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CHARACTERIZATION OF THE POTIGUAR RIFT STRUCTURE BASED ON EULER DECONVOLUTION

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ABSTRACT. The Euler deconvolution is a semi-automatic interpretation method of potential field data that can provide accurate estimates of horizontal position and depth of causative sources. In this work we show the application of 3D Euler Deconvolution in gravity and magnetic maps to characterize the rift structures of the Potiguar Basin (Rio Grande do Norte and Ceará States, Brazil) using the structural index as a main parameter, which represents an indicator of the geometric form of the anomalous sources. The best results were obtained with a structural index equal to zero (for residual gravity anomalies) and 0.5 (for magnetic anomalies reduced to the pole), a spatial window size of 10 km, which is used to determine the area that should be used in the Euler Deconvolution calculation, and maximum tolerance of error ranging from 0 to 7%. This parameter determines which solutions are acceptable. The clouds of Euler solutions allowed us to characterize the main faulted limits of the Potiguar rift, as well as its depth, dip and structural relations with the Precambrian basement.

Keywords: Euler deconvolution, potential field, structural index, Potiguar rift.

RESUMO. A deconvolução de Euler é um método de interpretação semiautomático de dados de métodos potenciais, capaz de fornecer uma estimativa da posição horizontal e da profundidade de fontes anômalas. Neste trabalho, mostraremos a aplicação da deconvolução de Euler 3D em mapas gravimétricos e magnéticos para caracterizar as estruturas rifte da Bacia Potiguar (RN/CE), utilizando como principal parâmetro o índice estrutural, que representa um indicador da forma geométrica da fonte anômala. Os melhores resultados foram obtidos com um índice estrutural igual a zero (para as anomalias gravimétricas residuais) e 0,5 (para as anomalias magnéticas reduzidas ao polo), tamanho da janela espacial igual a 10 km, que é utilizada para determinar a área que deve ser usada para o cálculo da deconvolução de Euler, e tolerância máxima do erro variando de 0 a 7%, que determina quais soluções são aceitáveis. As nuvens de soluções de Euler nos permitiram caracterizar os principais limites falhados do rifte Potiguar, bem como suas profundidades, mergulho e relações estruturais com o embasamento Pré-cambriano.

Palavras-chave: deconvolução de Euler, métodos potenciais, índice estrutural, rifte Potiguar.

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INTRODUCTION

From the 1970s, effective and rapid methods for automatic interpretation of aeromagnetic data were developed to identify anomalous sources in the subsurface. These methods are being applied to a vast amount of magnetic data collected over a few million flight lines, surveyed by various international governmental agencies and private companies (Barbosa & Silva, 2005). These methods are:

a) the Werner deconvolution, proposed for separating magnetic anomalies, especially "fine dikes", which was expanded to other models (Hartman et al., 1971; Ku & Sharp, 1983);

b) the Naudy method (Naudy, 1971), used to determine depth of sources shaped as plates and vertical prisms in aeromagnetic profiles;

c) the CompuDepth method (O'Brien, 1972), developed to calculate source depths based on the property that the horizontal and vertical derivatives of the magnetic field are the Hilbert transform of each other; and

d) the Euler deconvolution (Thompson, 1982) to determine the depths of magnetic and gravity sources.

This latter method has been extended for the 3D case by Reid et al. (1990), based on the Euler equation. Among these methods, the Werner and Euler deconvolutions are the most commonly used (Barbosa & Silva, 2005). According to these authors, from the 1990s, the Euler deconvolution has become the method most used worldwide for automatic, magnetic and gravimetric interpretation.

The tridimensional Euler method or 3D Euler uses regular grids of data, defining a spatial window that scans the whole area, and solves the systems of equations for each window. The solutions are filtered, so only those that meet certain prerequisites are accepted (Munis, 2009). The valid solutions are placed in a database and subject to new selection criteria, to be interpreted. Eliminating unnecessary solutions may result in more accurate results, using as selection criteria the dimension of the anomalous source and previously known geological information.

The Euler deconvolution uses the structural index as a parameter. This exponential factor corresponds to the rate at which the gravity or magnetic anomaly field decreases with distance, for a given geometry source and measurement point. The choice of the spatial window size is another important parameter for the successful implementation of the method (Munis, 2009). It is used to determine the area that should be used to calculate the Euler deconvolution, wherein the solution of the system of equations indicates the local of a particular source. The structural index and the spatial window will be chosen based on target structures, corresponding to the rift structures of the Potiguar Basin, in this study.

