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INFLUENCE OF MOHO DEPTH IN GRAVITY REGIONAL-RESIDUAL SEPARATION OF THE BARREIRINHAS BASIN, BRAZIL

INFLUÊNCIA DA PROFUNDIDADE DA MOHO NA SEPARAÇÃO REGIONAL-RESIDUAL DE DADOS GRAVIMÉTRICOS NA BACIA DE BARREIRINHAS, BRASIL

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RESUMO: A modelagem gravimétrica direta como uma abordagem de separação regional-residual orienta os geocientistas a melhorar a análise e interpretação dos dados de campo potencial. Esse procedimento é bem conhecido na comunidade geocientífica, pois nos permite compreender e identificar estruturas geológicas e fontes em diferentes profundidades. Selecionamos a bacia de Barreirinhas para uma nova interpretação com base em dados gravimétricos e modelos de profundidade do Moho, que variam desde 10 a 40 km de profundidade conhecida. Em seguida, escolhemos os conjuntos de dados gravimétricos ar-livre e Bouguer e avaliamos qual seria o mais adequado para fins de interpretação. Depois disso, adotamos três modelos crustais distintos para aplicar a separação regional-residual. Nossos resultados de dados regionais mostram o mesmo padrão de tendência na direção SW–NE, seguindo o declínio da profundidade crustal do continente para o oceano. Além disso, os resultados dos dados residuais ilustram o principal sistema de falhas ao longo da zona de transição continental-oceânica e outras características geológicas, como o lineamento de Pirapemas e a plataforma de Sobradinho. Apesar dos resultados aceitáveis, os modelos GEMMA e Sul-Americano funcionaram de maneira diferente. Os resultados indicam que as variações na profundidade do Moho utilizadas na modelagem direta influenciam significativamente os dados de gravidade residual. O primeiro identificou uma anomalia arredondada de baixa intensidade relacionada ao depocentro continental. O segundo modelo mostrou melhores resultados fora da bacia e na borda continental, identificando um possível sistema horste-graben e a reativação de falhas.
Palavras-chave: Isostasia. Modelos de Moho. Bacia de Barreirinhas.

ABSTRACT: Gravity-forward modeling as a regional-residual separation approach guides geoscientists to improve the analysis and interpretation of potential field data. This procedure is well-known in the geoscience community as it allows us to understand and identify geological structures and sources at different depths. We selected the Barreirinhas basin for a new interpretation based on gravity data and Moho depth models, which range from 10 to 40 km of known depth. Then, we chose Free-air and Bouguer gravity data sets and evaluated the most suitable for interpretation purposes. After that, we adopted three distinct crustal models to apply the regional-residual separation. Our results of regional data show the same pattern of trend in the SW–NE direction, following the crustal depth decline from the continent to the ocean. In addition, the results of residual data illustrate the principal fault system along the continental-oceanic transition zone and other geological features such as the Pirapemas lineament and Sobradinho platform. Despite acceptable results, the GEMMA and South American models worked differently. Results indicate that variations in Moho depth used in forward modeling significantly influence the residual gravity data. The first identified a low-intensity rounded anomaly related to the continental depocenter. The second model showed better results outside the basin and at the continental boundary, identifying a possible horst-graben system and fault's reactivation.
Keywords: Isostasy. Moho models. Barreirinhas Basin.

INTRODUCTION

Isostasy is a fundamental concept for applying the gravity method to Earth's investigation since there are a few significant isostatic deviations as most of the Earth's surface is close to isostatic equilibrium (Artemieva, 2011; Gvirtzman et al., 2016). The excess and lack of mass in the Earth's topographic relief and oceans are not compensated (Turcotte & Schubert, 2002; Watts, 2001), neither with crustal root nor lateral changes in density as early assumed for local isostasy (Airy, 1855; Pratt, 1855, 1859). These concepts are not widely accepted for cases of regional isostasy (Artemieva, 2011) once the Earth's crust reacts as a filter when some topographic load is applied (Wienecke, 2006, 2007). Such a case can cause variations in crustal depth and density distribution concomitantly (Allen & Allen, 2013; Tenzer & Bagherbandi, 2012; Turcotte & Schubert, 2002; Watts, 2001).

Crustal models in South America show that Moho depth can vary from 8 to 80 km (Laske et al., 2012, 2013; Reguzzoni & Sampietro, 2015; Uieda & Barbosa, 2016). Those depth variations are predominant under Andean foreland basins and transition areas at the Equatorial margin, where the crust is thinner than in the continent (Uieda & Barbosa, 2016). This Brazilian area is a prominent research focus as a large group of sedimentary basins formed during the separation process between Africa and South America (Soares Júnior et al., 2008, 2011; Zalán, 2004). Another characteristic of this area is the transition zone between continental and oceanic crust, which lies at a transform margin (Burke, 1976). Despite the complex tectonic evolution of those sedimentary basins, it is possible to ensure further discussions about reactivation and movements of faults and also the effect caused by Moho depth and geometry in the gravity studies, such as interpretation, inversion, and modeling.

Barreirinhas Basin is an area inside the Brazilian Equatorial Margin that extends from continent to ocean with more than 60000 km^2 of extension. Its genesis and development started in the Archean caused by the movements involving the fragmentation of Gondwana, which led to the separation of South America and Africa (Soares et al., 2007; Zalán, 2004, Zalán & Oliveira, 2005). Some researchers classify the Barreirinhas Basin as a sedimentary basin with a transforming margin associated with polycyclic tectonic events and structural fault systems (Milani et al., 2000, 2007; Montenegro et al., 2020). Indeed, these attributes characterize this basin as sag type, with smooth dips, large and deep deposition of sediments, and without abrupt faults (Conte & Oliva, 2021a; Conti & Oliva, 2021b; Szatmari et al., 1987). Moreover, the enthusiasm about this basin comes from its extension (from continent to ocean) and the lack of information about its crustal movements. The latter matters since this basin evolution correlates to the Moho lifting that occurred in the past due to the high pressure of sediment accommodation and thermal relaxation (Soares Júnior et al., 2008, 2011, Lopes et al., 2018).

We aim to investigate and discuss the effect of Moho depth in gravity modeling and interpretation, notably at the Barreirinhas Basin and surroundings. Previous geophysical studies identified the continental depocenter (Almeida-Filho et al., 2009; Ribeiro Filho, 2018), and the fault and deposition systems (Krueger, 2012; Krueger et al., 2012). However, the uncertainty remains. Because of that, the approach employed in this paper consists in firstly comparing residual gravity data obtained from forward modeling and crustal models (Ribeiro Filho, 2018; Ghomsi et al., 2021; Soares Júnior et al., 2019). Then the identification of geologic elements such as faults, lineaments, and minor sedimentary basins, if they exist. Results show that Moho depth values used in the forward modeling affect the residual gravity data. Unfortunately, the main issue relies on the transition zone, because crustal models are different. However, we also believe the best way to correct this issue and obtain a superior geological interpretation is by performing a statistical method from correlation jointly to an inversion approach.

In this paper, we first describe the geological settings in the Barreirinhas Basin and exhibit the geological elements we are interested in. Next is the selection of geophysical gravity data and Moho models, followed by a brief description of the methodology of using forward gravity modeling to obtain residual anomalies. We finish this manuscript by validating and interpreting our results.

STUDY AREA AND DATA ANALYSIS

Geological settings

The Barreirinhas Basin, situated in the northern region of Brazil, constitutes a passive margin basin within the Brazilian Equatorial Margin, spanning approximately 46,000 km^2 between the meridians 44º and 42º W and the parallels 0º and 3º S (Mohriak, 2003; Mohriack & Rosendahl, 2003). Its onshore section is demarcated to the south by the Sobradinho structural platform and a series of normal faults. A coastline delineates its northern boundary, with an offshore extension rea-ching into the high seas (Mohriak, 2003). Considering its offshore part, the region extends from the coastline to the high seas, bounded by the Alto de Tutóia in the east and the Santana Island Platform in the west (Pamplona, 1969; Mohriak & Rosendahl, 2003). Bathymetric data complements the geological mapping, revealing depth variations ranging from sea level along the coastal strip to depths of approximately 4500 m in the deepest regions. Figure 1 illustrates the topographic and bathymetric features extracted from Etopo1 (Amante & Eakins, 2009).

