}$$

where

$$t_{c_i} = S_i - (t_{w_i} + t_{s_i}). \tag{3}$$

Generally, the stresses calculated within the Earth are given in megapascals (MPa).

In this study, we expect the lithostatic stress at the base of our model to be approximately zero if the region is isostatically balanced according to the Airy's model. Otherwise, if the region is not isostatically balanced, we expect to interpret disturbances in the lithostatic stress. The Airy compensation mechanism predicts undulations in the Moho in order to balance the isostatic state.

4.4 Gravity Modelling

In geophysics, the interactive gravity forward modeling has been used in many interpretations for testing geological hypotheses about the density distribution within the Earth.

The gravity modeling requires the definition of a reference density distribution. In the present study, we assume a simple reference density distribution as preconized by TALWANI *et al*. (1959), OLDENBURG (1974) and FORSBERG (1984). Our reference density distribution consists of two layers separated by a flat and horizontal surface S_R (Figure 6). The upper layer has oceanic crust density (ρ_{oc}) and the lower layer has mantle density (ρ_m). The appropriate depth value for S_R is located deeper than the Moho interface and deep enough to enable an acceptable data fit by performing an interactive gravity forward modeling. To produce meaningful geophysical results, the use of the same value of S_R for all gravity modeling is recommended.

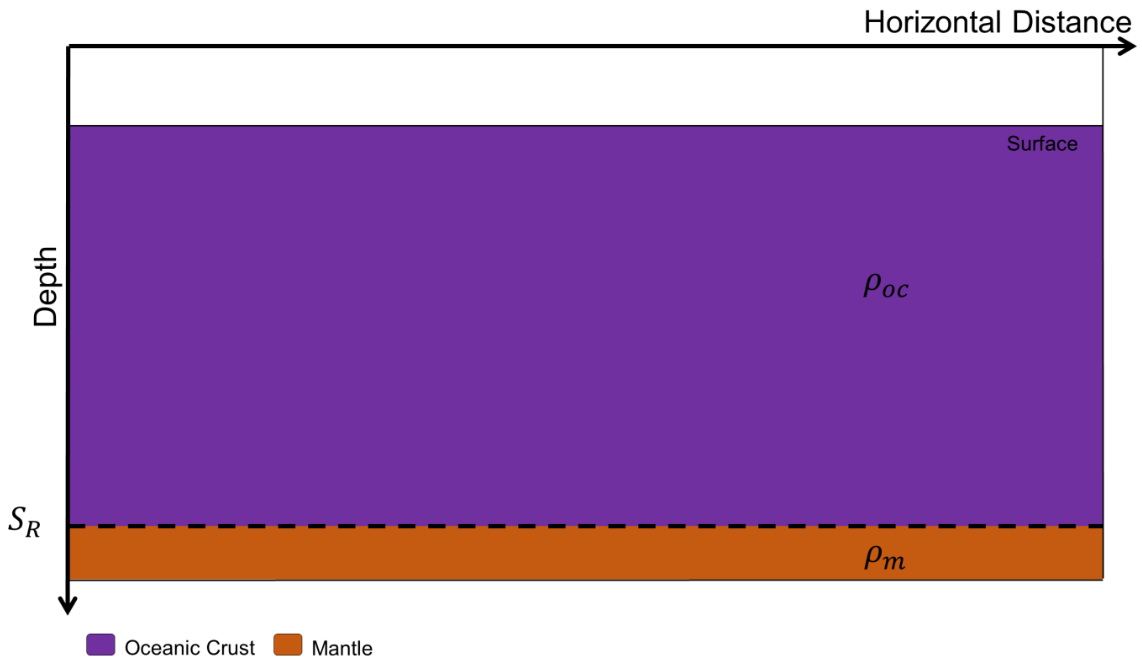

Figure 6. Schematic representation of the reference density distribution consists of homogeneous oceanic crust (upper layer) and mantle (lower layer) which are separated by a flat and horizontal surface $S_{R.}$ The oceanic crust and mantle are homogeneous media with densities equal to ρ_{oc} and ρ_m , respectively.

The difference between the actual density distribution inside the Earth and the assumed reference density distribution (Figure 6) is defined as a density-contrast distribution. If a density contrast $\Delta\rho$ is positive, we have a mass excess yielding a gravity high. Conversely, if a density contrast $\Delta\rho$ is negative, we have a mass deficiency yielding a gravity low. In our study, the actual Earth density distribution is given by the densities ρ_{w}, ρ_{s}, ρ_{cc}, ρ_{oc} and ρ_m (Figure 4) and the density contrasts $\Delta\rho_{\text{w}}$, $\Delta\rho_{\text{s}}$, $\Delta\rho_{\text{cc}}$, $\Delta\rho_{\text{oc}}$ and $\Delta\rho_m$ (Figure 7) have their origin from the difference between the actual Earth density distribution (Figure 4) and the assumed reference density distribution (Figure 6). We call to attention that the density contrast of the oceanic crust is zero ($\Delta\rho_{\text{oc}} = 0$ g/cm^3). In Figure 7, $\Delta\rho_{\text{CR}}$ represents the density contrast of the Ceará Rise to be investigated. If $\Delta\rho_{\text{CR}} = \Delta\rho_{\text{oc}}$, we are test the hypothesis of oceanic crust for the Ceará Rise. Otherwise, if $\Delta\rho_{\mathrm{CR}} = \Delta\rho_{\mathrm{cc}}$, we are test the hypothesis of continental crust.