POTIGUAR BASIN

The Potiguar Basin is part of a series of small to medium-sized rift basins in northeastern Brazil. It is embedded in the northern portion of the Borborema Province (Fig. 1), being controlled by a system of NE-SW trending rifts, and developed along the Cariri-Potiguar rifting axis (Matos, 1992). Its tectonic evolution is related to the development of the Equatorial and South Atlantic margins, which began at the end of the Jurassic under strong influence of the zones of weakness printed in its Precambrian basement (Françolin & Szatmari, 1987).

Matos (1987) proposes that the rheological stratification of the Borborema Province was a major factor defining the geometry and evolution of the basins formed there, when extensional stress began to predominate from the Silurian and on. The same extensional stress system gave origin to intracontinental rifts formed as a response to the stretching and crustal thinning processes (De Castro et al., 1998), active in the region during the fragmentation of the Gondwana continent in the Jurassic to Cretaceous. Thus, it is possible to highlight the influence of crustal heterogeneities on the structural control and tectonosedimentary evolution of the rift basins, with the reactivation of a previously deformed continental lithosphere (De Castro et al., 2012). The structural inheritance of the Precambrian basement continues to influence the recent tectonic activity on the basin areas that transcend the rift portion (Nogueira et al., 2006).

The basement of Potiguar Basin lies inside the Rio Grande do Norte domain (Fetter et al., 2000). This domain is situated between the Senador Pompeu shear zone to the west, and the Patos lineament to the south. It includes several small areas or subdomains; (from W to E) the Paleoproterozoic supracrustal sequences of the Orós-Jaguaribe Belt (Parente & Arthaud, 1995) and its basement, the Rio Piranhas massif, the Seridó Fold belt and its basement (Brito Neves et al., 2000), the São José do Campestre massif (Dantas, 1997; Dantas et al., 2004). It is also observed the occurrence of a long migmatite-gneiss complex, the Caicó complex, and large amounts of granitic bodies of Neoproterozoic age.

The onshore Potiguar Basin exhibits a structural style controlled by an extensional tectonic regime, which gives the region

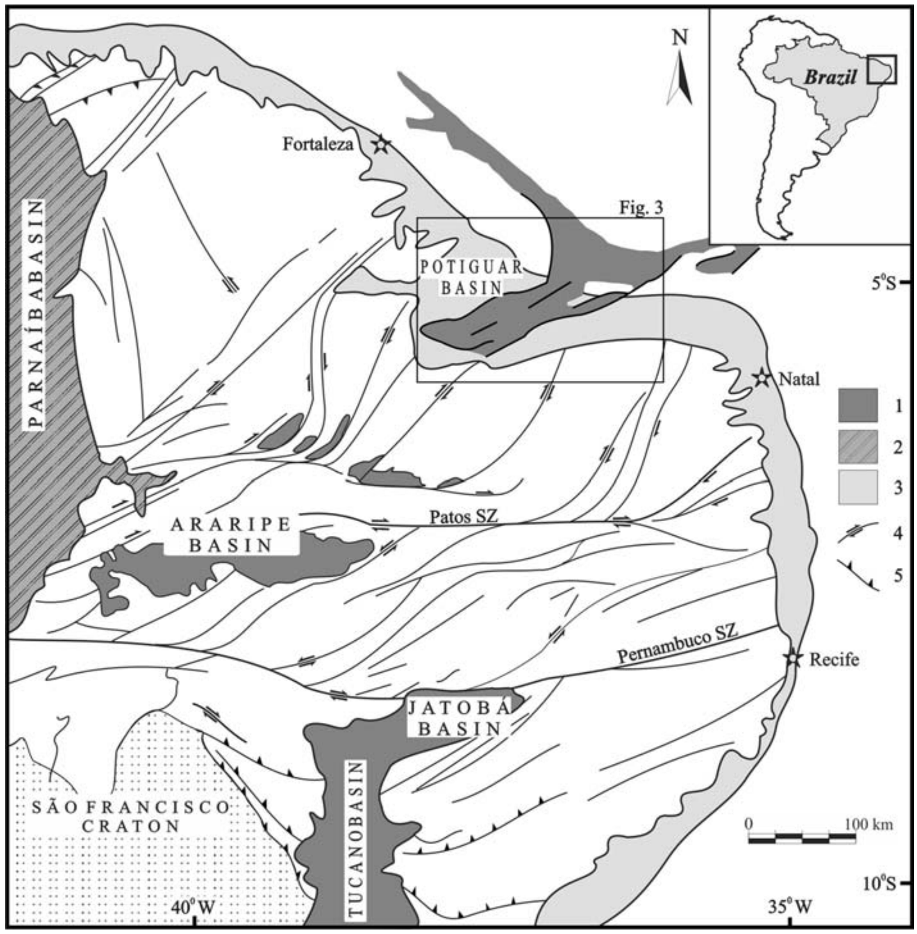

Figure 1 – Simplified geological map of the Borborema Province and sedimentary basins in northeastern Brazil (modified from De Castro et al., 1998). The Mesozoic structures in the Potiguar Basin were obtained from Matos (1992). (1) Cretaceous rift basins; (2) Paleozoic sedimentary sequences; (3) Recent sedimentary cover; (4) Shear zones; (5) Thrust zones.