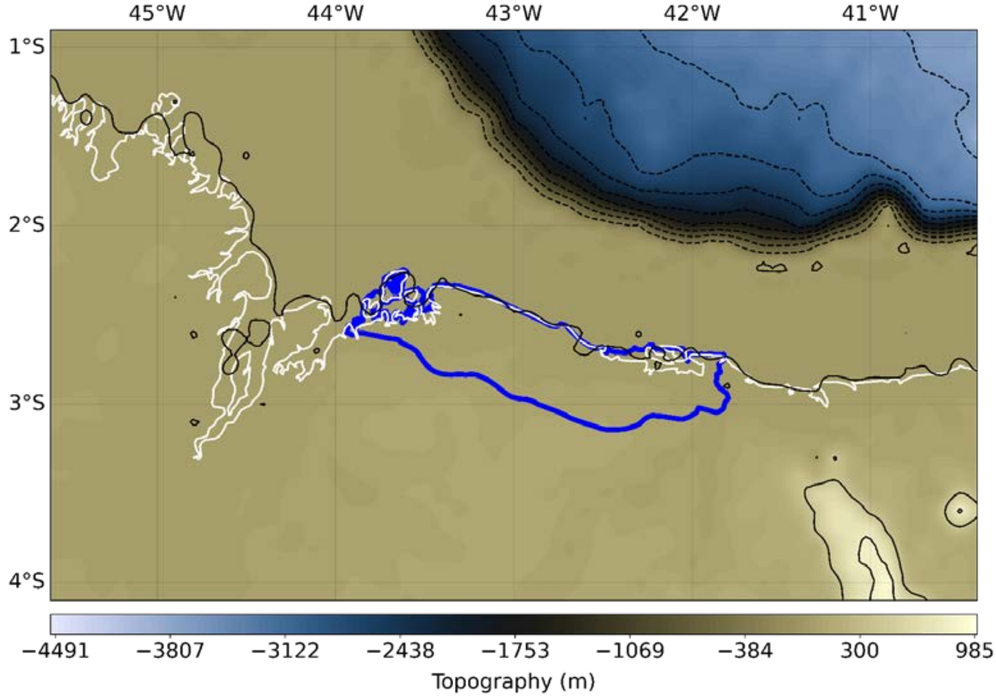

Figure 1 – Bathymetric and topographic data of the Barreirinhas basin. White line is the coastline. The blue line is the basin contour.

According to Lopes et al. (2018), the evolution of rift or margin-type basins closely links to Moho uplift, attributed to intermittent increases in pressure from sedimentary deposition and the thermal response associated with subsidence (Trosdtorf Júnior et al., 2007).

This basin's genesis and development intricately ties itself to the fragmentation of the supercontinent Gondwana, specifically the separation of the South American and African continents through shear movements (Trosdtorf Júnior et al., 2007). Figure 2 depicts the geological map of the Barreirinhas Basin.

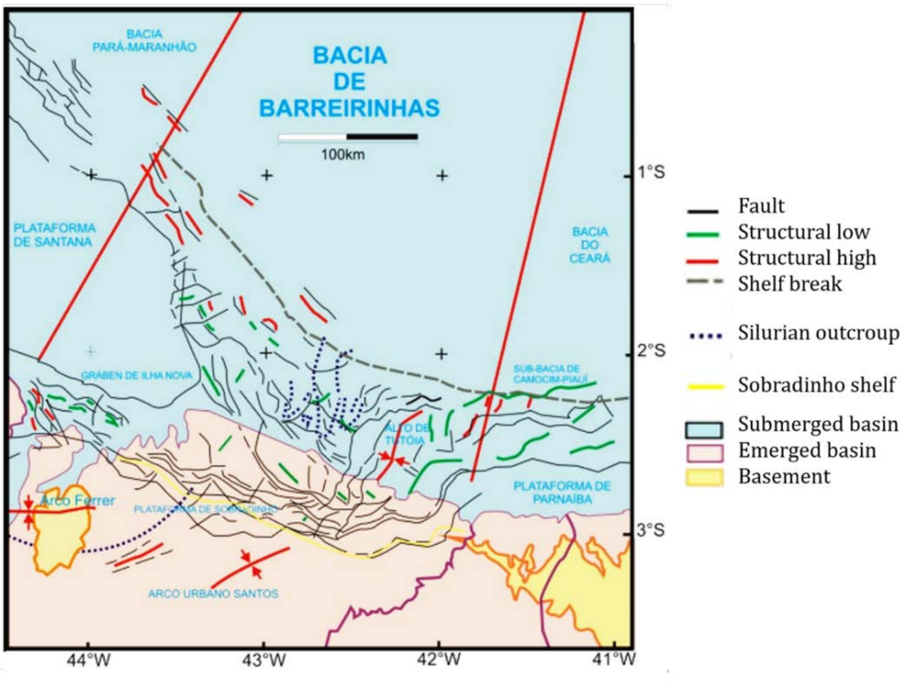

Figure 2 – Simplified geological map of the Barreirinhas Basin adapted from Mohriak (2003).

This understanding characterizes the Barreirinhas Basin as possessing rhombic geometry and distensional structures, its formation associated with transtensional regimes resulting from dextral movement and projection within the continental crust of the Romanche Fracture Zone (Azevedo et al., 1985; Azevedo, 1986).

This fracture zone demarcates distinct tectonic features. To the south, the basin exhibits pronounced deformation caused by transpressional structures dating back to the Cenomanian age, gradually diminishing towards the southern periphery, assuming the typical configuration of a passive margin basin and transitioning almost imperceptibly into the Pará–Maranhão Basin. Furthermore, the Barreirinhas Basin displays indiscriminate faulting and shear zones

Milani et al. (2000, 2007) proposed a classification of basins along the Brazilian Continental Margin based on their genesis and tectonic context, grouping them into two main categories: Distensional and Transforming margins. Within this framework, the Barreirinhas Basin falls under the Transforming margin category, its origin associated with a series of polycyclic tectonic events (Montenegro et al., 2020) and a continent-continent fault system responsible for the separation of Africa and South America (Tavares, 2017; Tavares et al., 2020). From an evolutionary perspective, the basins along the Brazilian continental margin can be divided into four fundamental megasequences: Pre-rift Supersequence, Synrift Supersequence, Post-Rift Supersequence, and Drift Supersequence (Pamplona, 1969; Mohriak & Rosendahl, 2003; Trosdtorf Júnior et al., 2007; Azevedo et al., 1985; Azevedo, 1986; Soares et al., 2007)

Tectonic phases description

The Pre-rift phase signifies the syneclysis stage, characterized by sedimentation in the Parnaíba Basin and defined by the accumulation of tension associated with lithospheric stretching, resulting in subsequent ductile deformation and flexural subsidence (Conceição et al., 1988). As noted by (Milani et al., 2007), these characteristics induce a sag-type geometry in the basin, characterized by gentle dips, extensive sedimentation, and the absence of pronounced faults.

The subsequent Synrift phase unfolds through intensified mechanical subsidence, driven by intense normal faults arranged in a backstepping pattern predominantly in a West-Southwest direction (Trosdtorf Júnior et al., 2007). This stage, as high-lighted by Milani et al. (2007) and Almeida Júnior (2018), witnesses the basin's expansion alongside the nucleation of discontinuities in extensive transcurrent faults, activated and reactivated throughout the separation of the African and South American continents. (Szatmari et al., 1987) emphasizes that this process significantly shapes the basin's structural style, resulting in faulted and rotated blocks with large depocenters associated with rhombic grabens.

The Post-Rift phase denotes a period of sustained lateral extension, accompanied by stress relief and a reduction in tectonic activity, primarily linked to the principal normal faults (Trosdtorf Júnior et al., 2007). Some authors assert that this phase witnesses the development of a secondary sag basin, directly correlated with heightened thermal subsidence processes (Soares Júnior et al., 2008, 2011).

Next, the Drift supersequence manifests the progressive separation of continents and the emergence of oceanic crust (Trosdtorf Júnior et al., 2007). The Breakup unconformity demarcates the initiation of this sequence in the stratigraphic record, reflecting shifts in the tectonic regime during the transition from the Post-Rift to Drift sequences.

During the continental drift period, a tilting process unfolds in the study area, contributing to increased sediment deposition in the basin and facilitating the evolution of its sag pattern (Milani et al., 2007).

Through investigations into thermal activity, tectonic forces, and the types of faults within the region, (Pamplona, 1969) associates these factors with the four stages described previously, characterizing the region as a product of a complex process of transformative kinematics.

The substantial deformation induced by the extension of the Romanche Fracture Zone in the extreme northeast and eastern regions during the rift phase fosters the development of numerous echelon folds and anticline arcs (Pamplona, 1969; Zalan, 2004).

Further studies by (Woodcock & Fischer, 1986) confirm the transtensional geometry in the basin's western region. Analysis of the basin's structural nature delineates a distensive system intersected by more recent transcurrent faults with NE-SW orientation (Pamplona, 1969; Woodcock & Fischer, 1986; Zalán, 2004).

Preliminary analysis of gravity anomalies

Free-air and Bouguer gravity disturbances are data products derived from gravity field measurements. Free-air disturbances represent gravity measurements adjusted from a reference height, enabling assessment of isostatic equi-librium across specific regions (Watts, 2001; Wang & Cochran, 1993; Watts et al., 2020).

Conversely, Bouguer gravity data entails Free-air observations corrected for the influences of topography and terrain, facilitating the investigation of variations in topographic masses between different points (Telford et al., 1990; Blakely, 1996).

Figure 3 depicts the Free-air disturbance map, where negative values predominate in the continental region, attributed to the Barreirinhas at the central part of the map.

Positive values reflect the influence of the Serra Grande elevation. Within the Barreirinhas Basin, two localized gravimetric lows are evident, likely associated with existing faults and the primary crustal depocenter. Additionally, a two-lobe pattern provides significant insights into the continental-oceanic boundary. Such signatures in Free-air disturbances stem from abrupt changes in crustal depth and isostatic compensation dynamics (Watts, 2001; Allen & Allen, 2013).