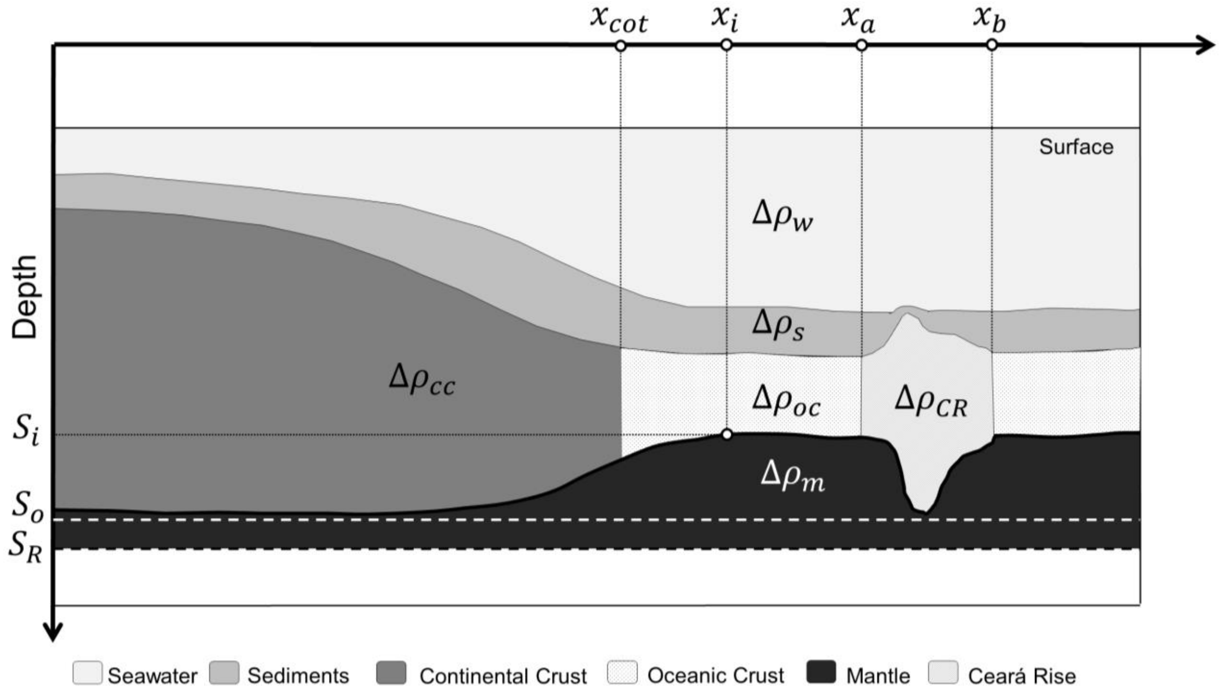

Figure 7. Schematic parametrization used to compute the vertical component of the gravitational attraction for a rifted margin. The anomalous masses were parametrized by 2D bodies (gray polygons) whose vertices are not shown. The density-contrast distribution consists of $\Delta\rho_{\mathrm{w}}$, $\Delta\rho_{\mathrm{s}}$, $\Delta\rho_{\mathrm{cc}}$, $\Delta\rho_{\mathrm{oc}}$ and $\Delta\rho_{\mathrm{m}}$ that represent the water, sediment, continental crust, oceanic crust and mantle density contrasts. $\Delta\rho_{\mathrm{CR}}$ represents the density contrast of the Ceará Rise to be investigated. The surfaces S_o and S_R are explained in Figures 5 and 6, respectively.

In this study, we approximate the gravity disturbance (HOFMANN-WELLENHOF e MORITZ, 2006) by the vertical component of the gravitational attraction of the anomalous masses using the gravity forward modeling method from TALWANI *et al*. (1959). To do this, the geometries of the 2D masses shown in Figure 4 are approximated by 2D bodies with polygonal cross sections. Next, we calculate the vertical component of the gravitational attraction in an arbitrary observation point produced by these 2D bodies.

For convenience, the 2D bodies (gray polygons) with constant density contrasts shown in Figure 7 are called anomalous masses. Here, we use UIEDA *et al*. (2013) to compute the vertical component of the gravitational attraction on the sea level produced by the anomalous masses located between the sea level and the S_R surface (Figure 7).

5 Results

5.1 Seismic Interpretation

The ultradeep regional seismic line GB1-4500 (Figure 8) was acquired by ION GEOPHYSICAL company in 2011 during BrasilSPAN's project. The SW-NE dip oriented profile is the first seismic imaging of the Ceará Rise where it is possible to observe its crustal architecture and the western region of the rise. HENRY *et al*. (2011) interpreted the basement of the Ceará Rise as a possible continent fragment with thickness of 25 km which is partially buried by sediments from the Amazon Cone. According to HENRY *et al*. (2011), the black lines (Figure 8) on the Ceará Rise represent gravitational thrust faults and consequently potential structural oil traps that may control the petroleum system and lead to hydrocarbon discoveries.

The reinterpretation of the seismic profile (Figure 8) was accomplished in our study aiming at helping the gravity and isostatic modelling. Here, we interpret the crystalline basement topography (thick blue line in Figure 8) at the basal termination of the reflective and stratified sedimentary section. We interpret that the continental crust thins considerably and it is separated from oceanic crust by the existence of an exhumed subcontinental mantle domain which has transparent seismic facies. For this reason, we understand that the crust broke up entirely preceding the lithospheric mantle breakup. In the proximal domain, we identified a detachment between the upper crust and the mantle caused by huge normal faults which form the rift sections. The oceanic crust is interpreted as a typical box-shaped geometry with a three-layer array: lower gabbros, mid-crust sheeted dykes and upper pillow basalts. The gabbros are slightly reflective and thick. The sheeted dykes present high-angle crossed reflections and thick seismic facies. Ultimately, the basalts show thick transparent seismic facies. In terms of thickness, we interpret the oceanic crust as a tabular crust from 7 to 10 km thick, which gradually thins toward the Mid-Oceanic Ridge (not shown). The same pattern of oceanic crust was found by ZALÁN *et al*. (2011) in the crustal and mantle investigations of the South Atlantic Passive Margin. The geometry of the COT is an essential parameter for deepwater exploration potential of continental margins (MOHRIAK *et al*., 2013). Here, we interpret the COT from the seismic profile (Figure 1) analogously as proposed by PERON-PINVIDIC *et al*. (2013) in their schematic section of a typical magma-poor rifted margin (Figure 2). The seismic Moho surface (orange line in Figure 8) is strongly influenced by the Saint Paul Fracture Zone and by the major continental structures associated to this region.

We stress that our reinterpretation of the seismic profile (Figure 8) is corroborated by ZALÁN (2015). Based on seismic facies interpretation we extracted from Figure 8 two seismic horizons: the crystalline basement surface (thick blue line) and the seismic Moho surface (orange line). Both horizons are used on the gravity interpretation as *a priori* information.

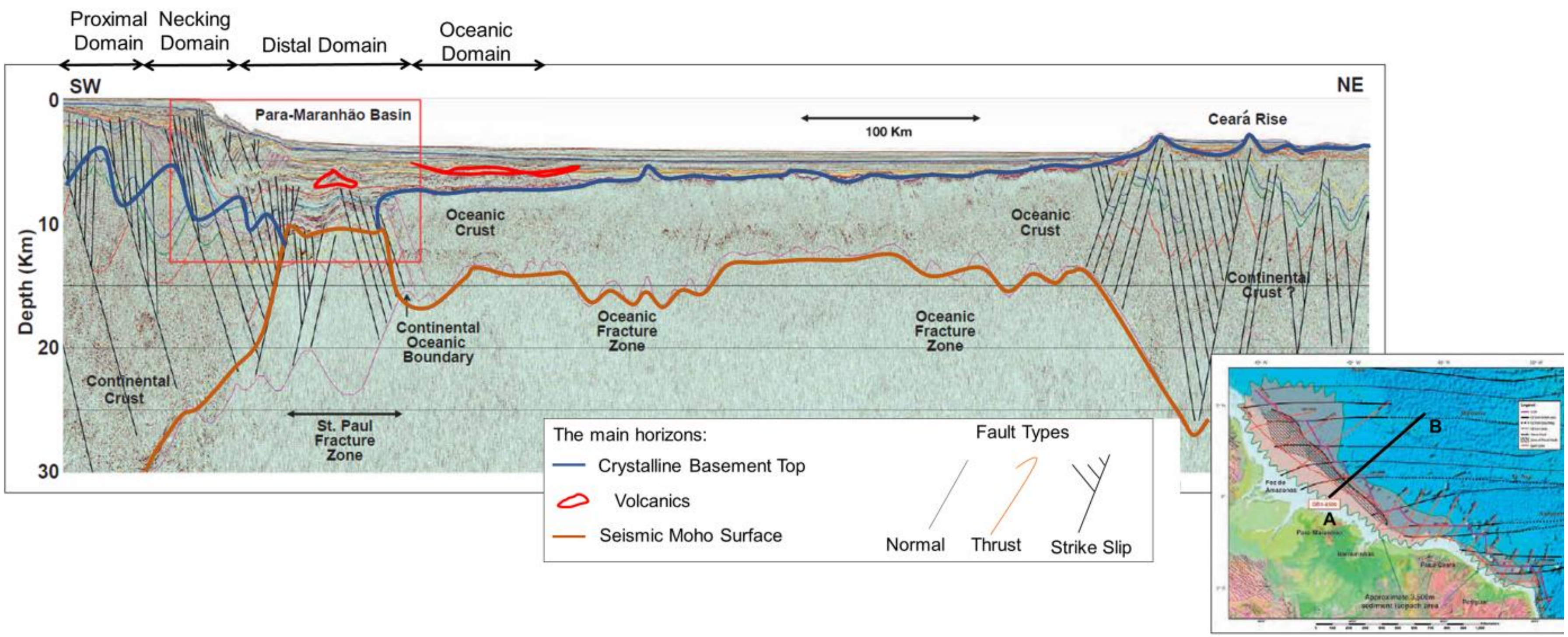

Figure 8. Ultradeep regional seismic line after HENRY *et al*. (2011). The thick orange and the thick blue lines represent, respectively, the seismic Moho and the crystalline basement surfaces. The red polygons represent volcanic rocks. The interpretation of this seismic profile was based on HENRY *et al*. (2011) who considered the Ceará Rise as an abandoned continental fragment. The continental-oceanic transition is characterized according to the geological model of magma-poor margins (Figure 2) as suggested by FRANKE (2013).