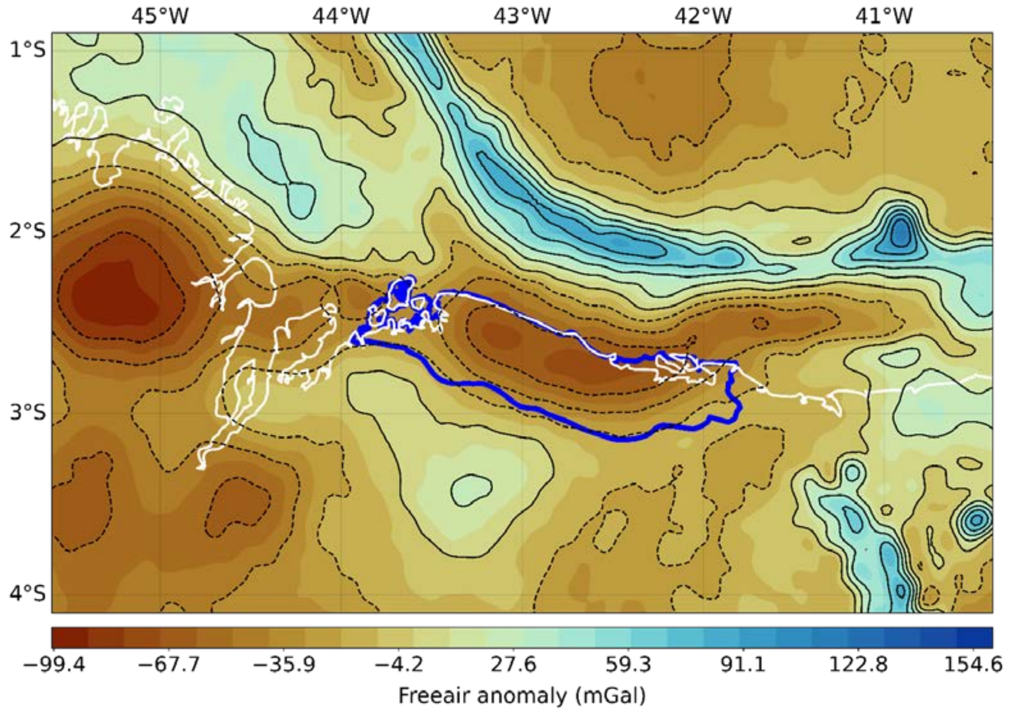

Figure 3 – Map of the Free Air gravity disturbance in the Barreirinhas Basin. White line is the coastline. The blue line is the basin contour.

Figure 4 illustrates the Bouguer disturbance map, providing a contrasting perspective to the Free-air map (Figure 3) and serving distinct interpretative purposes. A notable distinction lies in their patterns, where the Bouguer disturbance exhibits positive values in the ocean and negative values on the continent.

This disparity indicates that Free-air and Bouguer disturbances highlight different geological structures. Therefore, researchers must align their objectives with the appropriate data selection for analysis and interpretation.

Negative anomalies observed in the continent on the Bouguer disturbance map resemble those in the Free-air data, associated with local sedimentary basins (Ribeiro Filho, 2018; Ghomsi et al., 2021). Conversely, positive anomalies in the ocean result from the Bouguer correction pattern applied at depths below sea level. Noteworthy changes from negative to positive anomalies within the continental portion correspond to boundaries.

Crustal depth comparison

Here, we delineate three types of Moho models. The first model is an isostatic compensation model formulated based on Pascal's law by Airy (Airy, 1855). In this model, we postulate that the Earth's crust behaves similarly to a rigid shell floating atop a denser substratum, with compensating roots composed of lower-density lithospheric rocks accounting for topographic elevations, replacing denser mantle materials.

Consequently, the Moho exhibits greater depths beneath continents and shallower depths beneath oceans. In essence, the Moho depth derived from the Airy model mirrors a non-scaled reflection of topography, as depicted in figure 5. Moreover, it progressively deepens following a northeastward direction, ranging from 14 to 40 km.

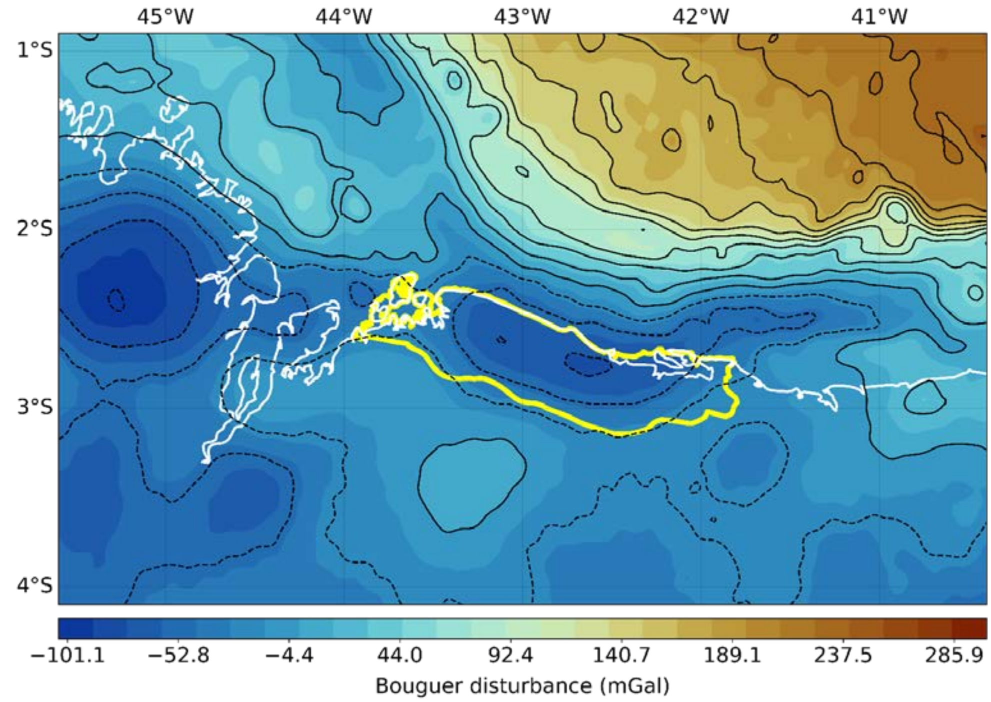

Figure 4 – Map of the Bouguer gravity disturbance in the Barreirinhas Basin. White line is the coastline. The yellow line is the basin contour.

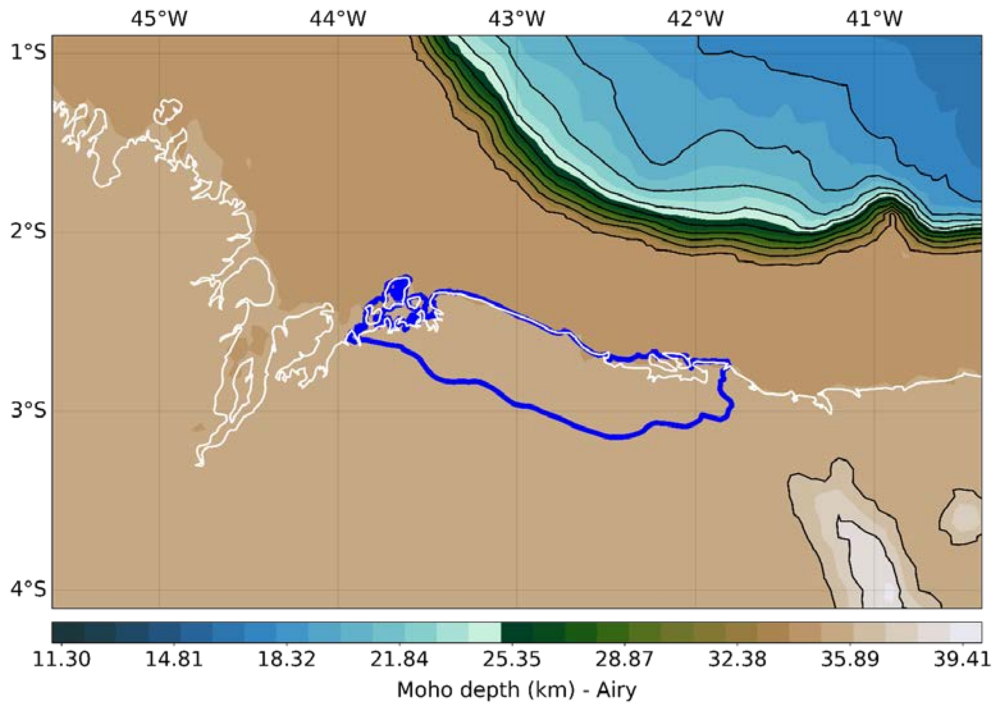

Figure 5 – Map of crustal depths calculated from the Airy model (Airy, 1855). White line is the coastline, and the blue line is the basin contour.

The second Moho model utilized is the high-resolution GOCE Exploitation for Moho Modeling and Applications (GEMMA) global model (Reguzzoni & Sampietro, 2015; Sampietro, 2016), regarded as an advancement of the CRUST2.0 Moho model, as depicted in figure 6.

The GEMMA model employs a 0.5º x 0.5º global grid, computed using data from the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite observations (Drinkwater et al., 2006; Migliaccio et al., 2011), and integrates seismic survey information to enhance result reliability.

Within the study area, the GEMMA model portrays deeper Moho depths in the São Luis Basin and shallower depths in the oceanic regions. Notably, the patterns observed in previous datasets are absent in this model. Additionally, a consistent Moho depth of 25 km may be observed at the continental-oceanic boundary. The Moho depths derived from the GEMMA model range from 14 to 45 km.

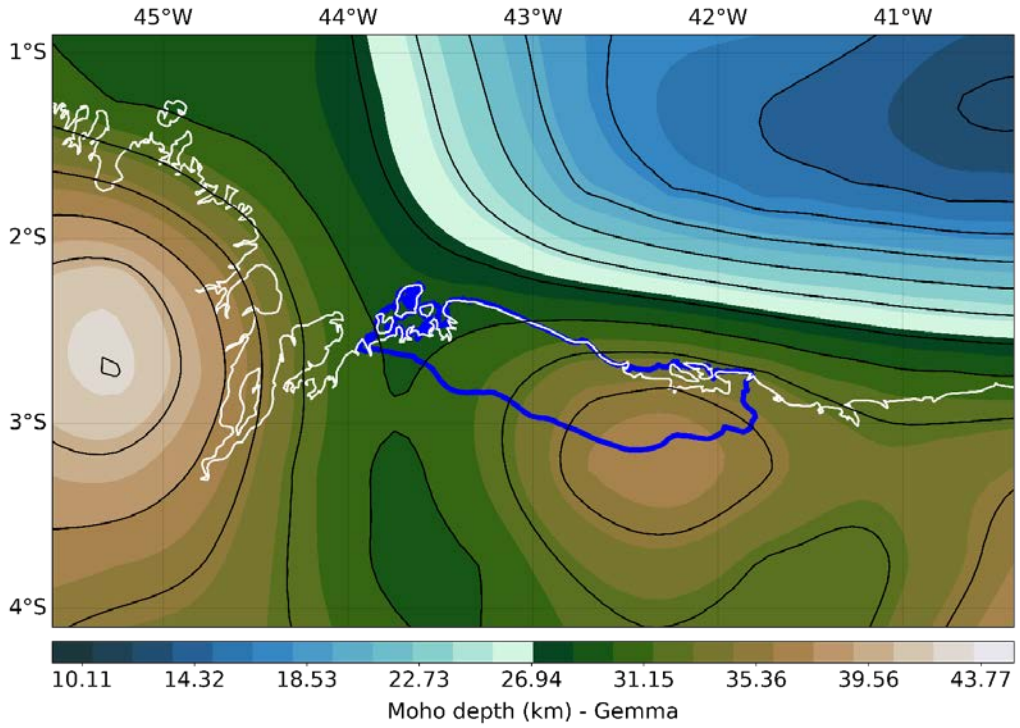

Figure 6 – Map of crustal depths calculated from the GEMMA model (Reguzzoni & Sampietro, 2015; Sampietro, 2016). The white line is the coastline, and the blue line is the basin contour.

The third Moho model discussed is the South American Moho model proposed by (Uieda & Barbosa, 2016). This model employs Gauss-Newton's formulation of improved Bott's method (Bott, 1960; Barbosa et al., 1997) with Tikhonov's regularization. The authors assert that the model effectively fits gravity and seismic data across all oceanic regions, coastal areas, and central portion of Brazil. However, it encounters challenges in regions with sharp variations in Moho depth, such as beneath the Andes and at the boundaries of the geotectonic provinces of the South American Plate (Uieda & Barbosa, 2016). Figure 7 illustrates a smooth variation over the São Luis Basin and exhibits a similar pattern to figure 6 across oceanic regions. The Moho depths range from a minimum of 14 km to nearly 41 km.

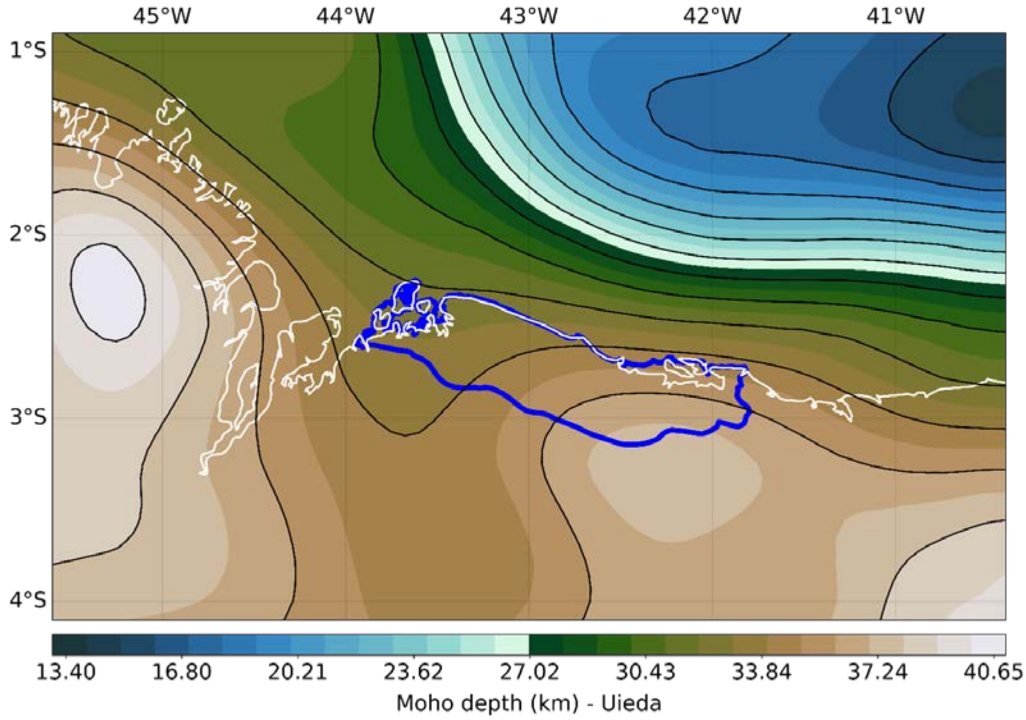

Figure 7 – Map of crustal depths calculated from the South American model (Uieda et al., 2016; Uieda & Barbosa, 2016). The white line is the coastline, and the blue line is the basin contour.

A comprehensive crustal depth model utilizing active source seismology was developed by Afonso et al. (2019) and Szwillus et al. (2019). The authors reached this model by employing a geostatistical interpolation approach, which was derived the crustal model, providing quantitative estimates of its uncertainty from a seismic point database, with *a priori* separation into oceanic and continental domains. Their findings are consistent with previous global crustal models, such as Crust 1.0 (Laske et al., 2012, 2013). Notably, in South America, the Moho depth exhibits the highest uncertainty, reaching up to 12 km. Continental and oceanic regions display smoother variations without abrupt changes, as illustrated in figure 8. However, the continent-oceanic boundary is distinctly delineated. The Moho depths range from a minimum of 11 km to a maximum of 38 km.

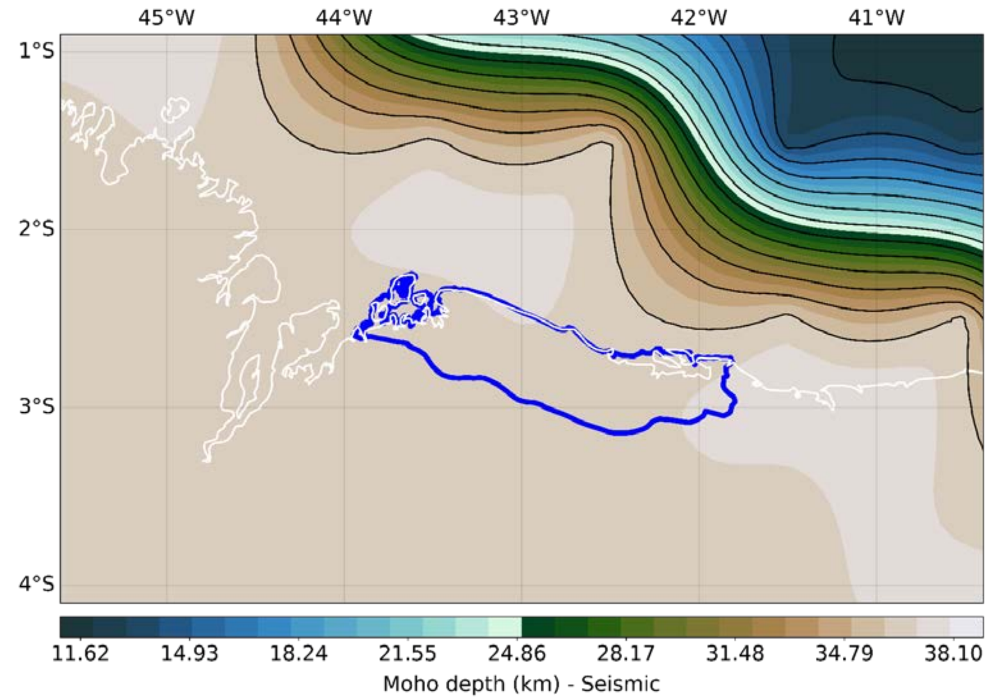

Figure 8 – Map of crustal depths calculated from the seismic model of Szwillus et al. (2019). White line is the coastline, and the blue line is the basin contour.