Our seismic data interpretation showed the following key aspects: attenuated continental crust, high-angle listric faults, detachment surface, rift infill, mafic intrusions, sills and exhumed mantle. For this reason, the Brazilian Equatorial continental Margin is suggested in this study as a classic example of magma-poor passive margin as illustrated in Figure 2. The interpretation of the Brazilian Equatorial Margin as a magma-poor margin is corroborated by ZALÁN (2015) who classified the Brazilian passive margins, from Santos to Camamu-Almada in the Eastern Margin, and from Barreirinhas to Foz do Amazonas in the Equatorial Margin, as magma-poor passive margins. WATTS *et al*. (2009) defined the margin that underlies the Amazon fan as “nonvolcanic”. These authors also compared the Brazilian Equatorial Margin with the well-known “non-volcanic” Iberia-Newfoundland conjugate margin and highlighted that there is a greater sediment accumulation and a narrower zone of transitional crust in the Brazilian margin. RODGER (2008) interpreted seismic reflection profile and wide-angle refraction data and gravity data acquired during the Amazon Cone Experiment (ACE) to determine the structure of the sediment, crust and mantle beneath the Amazon continental margin. This author observed that the maximum sediment thickness on the region is greater than 13 km and classified the margin as a “non-volcanic” rifted margin due to the lack of evidence of rift-related magmatism or underplating. The seismic reflection interpretation of RODGER (2008) showed an unusual thin oceanic crust (~4.25 km) which is attributed to slow seafloor spreading and possible reduced mantle temperatures in the Equatorial Atlantic.

5.2 Isostasy and 2D Modelling

Considering the horizontal coordinate of the COT $x_{cot} = 623.86$ km, we investigate the isostatic state of the study area under the hypothesis that the geophysical model for Brazilian Equatorial Margin satisfies the Airy isostatic compensation model. Regarding the lateral density variation within the crust layer, the densities assumed to the continental (ρ_{cc}) and oceanic crusts (ρ_{oc}) are, respectively, 2.67 g/cm³ (FORSBERG, 1984; HOFMANN-WELLENHOF e MORITZ, 2006; OLDENBURG, 1974) and 2.84 g/cm³ (OLDENBURG, 1974; TALWANI *et al.*, 1959). We analyze if all the geological loads are supported by Moho undulations (Airy isostasy). The densities ρ_{w}, ρ_{s} and ρ_m are assumed to be constant and, respectively, equal to 1.03 g/cm³ (WORZEL, 1965; OLDENBURG, 1974), 2.10 g/cm³ (TALWANI *et al.*, 1959) and 3.27 g/cm³ (FORSBERG, 1984; HOFMANN-WELLENHOF e MORITZ, 2006; OLDENBURG, 1974; TALWANI *et al.*, 1959). By assuming these densities, we find the density contrasts $\Delta\rho_{\mathrm{w}}$, $\Delta\rho_{\mathrm{s}}$, $\Delta\rho_{\mathrm{cc}}$, $\Delta\rho_{\mathrm{oc}}$, and $\Delta\rho_m$ (Figure 9) with respect to the reference density distribution shown in Figure 6, with ρ_{oc} equal to 2.84 g/cm³ and ρ_m equal to 3.27 g/cm³.

In this study, the geological loads interpreted in the isostatic model are understood as anomalous masses in geophysical modeling. The S_R limiting surface for the reference density distribution (Figure 6) is equal to 49.5 km and it was chosen based on trial-and-error procedure. Hence, several tentative values were assigned to S_R and we take as the best S_R the one that yields the minimum difference between the observed and the predicted gravity disturbances. Finally, the bathymetry ($\mathbf{t}_w$) and the sedimentary thickness ($\mathbf{t}_s$) were deduced from the ETOPO1 (AMANTE e EAKINS, 2009) and from the seismic profile interpretation (Figure 8), respectively. All the parameters deduced from geophysical and geological data described above were used to build the isostatic model and to perform all the 2D gravity disturbance forward modeling.

Anomalous masses:	Assumed Densities (g/cm^3)	Density Contrasts (g/cm^3)
Water	ρ_w = 1.03	$\Delta\rho_w$ = - 1.81
Sediments	ρ_s = 2.10	$\Delta\rho_s$ = - 0. 74
Continental Crust	ρ_{cc} = 2.67	$\Delta\rho_{cc}$ = - 0.17
Oceanic Crust	ρ_{oc} = 2.84	$\Delta\rho_{oc}$ = 0.00
Mantle	ρ_m = 3.27	$\Delta\rho_m$ = 0.43

Figure 9. Anomalous masses with the assumed densities and the assigned density contrasts. The density-contrast distribution consists of $\Delta\rho_w$, $\Delta\rho_s$, $\Delta\rho_{cc}$, $\Delta\rho_{oc}$ and $\Delta\rho_m$ that represent the water, sediment, continental crust, oceanic crust and mantle density contrasts. The masses are anomalous with respect to the reference density distribution (Figure 6) with ρ_{oc} equal to 2.84 g/cm^3 and ρ_m equal to 3.27 g/cm^3.

Here, we interpret that the observed gravity disturbance is caused by four main sources: the continental platform breakup, the COT, the Moho undulations and the Ceará Rise. We consider that the shortest gravity wavelength can be associated with near-surface tectonic regime of the uppermost 11 km. On the other hand, the longest gravity wavelengths can be produced by Moho variations. Through 2D gravity disturbance forward modeling by using either the isostatic Moho (equation 1) or the seismic Moho (thick orange line in Figure 8), we test hypotheses about the COT and the crustal density of the Ceará Rise. According to

PERON-PINVIDIC *et al*. (2013), the COB is located in the distal domain and it can be characterized either by a crustal thinning with crustal hyperextension (abrupt COT) as shown in Figure 3 or by a mantle exhumation as illustrated in Figure 2. In the literature, the two geologic hypotheses about the Ceará Rise to be tested are: (i) an anomalous oceanic crust accumulation (DAMUTH e KUMAR, 1975; KUMAR e EMBLEY, 1977; SIBUET e MASCLE, 1978; WATTS *et al*., 2009; COFFIN *et al*., 2006) or (ii) a continental crust fragment (HENRY *et al.*, 2011). All these hypotheses were tested in this study through 2D gravity disturbance forward models from the isostatic model and from the seismic model.

5.2.1 Isostatic Moho

To determine the isostatic Moho surface S_i using equation 1, where the crust is in isostatic state, we need to choose an appropriate S_0 compensation depth (Figure 5). In general, the compensation depth S_0 is defined according to the average crustal thickness of the Earth, which is about 30 km (HOFMANN-WELLENHOF e MORITZ, 2006). In this study, S_0 is chosen by trial-and-error procedure and subject to respect two conditions. The first one imposes that the calculated isostatic Moho surface $S_i,\ i = 1, \dots, L,$ can be closest to the seismic Moho (thick orange line in Figure 8). The second condition imposes that the oceanic crustal thickness $t_{c_i}, i = 1, \dots, L,$ can vary between 7 and 10 km. Thin oceanic crusts in "nonvolcanic" margins has been interpreted by WHITMARSH *et al*. (1996) when studying the West Iberia area.