A comparative profile illustrated in figure 9 was extracted along the transect extending from coordinates (-43.5°, -3.0°) to (-42.5°, -2.5°) to analyze the variation of the Moho depth among the for the Airy, GEMMA, South American and seismic models discussed.

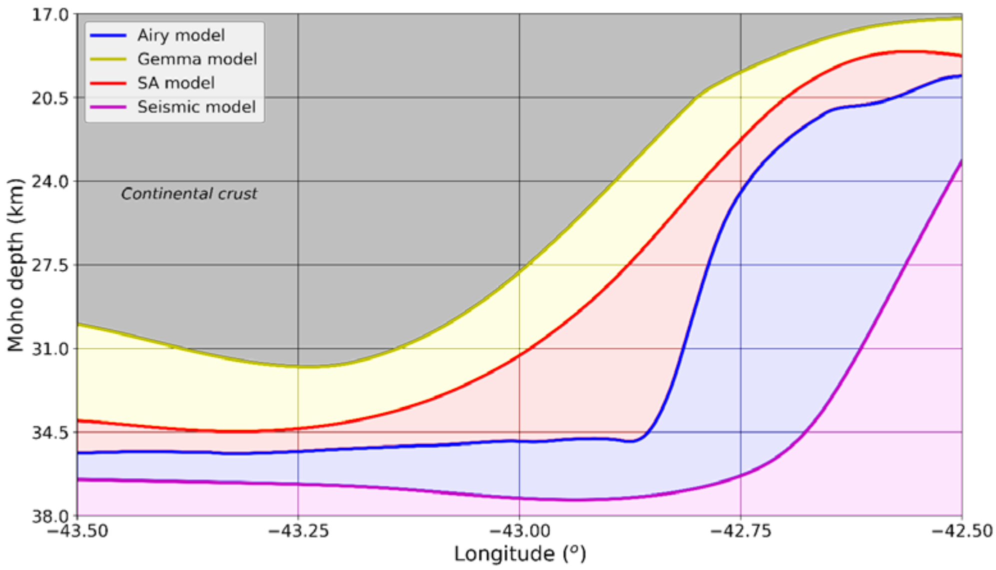

Figure 9 – Comparative crustal depth profile from longitude -43.5° to -42.5° and latitude -3.0° to -2.5°, showing the behavior of the Moho for the Airy (blue), GEMMA (yellow), South American (red), and seismic (magenta) models. Note the smooth crustal transition in all models except Airy, which presents an abrupt discontinuity at the continental–oceanic boundary.

The results reveal that, in general, the Moho exhibits a smooth and continuous behavior across the transition between continental and oceanic domains for the GEMMA, SA, and seismic models, indicating consistent mechanical and gravitational compensation.

However, the suggested Airy model shows a pronounced and abrupt discontinuity at the continent-ocean boundary, reflecting the limitations of pure isostatic compensation when confronted with real-world crustal continent-ocean complexities.

This sharp contrast emphasizes that the Airy model tends to overestimate crustal thickening in continental regions and underestimate it in oceanic zones, whereas the other models present smoother transitions that align more closely with geophysical observations.

RESULTS AND DISCUSSION

Preliminary Results

After the gravity and Moho datasets selection, we proceeded with the computation of residual gravity data. This step involved performing a regional-residual separation utilizing a forward gravity modeling approach coupled with crustal depths (Ribeiro Filho, 2018; Santos Júnior et al., 2019; Ghomsi et al., 2021; Rezende et al., 2021). In essence, this method entails decomposing the gravity data into two components: the residual signature, containing topographic and geological information, and the regional data, comprising the observed gravity signal attributed to the presence of the Moho discontinuity and deeper lithospheric regions, characterized by significant variations in physical properties (i.e. $\rho_{mantle} > \rho_{crust}$).

To execute this process, we partitioned the surface into a regularly spaced grid of rectangular prisms, with the topography and Moho depth representing the top and bottom boundaries, respectively. Subsequently, we computed the gravity data resulting from these geometric parameters, which serve as regional data. Finally, we subtracted this result from the observed data (i.e., $d_{res} = d_{obs} - d_{calc}$) to derive the residual gravity data.

For the computational aspects of this procedure, we employed the Fortran programming language and utilized the Matplotlib library (Hunter, 2007; Tosi, 2009; Ari & Ustazhanov, 2014) for generating visualizations. In sequence, figures 10, 11, 12 and 13 depict the regional data, while figures 14, 15, 16, and 17 present the residual maps resulting from the forward problem and gravity separation using crustal depths. It is imperative to provide a concise explanation of what to anticipate from regional and residual gravity maps.

Regional maps primarily capture trends or overarching patterns. As such, regional gravity data tends to exhibit smoother variations compared to residual data, offering insights into the behavior of deeper features. This fact holds true across all subsequent regional maps, where gravity data increases in the SW–NE direction.

Conversely, residual maps encapsulate abundant physical, geophysical, and geological information. Interpretation of residual maps necessitates careful consideration of gravity signal intensity and location. Negative anomalies often correspond to geological features such as basins, faults, and horst-graben systems in continental and oceanic areas.

Positive anomalies, on the other hand, typically indicate the presence of intrusive elements (e.g., dykes and sills), uplifted blocks, or regions with dense physical properties. However, it is essential to acknowledge the potential influence of shallower basement features near the surface as a contributing cause to the observed anomalies.

Regional data analysis

Regional data from the Airy model shows a trend in the SW-NE direction as expected (see Figure 10). However, we can see no contour representation on it. It occurs because the Barreirinhas Basin does not appear on the regional map, unlike the São Luis Basin. Another significant detail is the absence of a gravity signature from the Serra Grande, which should have an intense regional signal. Also, regional data ranges from -72 to 111 mGal, smaller than expected.

The regional map derived from the GEMMA model (see Figure 11) exhibits a similar feature to that observed in the Airy approach, characterized by a trend and intensity changes in the SW–NE direction corresponding to the decreasing crustal depth. Given that the GEMMA model integrates gravity and seismic data, this alignment underscores how the regional map mirrors the pattern of crustal depth, with higher regional data correlating to shallower crust and lower values over continental regions where the Moho has high depths.

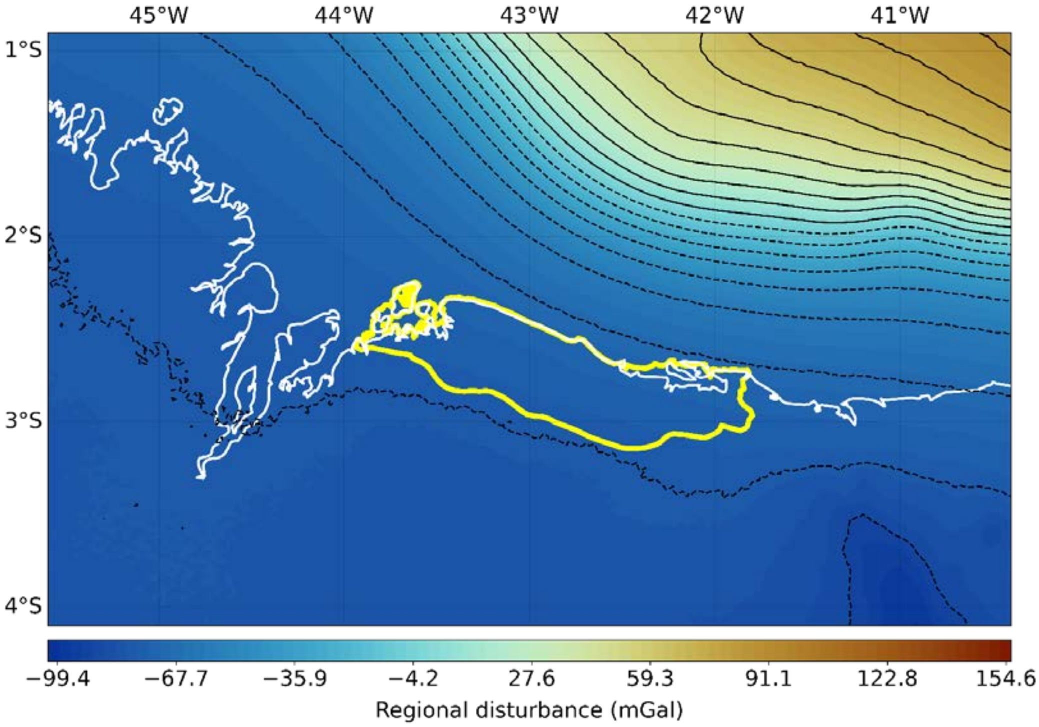

Figure 10 – Map of the Regional Bouguer disturbance from the Airy model. The white line is the coastline, and the yellow line is the contour of the Barreirinhas basin.

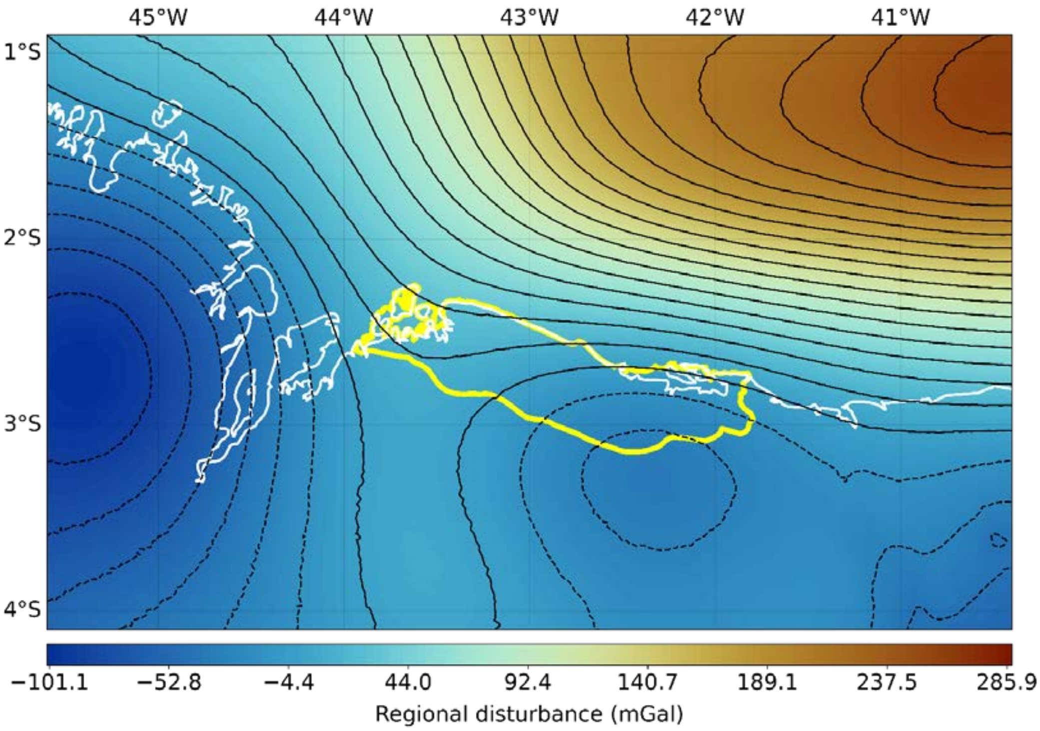

Figure 11 – Map of the Regional Bouguer disturbance from the GEMMA model. The white line is the coastline, and the yellow line is the contour of the Barreirinhas basin.

Upon evaluating the regional map generated from the seismic model (see Figure 12), discernible geological structures are challenging to identify, as the map displays a distinct trend compared to the others. Notably, the regional data exhibits negative values ranging from -119 mGal over the continent to 54 mGal over the ocean, contrary to expectations. While this shift in trend may suggest variations in physical properties, it hampers the identification of structural faults and lineaments, resembling the pattern observed in the Airy regional map.

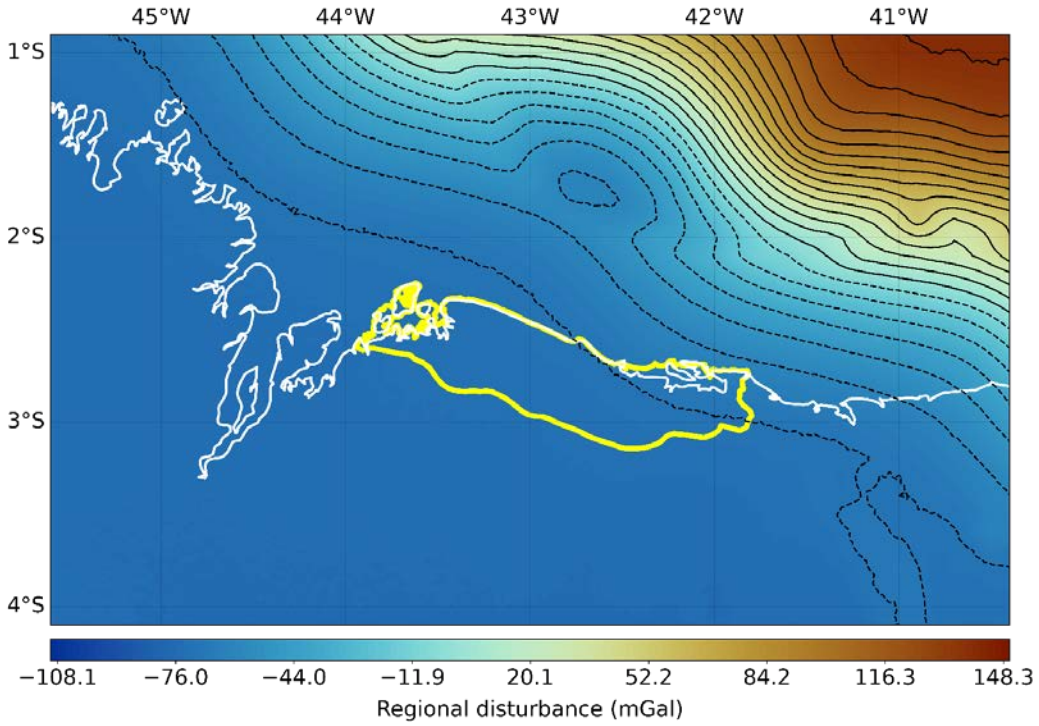

Figure 12 – Map of the Regional Bouguer disturbance from the seismic model. The white line is the coastline, and the yellow line is the contour of the Barreirinhas basin.

Figure 13 showcases a regional signal similar to that depicted in the GEMMA results. However, the regional gravity data computed using the South American Moho model appears smoother across continental and oceanic regions. Furthermore, it displays a consistent SW-NE directional pattern. Notably, tectonic structures and structural faults near the continental-oceanic transition zone are evident. Both regional maps exhibit data ranging from -115 to 88 mGal, mirroring the offset observed in the GEMMA model results. This deviation may be suggestive of the superior performance of the South American Moho model, boasting higher resolution (0.2º x 0.2º) compared to the GEMMA model (0.5º x 0.5º).

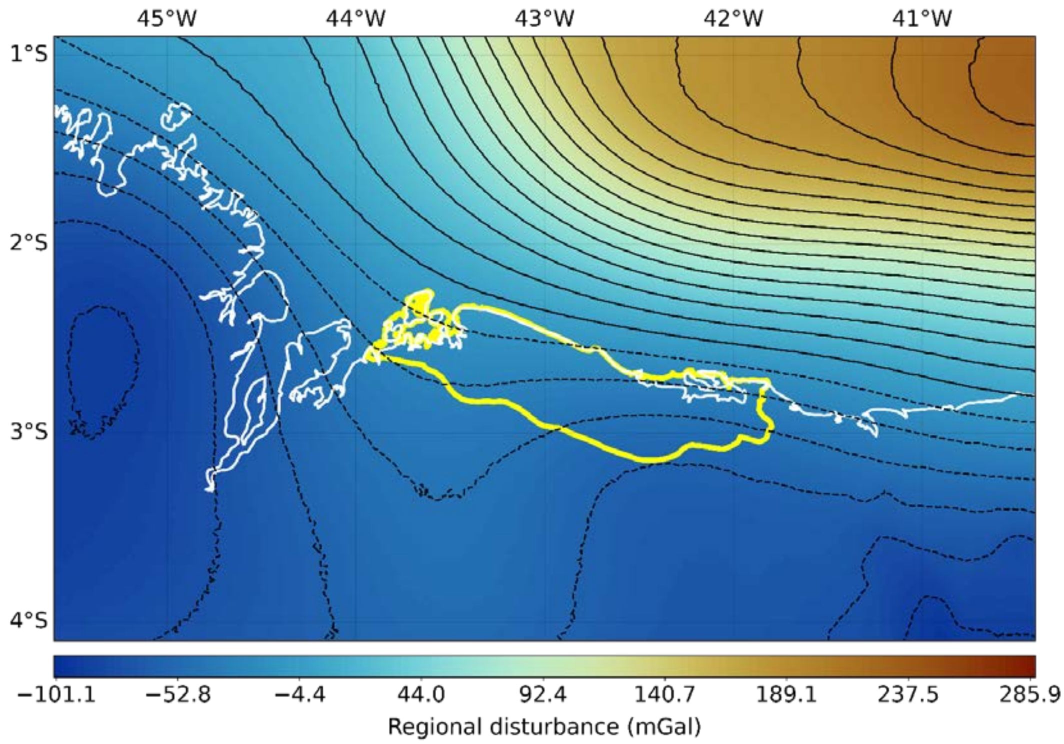

Figure 13 – Map of the Regional Bouguer disturbance from the South American model. The white line is the coastline, and the yellow line is the contour of the Barreirinhas basin.

Residual anomaly analysis

The residual map derived from the Airy Moho depth computation (see Figure 14) outperforms the regional data.