Figure 10 shows the computed isostatic Mohos $S_i,\ i = 1, \dots, L,$ (Eq. 1) with the compensation depth S_0 equal to 34 km (solid black line), 36 km (dots and solid black line) and 38 km (dashed black line). By varying S_0 we shift S_i vertically without changing its shape. In this study, the optimum S_0 is 34 km because the isostatic Moho S_i (solid black line in Figure 10) is closest to the seismic Moho (solid red line in Figure 10) and produces "normal" oceanic crust thickness from 7 to 10 km. In this study, we assume that the term "normal" oceanic crust refers to an oceanic crust formed in spreading centers on oceanic ridges and composes the oceanic lithosphere in divergent plate boundaries. Specifically, the "normal" oceanic crust is comprehended in the interval from COT to the Ceará Rise.

Considering the isostatic Moho computed with S_0 equal to 34 km (solid black line in Figure 10), we compute the lithostatic stress σ_i (equation 2) along the seismic reflection profile. Figure 11 shows that the calculated stress σ_i is zero because the Moho undulations support all geological loads on the surface of the isostatic model.

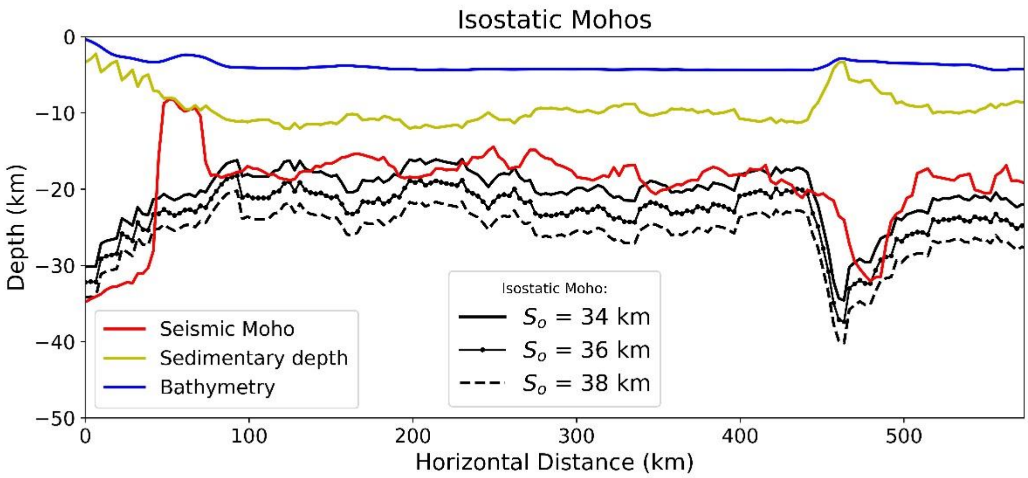

Figure 10. Depths of the isostatic and seismic Mohos, bathymetry and sedimentary layer. The seismic Moho (solid red line) is the interpreted seismic Moho (thick orange line in Figure 8). The isostatic Mohos are computed by using Eq. 1 with the compensation depth S_0 equal to: 34 km (solid black line), 36 km (dots and solid black line) and 38 km (dashed black line).

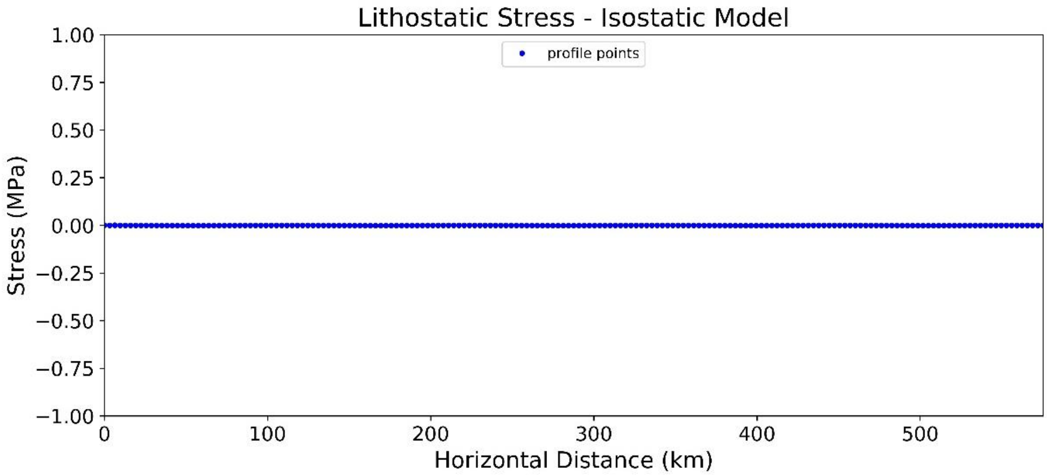

Figure 11. The lithostatic stress (Equation 2) with Moho calculated with S_0 equal to 34 km (solid black line in Figure 10). The stress reflects how successful is the isostatic Moho geometry in supporting the geological loads.

5.2.1.1 Ceará Rise as an oceanic crust

By using the isostatic Moho S_i calculated through equation 1 with S_0 equal to 34 km (solid black line in Figure 10), we investigate here the hypothesis that the Ceará Rise is a huge oceanic crust accumulation. Figure 12 shows the gravity disturbance model from the isostatic Moho which is interpreted as a narrow proximal margin with substantial thinning of the crust over a short distance, attenuated continental crust and an abrupt COT area (Figure 12b). This model (Figure 12b) yields an acceptable data fitting (solid line in Figure 12a) in the interval $x \in [150\ km, 420\ km]$; however, it yields an unacceptable data fitting in the intervals $x \in >\ 420\ km$ (Ceará Rise) and $x \in <\ 150\ km$ (proximal, necking and distal domains). Specifically, in the interval of Ceará Rise and surroundings, the predicted gravity data (solid line in Figure 12a) overestimate considerably the observed gravity data (red dots in Figure 12a). Notice that the maximum value of the predicted gravity data is about 75 mGals, greatly overestimates the observed gravity data (red dots in Figure 12a). Hence, the hypothesis that the Ceará Rise is a huge oceanic crust accumulation that achieves about 30 km thick is not supported by the gravity disturbance and it must be rejected.

If the Ceará Rise had oceanic crust composition, we would interpret it as a transient hotspot in the context of LIPs (Large Igneous Provinces) (COFFIN e ELDHOLM, 1994). These intrusive and extrusive rocks are strictly related to volcanic rifted margins and are caused by mantle plumes (COFFIN e ELDHOLM, 1994; FRANKE, 2013). It occurs because this kind of margin is characterized by large volumes of syn-rift igneous rocks (FRANKE, 2013). The assumption that the Brazilian Equatorial Margin is a volcanic rifted margin as shown in Figure 3 is doubtful for two reasons. First, the interpretation of the seismic reflection profile (Figure 8) does not evidence relevant magmatism manifestation (SDRs) during the rifting process. Second, by considering rifted continental margins, the poor gravity data fitting in the COT area (Figure 12a) suggests that the transition between the continental and oceanic crusts is not characterized by extreme crustal thinning. Hence, the combination of the poor gravity data fitting over the platform breakup and COT and the lack of SDRs structures imposes that the study area cannot be classified as a volcanic rifted margin according to the geological model developed by PERON-PINVIDIC *et al*. (2013) and FRANKE (2013).

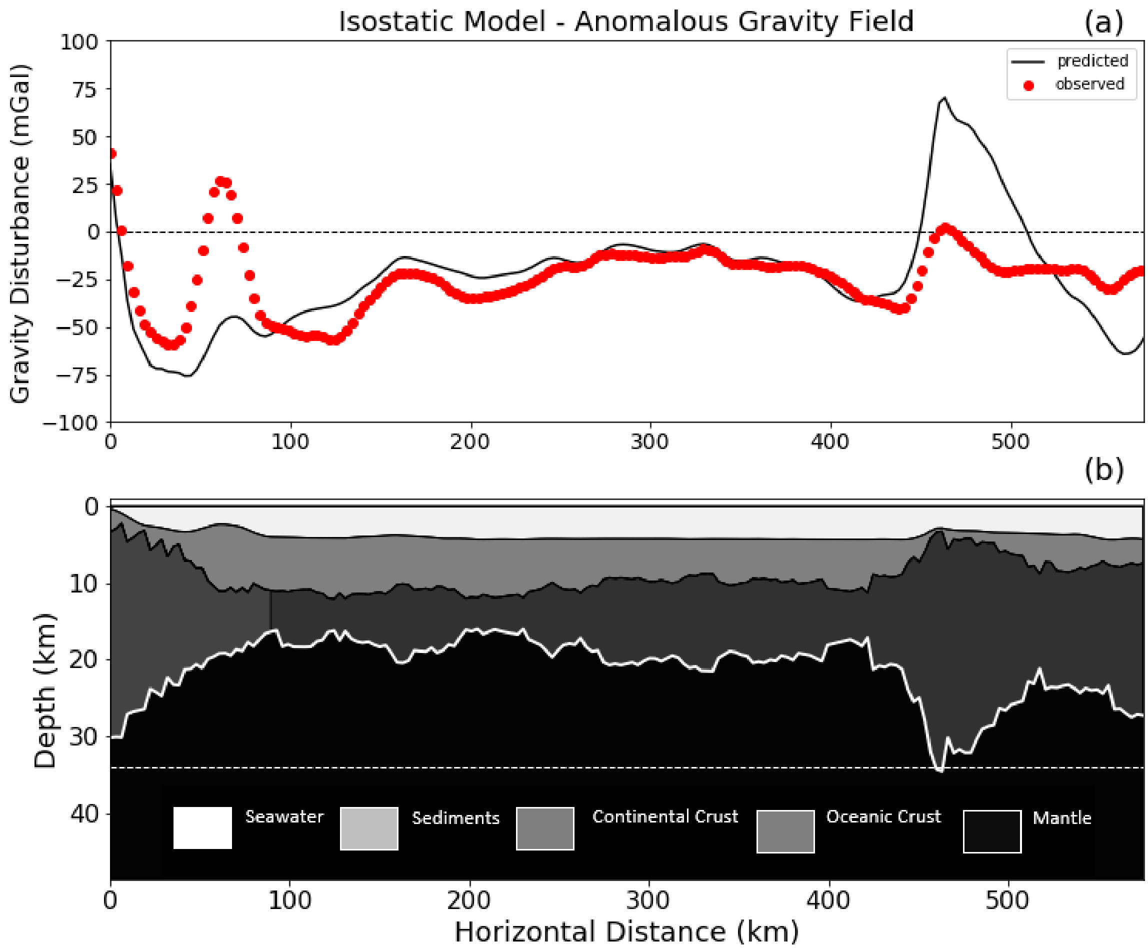

Figure 12. a) Observed (red dots) and fitted (solid line) gravity disturbances produced by (b) the geological model composed by seawater layer (white polygon), sedimentary layer (light gray polygon), continental crust (light-dark gray polygon), oceanic crust (dark gray polygon) and mantle (black polygon). The geological model in b uses the isostatic Moho calculated with depth compensation S_0 (white dashed line) equal to 34 km under the hypothesis in which the Ceará Rise is a huge accumulation of oceanic crust of 2.84 g/cm³. The model is limited in depth by the S_R surface equal to 49.5 km.

The isostatic and the gravity disturbance models in Figure 12, under the hypothesis that the Ceará Rise is a huge oceanic crust accumulation, establish some key aspects of the Brazilian Equatorial Margin. The poor data fitting over the Ceará Rise suggests that the Moho must be deeper than the one shown in Figure 12b to produce an acceptable data fitting. However, a deeper Moho surface would imply an isostatically unbalanced crustal masses. Other possibility to produce an acceptable data fitting in the Ceará Rise area is to consider a less dense crustal composition such as a continental crust density.

5.2.1.2 Ceará Rise as a continental crust

To investigate the hypothesis that the Ceará Rise is a continental fragment, we consider $x_a = 440$ km and $x_b = 570$ km as the continentward and seaward limits (red solid line in Figure 13b). Basically, we attribute to the interval $[x_a;\ x_b]$ a continental crust density of 2.67 g/cm³ and calculate the new isostatic Moho S_i (equation 1) with compensation depth S_0 equal to 34 km which is shown in Figure 13b. As expected, by reducing the Ceará Rise density in the equation 1, we computed shallower isostatic Moho S_i (solid white line in Figure 13b) under the Ceará Rise in comparison to the isostatic Moho S_i with the hypothesis that the Ceará Rise is an oceanic crust (solid white line in Figure 12b). Notice that the anomalous crust in the Ceará Rise (Figure 13b) is 5 km less thick in comparison to the model shown in Figure 12b. Since the anomalous crust that underlies the Ceará Rise is 0.17 g/cm³ less dense in comparison to the model in Figure 12, the predicted gravity data (solid line in Figure 13a) yield a better data fitting. Hence, the anomalous Ceará Rise crust under the hypothesis of continental crust with isostatically balanced masses produces crustal roots with maximum depth of 27 km.