Given that the Airy depth reflects topography, the residual map fails to delineate faults and lineaments, such as the Pirapemas lineament and Sobradinho Platform (Almeida-Filho et al., 2009), as well as the contours of the Barreirinhas and São Luis basins. However, it does reveal fault tendencies at the continental-oceanic transition zone where the two-lobed pattern emerges in the Free-air data. This signature typically arises when the Moho undergoes abrupt changes.

Therefore, in this specific scenario, the residual data from the Airy model is reasonably accurate, particularly in capturing Moho variations, despite the lower intensity observed in the São Luis and Barreirinhas basins. However, it is essential to note that these low-intensity values may be misconstrued with adjacent negative values, potentially obscuring fault and depocenter zones within the Barreirinhas Basin.

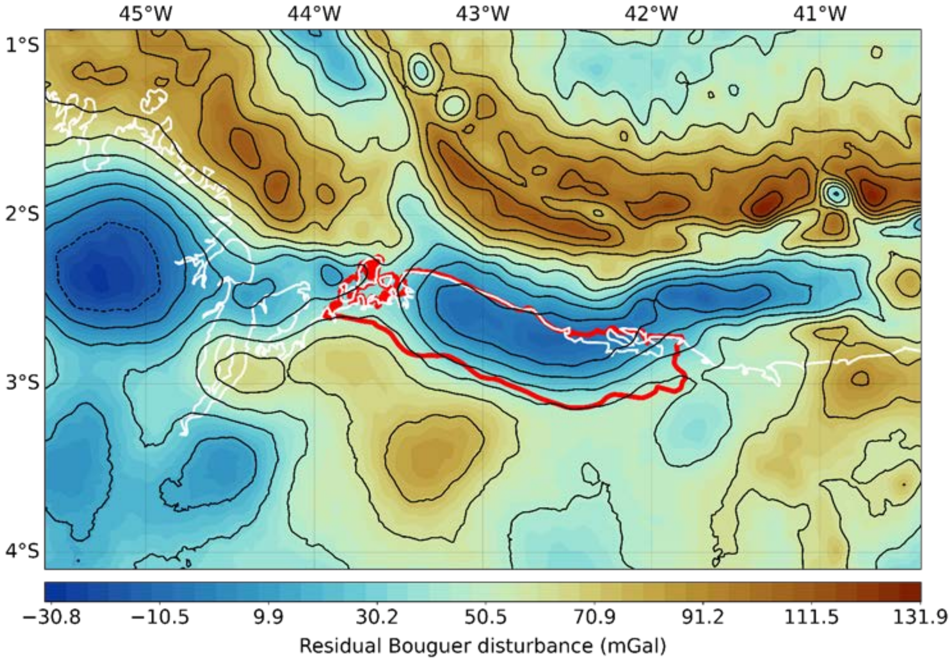

Figure 14 – Map of the Residual Bouguer disturbance from the Airy model. The white line is the coastline, and the red line is the contour of the Barreirinhas basin.

Figure 15 obtained by using GEMMA model portrays a predominantly negative zone at the continent-ocean boundary encompassing the Pará–Maranhão, Barreirinhas, and Ceará basins. Notably, the regions with negative values within the ocean correlate with structural faults and existing basins (blue lines). The green lines on the continental portion denote the presence of the Pirapemas Lineament, characterized by a positive anomaly. Furthermore, a negative oblong signature is discernible within the Barreirinhas Basin, located near 43º W and 2.5º S. This oblong shape potentially signifies the crustal depocenter, a feature highlighted by (Almeida-Filho et al., 2009).

The deep-seated nature of this structure aligns with gravity and seismic data, thus providing further validation of its significance. The residual map derived from the seismic model, depicted in figure 16, presents intriguing characteristics. While the regional data aligns well with the Airy regional model, the residual map exhibits a predominance of positive values, contrasting with other maps. However, upon closer examination of the contours and shape of the residual data, we observe lower values corresponding to the Barreirinhas and São Luis basins. Additionally, there is a noticeable change in intensity at the continent-oceanic transition zone, consistent with expectations.

Upon meticulous examination of the residual map derived from the South American model (see Figure 17), it becomes apparent that structural faults and lineaments exert a discernible influence on the gravity data, delineating pronounced signatures. Tectonic lineaments are predominantly discerned within the positive domain of the map, alongside gravimetric and magnetic lineaments, primarily oriented in the SW-NE direction. A gravity lineament located near the boundary of the Barreirinhas Basin, around latitude 2.5º S, appears to be connected to the basin's structural limits or possibly influenced by them, which requires careful analysis to confirm this relationship.

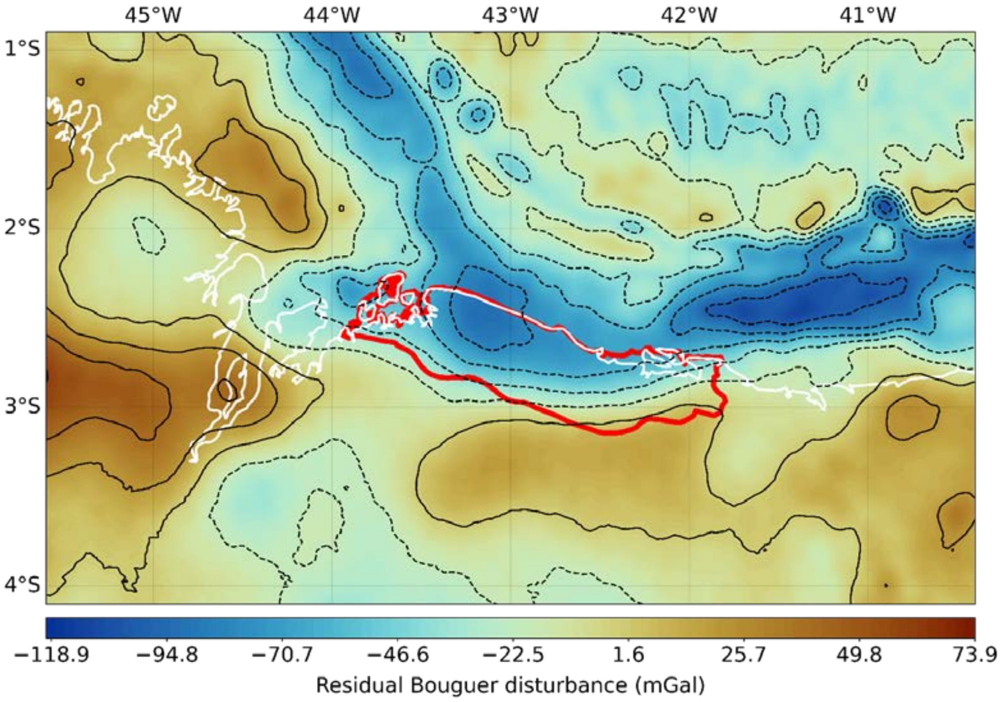

Figure 15 – Map of the Residual Bouguer disturbance from the GEMMA model. The white line is the coastline, and the red line is the contour of the Barreirinhas basin.

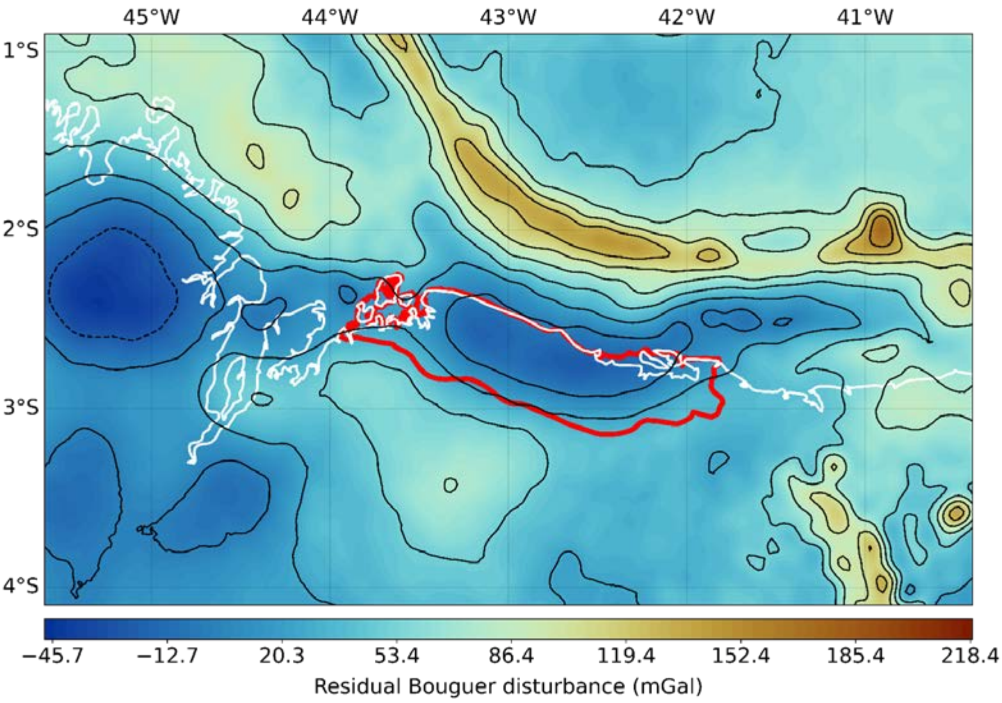

Figure 16 – Map of the residual Bouguer disturbance from the seismic model. The white line is the coastline, and the red line is the contour of the Barreirinhas basin.