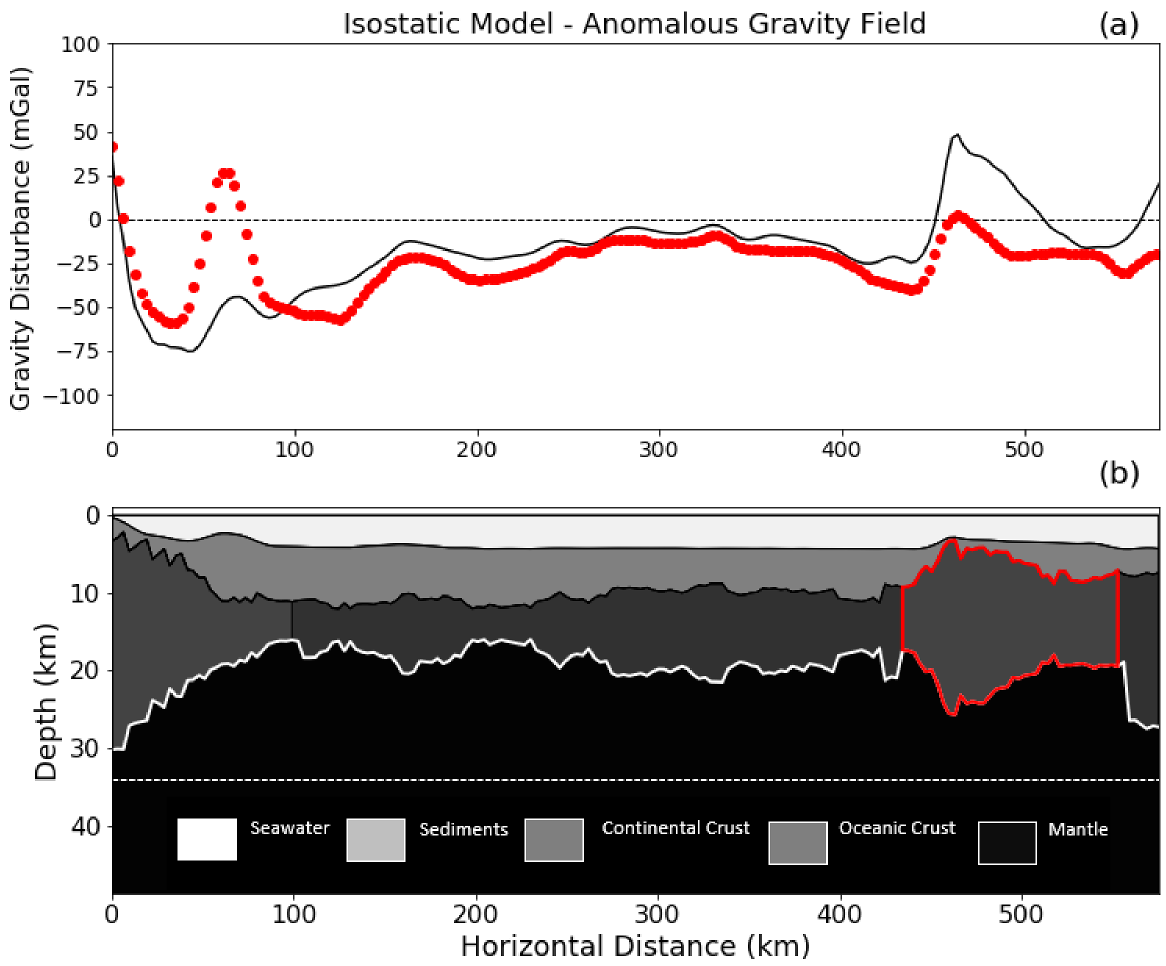

Figure 13. (a) Observed (red dots) and fitted (solid line) gravity disturbance produced by (b) the geological model composed by seawater layer (white polygon), sedimentary layer (light gray polygon), continental crust (light-dark gray polygon), oceanic crust (dark gray polygon) and mantle (black polygon). The assigned density contrasts are shown in Figure 9. The geological model in b uses the isostatic Moho (solid white line) calculated with compensation depth S_0 (dashed white line) equal to 34 km under the hypothesis of Ceará Rise (outlined in red polygon) as a continental fragment with 2.67 g/cm³. The model is limited in depth by the S_R surface equal to 49.5 km.

The most striking feature of testing the geologic hypothesis of Ceará Rise as a continental fragment is that it leads to an isostatic Moho (solid white line in Figure 13b) that produces an acceptable data fitting in the interval $x \in [150\ km, 420\ km]$ defined as the "normal" oceanic crust. Hence, in the "normal" oceanic crust, we can conclude that the isostatic Moho combined with the hypothesis of Ceará Rise as a continental fragment besides producing a better gravity data fitting, they also support an isostatically balanced anomalous masses. However, this combination does not yield an acceptable data fitting (solid line in Figure 13a) either in the Ceará Rise or in the proximal, necking and distal domains.

5.2.2 Seismic Moho

By replacing the isostatic Moho S_i (equation 1) by the seismic Moho interpreted in Figure 8 (thick orange line), we evaluate two different scenarios: one for the COT area and other one for the Ceará Rise. First, our interpretation of the seismic profile (Figure 8) suggests that the continental crust is separated from the oceanic crust by an exhumed subcontinental mantle domain. Second, we interpreted that the seismic Moho under the Ceará Rise is deeper and has a different geometry in comparison to the isostatic Moho shown in Figure 13b.

Figure 14 shows the geological model by using our interpretation of the seismic Moho and under the hypothesis that the Ceará Rise is a continental fragment with density of 2.67 g/cm^3. In this model, the COT area is characterized by mantle exhumation. Hence, we interpret that an entire crust breakup occurred prior to the lithospheric mantle breakup (FRANKE, 2013). For this reason, the study area did not originate large volumes of volcanic flows. Therefore, the geological model shown in Figure 14b tests the hypothesis that the Brazilian Equatorial Margin is a magma-poor-type as shown in Figure 2. This geological model based on the seismic Moho (Figure 14b) yields an acceptable data fitting (solid line in

Figure 14a) either in the Ceará Rise or in the proximal, necking and distal domains. We find Moho depths for the Ceará Rise between 20 and 33 km which implies that the Ceará Rise achieves approximately 26 km of thickness. The deepening of the Ceará Rise crustal roots is steeper from East toward its central part which explains the asymmetry in the bathymetric data. However, we stress that the seismic Moho under the "normal" oceanic crust, comprehended in the interval from COT to the Ceará Rise, yields a poor gravity data fitting.

By considering that the Ceará Rise (Figure 14b, outlined in red polygon) is a continental crust surrounded by oceanic lithosphere, it is necessary to investigate the microcontinent formation hypothesis. According to ABERA *et al.* (2016), initially the seafloor spreading follows the continental breakup and the rifted margin slowly cools and strengthens. The active spreading ridge has sufficient magma supply during this stage. Second, the magma supply decreases and the plate boundary strengthens. The ridge may be abandoned while tectonic extension begins somewhere else or spreading may continue while a new ridge begins its development. Finally, the old ridge is abandoned and there is a new seafloor spreading ridge. At this moment, the ridge jumps within the oceanic lithosphere and an asymmetric oceanic basin is formed or the ridge jumps into the rifted margin and a microcontinent is formed.

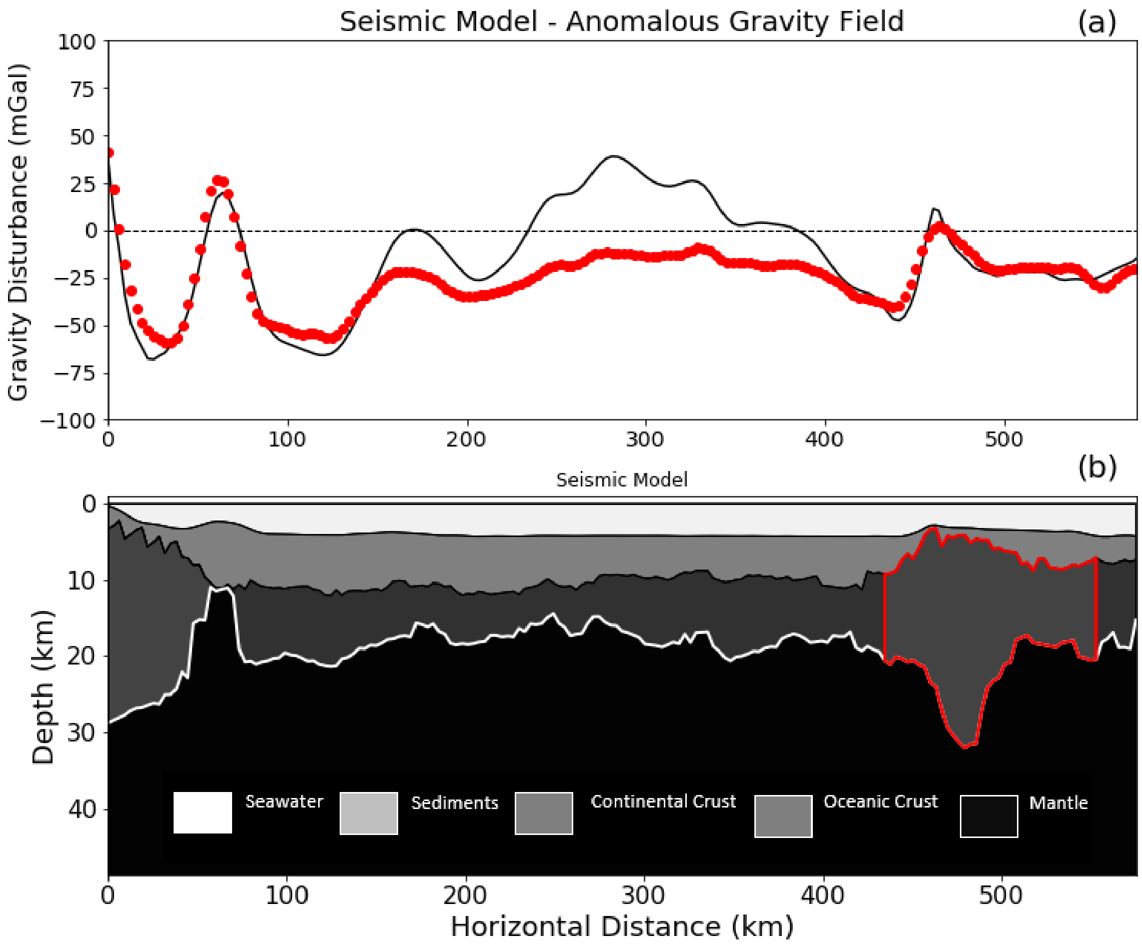

Figure 14. (a) Observed (red dots) and fitted (solid line) gravity disturbance produced by (b) the geological model composed by seawater layer (white polygon), sedimentary layer (light gray polygon), continental crust (light-dark gray polygon), oceanic crust (dark gray polygon) and mantle (black polygon). The assigned density contrasts are shown in Figure 9. The geological model in b uses the seismic Moho (orange line in Figure 8) that interpreted a mantle exhumation in the COT area and an asymmetrical deeper Moho over the Ceará Rise (outlined in red polygon) under the hypothesis of Ceará Rise as a continental fragment with density of 2.67 g/cm³. The dashed white line is the compensation depth S_0 (not used). The model is limited in depth by the S_R surface equal to 49.5 km.

To evaluate the isostatic state of the geological model based on our interpretation of the seismic model (Figure 14b), we calculate the lithostatic stress σ_i (equation 2) shown in Figure 15. This lithostatic stress indicates that this model is not isostatically balanced according to Airy compensation mechanism. The most striking feature of Figure 15 is the strong correlation between the stress and the observed gravity disturbance data (red dots in Figure 14a). It happens because the gravity disturbance data reflect the direct gravitational effects of the geological loads in the study area: ocean bathymetry, sedimentary layer and crust in the study area. Note that the lithostatic stress is close to zero over the platform breakup and the "normal" oceanic crust. However, higher values of lithostatic stress are found over the exhumed mantle and the Ceará Rise. This means that these features disturbed the lithostatic stress and cannot be isostatically accommodated just by changes in Moho depths.

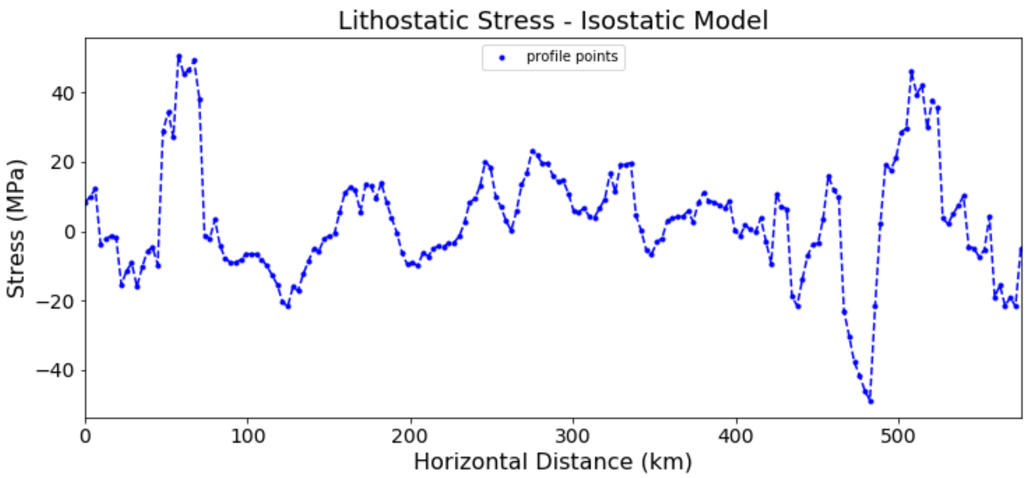

Figure 15. The lithostatic stress (equation 3) of the geological model based on our interpretation shown in Figure 14b that uses a seismic Moho (thick orange line in Figure 8). The stress reflects how successful is the isostatic Moho geometry in supporting all geological loads.

5.2.3 Hybrid Moho

Aiming to build a geophysical model for the Brazilian Equatorial Margin, we join the isostatic (Figure 13b) and the seismic models (Figure 14b) under the hypothesis of Ceará Rise as a continental fragment with density of 2.67 g/cm³. Basically, we choose the x −intervals where the observed and fitted gravity disturbances produced by the isostatic and seismic models are well fitted and combine them into a single geophysical model called hybrid model. The intervals selected are $x \in [150\ km,\ 420\ km]$ ("normal" oceanic crust) for the isostatic model (Figure 13b) and $x \in [0\ km,\ 150\ km[$ (proximal, necking and distal domains) and $x \in]420\ km, 580\ km]$ (Ceará Rise) for the seismic model (Figure 14b).

As preconized in the magma-poor margin model (Figure 2) proposed by FRANKE (2013), our hybrid geological model (Figure 16b) is characterized in the proximal domain by a wide area of highly attenuated continental crust where the upper crust deformation occurred due to listric faults. In the distal domain, the COT area is characterized by mantle exhumation and the oceanic domain presents oceanic crust from 7 to 10 km thick. The hypotheses that the Brazilian Equatorial Margin is a magma-poor type and that the Ceará Rise is a continental crust fragment are supported by the hybrid model (Figure 16b) which yields an acceptable gravity data fitting (solid line in Figure 16a) either in the proximal, necking, distal or in the oceanic domains.