Upon meticulous examination of the residual map derived from the South American model (see Figure 17), it becomes apparent that structural faults and lineaments exert a discernible influence on the gravity data, delineating pronounced signatures. Tectonic lineaments are predominantly discerned within the positive domain of the map, alongside gravimetric and magnetic lineaments, primarily oriented in the SW-NE direction. A gravity lineament located near the boundary of the Barreirinhas Basin, around latitude 2.5º S, appears to be connected to the basin's structural limits or possibly influenced by them, which requires careful analysis to confirm this relationship.

Furthermore, structural faults along the continental-oceanic boundary manifest as negative anomalies, evocative of crustal density and depth changes. This spatial distribution exhibits resemblances to the residual map derived from the

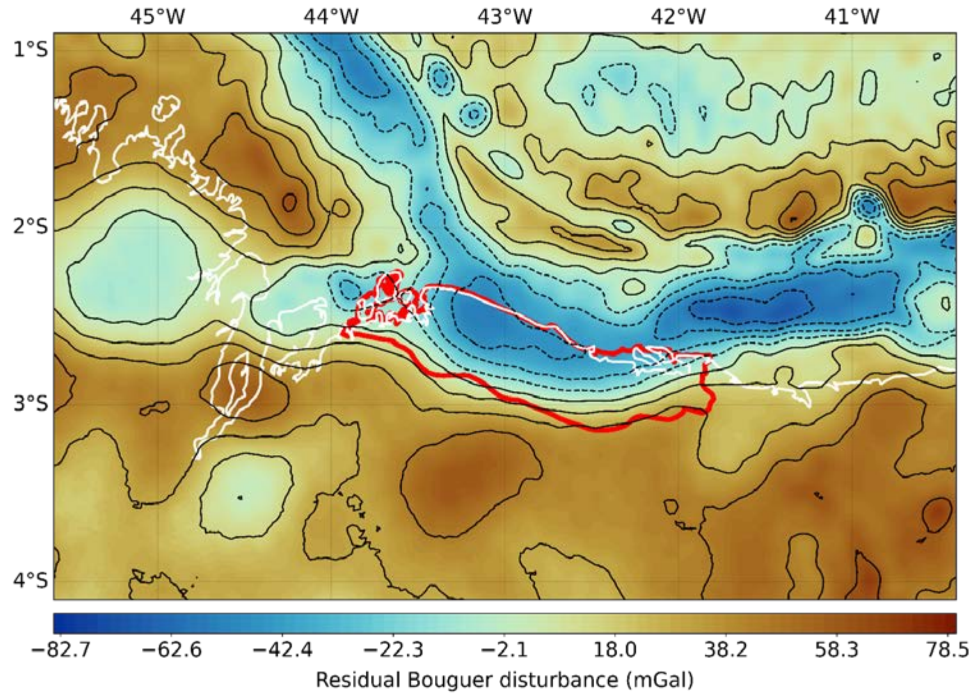

Figure 17 – Map of the Residual Bouguer disturbance from the South American model. The white line is the coastline, and the red line is the contour of the Barreirinhas basin.

GEMMA model. Moreover, upon closer inspection of the signature within the Barreirinhas Basin, small-scale anomalies are discernible, confined within geological fault zones. However, the anticipated crustal depocenter situated at 43º W and 2.5º S manifests as a slightly altered small-scale circular anomaly, albeit with diminished intensity compared to initial expectations

A comparative profile of the residual Bouguer disturbance was generated along the same transect extending from coordinates (-43.5°, -3.0°) to (-42.5°, -2.5°), aiming to assess the behavior of the computed residual signals for each Moho model. The analysis reveals that all four curves exhibit a consistent minimum anomaly precisely at the point corresponding to the crustal depocenter of the Barreirinhas basin. This alignment among the Airy, GEMMA, South American, and seismic residuals confirms that the chosen transect effectively intersects the basin's deepest crustal portion, as shown in figure 19.

Despite the similarity in the location of the minimum, the amplitude of each anomaly differs slightly, which can be attributed to computational constants, density assumptions, and regional model parameters inherent to each approach. Such amplitude discrepancies, although minor, highlight the importance of conducting a refined geophysical inversion to more accurately constrain the density–depth relationship and the true extent of the depocenter. Overall, the coherence among the models reinforces the structural interpretation of the region, where the residual signal minimum reliably marks the position of the crustal depocenter.

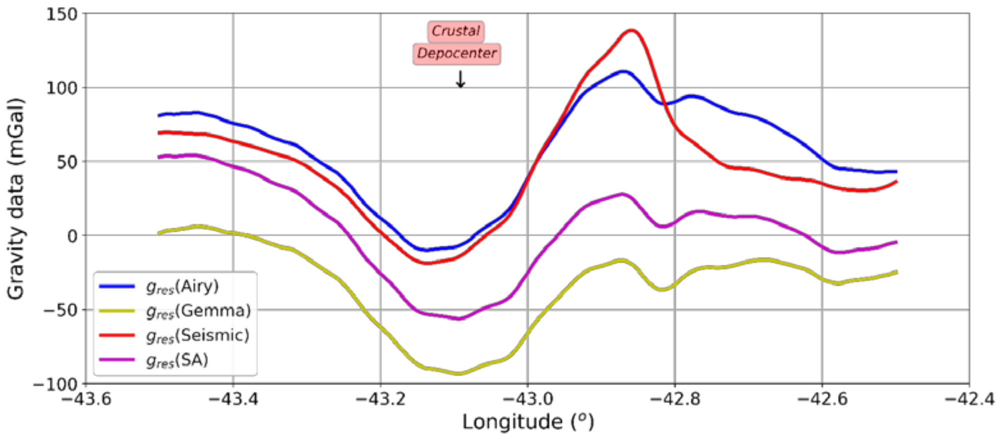

Figure 18 – Residual gravity Bouguer disturbance profile at the Barreirinhas basin, by using Airy (blue line), GEMMA (yellow line), seismic (red line) and South American (pink line) models.

FINAL REMARKS

In this study, we underscored the critical importance of employing regional-residual separation techniques for robust geophysical and geological interpretation, particularly in complex regions like the Barreirinhas Basin situated at the continental-oceanic boundary, characterized by the presence of numerous faults and structural lineaments.

These geological features could potentially obscure the primary interpretation, making it imperative to apply a rigorous methodology. By utilizing Free-air and Bouguer gravity disturbance data, we managed to identify both negative and positive anomalies. The low-intensity data corresponded to responses from existing basins in the Brazilian equatorial margin, including the São Luis, Barreirinhas, and northern parts of the Parnaíba terrestrial basins, as well as the Pará–Maranhão, Barreirinhas, and Ceará basins in the oceanic realm.

Conversely, positive anomalies highlighted the influence of the Serra Grande and marked abrupt changes in crustal depth at the continental-oceanic transition zone. Given the potential complications posed by the two-lobe signature observed in Free-air disturbance data at the continental boundary, we opted to use Bouguer gravity disturbance data for the regional–residual application to ensure more reliable results and facilitate interpretation.

In terms of geophysical interpretation, all regional maps exhibited a consistent pattern, demonstrating an intensity increase in the SW-NE direction. This trend indicates that the crust is thicker and deeper in the continent, while it is shallower and thinner in the oceanic regions. However, it's noteworthy that the regional map derived from the Airy model displayed lower intensity when compared to others, likely due to the direct calculation of Moho depth. Moving on to the residual Bouguer maps, they exhibited some similarities across different models.

For instance, the residual map generated from the Airy model revealed structural faults within the Barreirinhas Basin, isolated the negative anomaly associated with the São Luís basin, and highlighted a gravimetric lineament in the central part of the map. Similarly, the residual map from the GEMMA model demonstrated compatibility, enabling the identification of an isolated anomaly within the Barreirinhas Basin, interpreted as a crustal depocenter.

Comparatively, the results obtained from the seismic Moho model resembled those from the Airy model, albeit with differences in intensity. The residual map derived from the seismic model exhibited negative values, which is unusual for shallower Moho depths. However, this negative pattern could be evocative of geological faults and lineaments present in continental and oceanic areas.

On the other hand, the residual map from the South American Moho model showed inconsistencies in identifying structures within the Barreirinhas Basin. Nonetheless, it effectively emphasized structural faults in continental and oceanic regions, shedding light on potential fault reactivation. In summary, we conclude that the GEMMA model provided a superior interpretation and description of the Barreirinhas Basin. Moreover, the South American Moho model highlighted anomalies associated with faults, lineaments, and features linked to the continental-oceanic boundary.

Finally, we propose an interpretation based on the behavior of elastic thickness, considering that Free-air gravity data can be associated with isostatic equilibrium. We also posit that isostatic anomaly could be equally effective as Bouguer disturbance data. Consequently, we advocate for a geophysical inversion approach to estimate the effective elastic thickness. This methodology could enhance the results and provide insights into whether the reactivation of faults is a plausible consideration for future research endeavors.

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