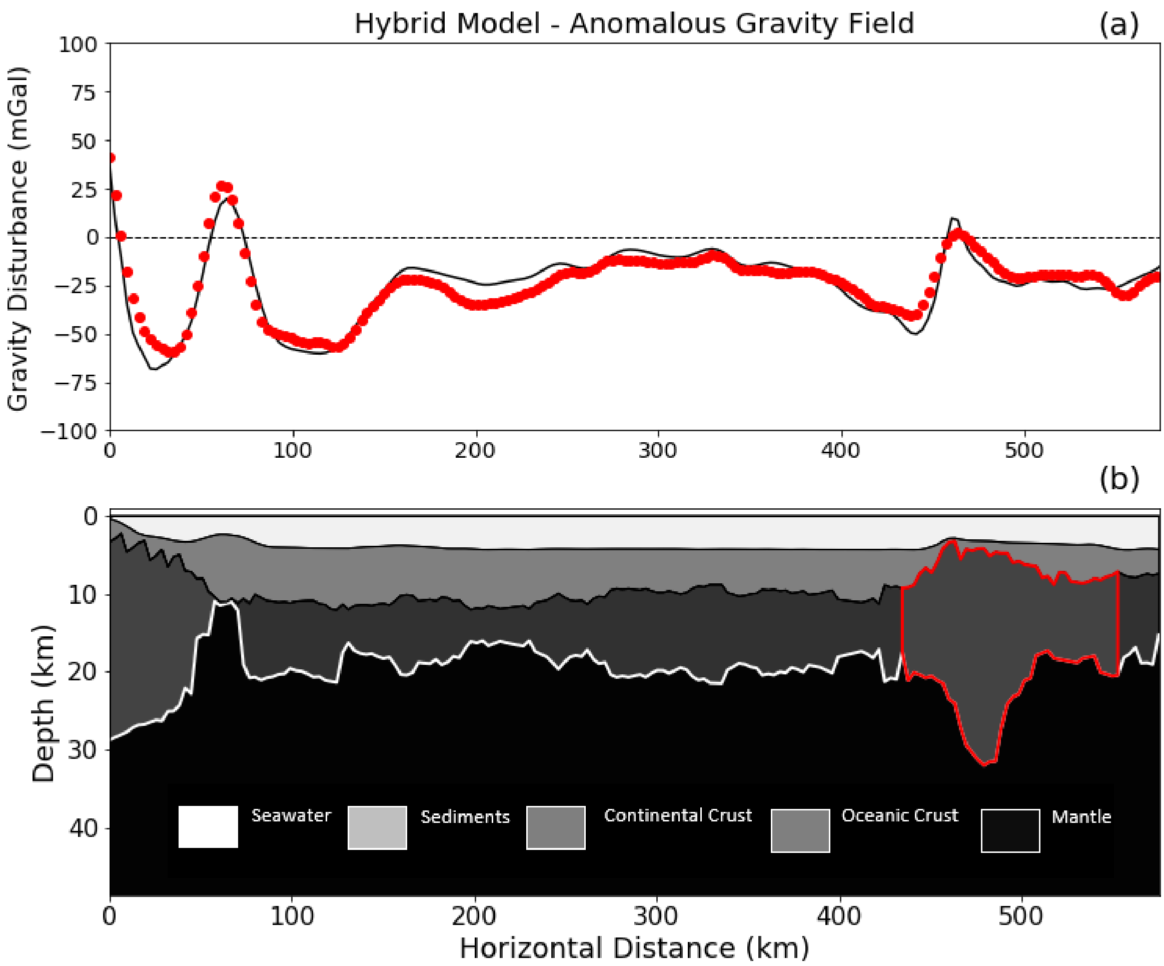

Figure 16. a) Observed (red dots) and fitted (solid line) gravity disturbance produced by (b) the hybrid geological model composed by seawater layer (white polygon), sedimentary layer (light gray polygon), continental crust (light-dark gray polygon), oceanic crust (dark gray polygon) and mantle (black polygon). The assigned density contrasts are shown in Figure 9. The hybrid geological model in b combines part of the isostatic Moho under the hypothesis of Ceará Rise as a continental fragment with density of 2.67 g/cm³ (Figure 13b) with part of the seismic Moho (Figure 14b). These parts are chosen only in the intervals where the gravity data fitting is acceptable. The Ceará Rise is outlined in red polygon. The model is limited in depth by the S_R surface equal to 49.5 km.

To validate the hybrid model, we calculate the lithostatic stress (Figure. 17) which shows that the study area is partially in isostatic equilibrium according to Airy compensation mechanism. The lithostatic stress is different from zero over the proximal, necking and distal domains and the Ceará Rise in the oceanic domain. Moreover, higher values of lithostatic stress are found over the exhumed mantle. This means that these geological features disturbed the lithostatic stress and cannot be isostatically accommodated just by changes in Moho depths. However, over the oceanic domain, the lithostatic stress of the "normal" oceanic crust is equal to zero because the Moho undulations support all the geological loads.

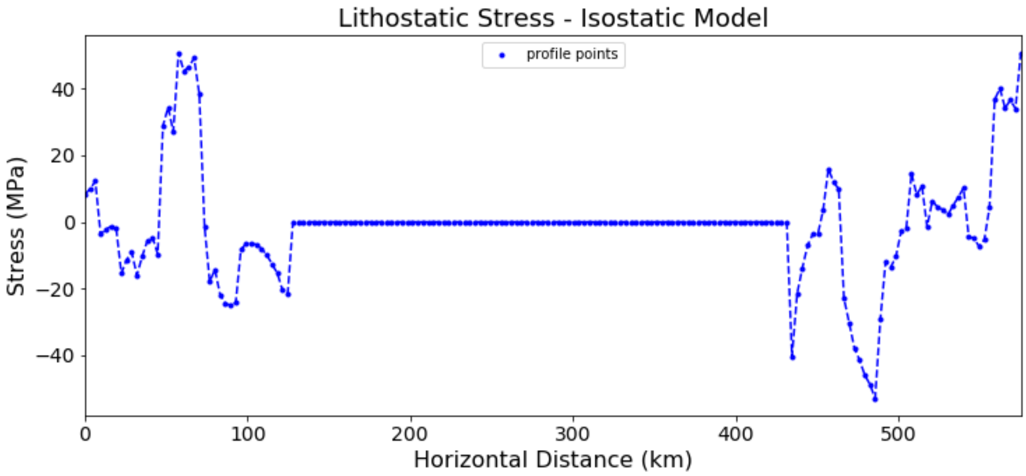

Figure 17. The lithostatic stress (equation 2) of the hybrid geological model (Figure 16) based on our joint interpretation of the isostatic (Figure 13b) and seismic (Figure 14b) models. The stress reflects how successful is the isostatic Moho geometry in supporting all geological loads.

6 Conclusions

We have studied the Ceará Rise in the Brazilian Equatorial Margin and the following conclusion can be drawn. The key architectural elements of a volcanic passive margin, such as large igneous provinces and seaward dipping reflectors are not recognized in the study area. We have investigated the Moho depth in the study area by using Airy isostatic compensation model and seismic interpretation. The hypothesis that the Ceará Rise is an isostatically balanced anomalous oceanic crust accumulation is not supported by the gravity disturbance forward modeling because it produces poor data fitting. On the other hand, the hypothesis of continental crust to the Ceará Rise in isostatic equilibrium yields an acceptable gravity data fitting over the "normal" oceanic crust enclosed in the interval from COT to the Ceará Rise. Under this hypothesis, the "normal" oceanic crust is in isostatic equilibrium with a null lithostatic stress and its thickness varies from 7 to 10 km. By disregarding the isostatic state of masses, the gravity disturbance modeling using the seismic Moho and under the hypotheses of continental crust to the Ceará Rise and of exhumed mantle at the COT area yields an acceptable gravity data fitting either in the Ceará Rise or in the proximal, necking and distal domains. However, the seismic Moho yields a poor data fitting in the "normal" oceanic crust.

We have proposed a hybrid modeling that combines the isostatic and seismic Mohos under two hypotheses: i) continental crust to the Ceará Rise and ii) exhumed mantle at the COT area. We have used the isostatic Moho over the "normal" oceanic crust and the seismic Moho over the Ceará Rise and over the proximal, necking and distal domains. Hence, the proposed hybrid modeling supports the Brazilian Equatorial Margin as a magma-poor rifted margin. The lithostatic stress calculated from the hybrid model shows that the study area is partially in isostatic equilibrium because it is different from zero over the proximal, necking and distal domains and the Ceará Rise, but it is equal to zero over the "normal" oceanic crust. Therefore, the Ceará Rise disturbed the lithostatic stress and cannot be isostatically accommodated just by changes in Moho depths. Our joint interpretation of the seismic reflection profile and the gravity disturbance forward modeling has evidenced a well-marked exhumed mantle at the COT area which flanks the Pará-Maranhão Basin. The COT area is of the order of 20 km wide and it is strongly influenced by the Saint Paul Fracture Zone. Our joint interpretation has indicated that the Ceará Rise is a continental crust and may be an abandoned continental fragment due to a ridge jump of the Monrovia oceanic fracture zone into the continental margin.

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