a framework composed of system of horsts (internal highs) and grabens oriented according to the structural NE-SW trend (Fig. 2). The internal structures of the rift are governed primarily by the anisotropy zones of the basement (Bertani et al., 1990).

The Apodi, Umbuzeiro, Guamaré and Boa Vista grabens, located in the onshore portion of the basin, are filled with sedimentary sequences of the Early Cretaceous. They display asymmetric shape and linear NE-SW features, bordering NW and SE by faults that exceed 5,000 m of throws. Offshore, the grabens are also asymmetric, with axes subparallel to the coast line (Bertani et al., 1990). The internal highs consist of elongated crests of the basement, separating the main grabens. The horsts of Quixaba, Serra do Carmo and Macau represent the main internal highs of the basin, being composed of blocks of gneisses, migmatites and schists uplifted by normal faults, and subparallel to the axes of the adjacent grabens. Normally, no Lower Cretaceous sequences occur on the structural highs due to erosion or non-deposition (Bertani et al., 1990).

METHODOLOGY

The solutions of the 3D Euler deconvolution in this work are based on a semi-quantitative processing, to determine the depth and behavior of gravity and magnetic sources. The apparent depth of a potential source is derived from the homogeneity of the Euler equations. This technique developed by Thompson (1982) considers the magnetic or gravity anomaly $T \equiv T(x, y, z)$ corrected from an additive constant regional field and produced by a 3D point source located in the Cartesian coordinates, x_0, y_0, z_0. The anomaly satisfies the homogeneous 3D Euler equation (Reid et al., 1990).

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = -nT \quad (1)$$

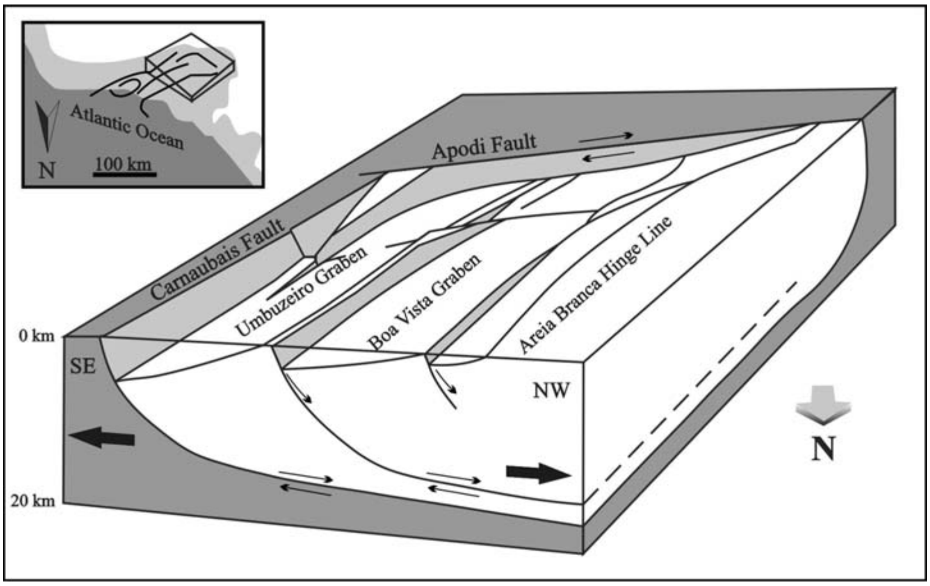

Figure 2 – Internal architecture of the anshore Potiguar rift Basin proposed by Matos (1992) (modified from Dantas, 1998).

n is the structural index; T, the value of the function (magnetic or gravity field); x and y, coordinates of the measuring point; z, source depth; $\partial T/\partial x$, $\partial T/\partial y$ and $\partial T/\partial z$, the first partial field derivatives; and x_0, y_0 and z_0, the source coordinates. The structural index is an exponential factor that corresponds to the decay rate of the potential field as a function of the distance between the source and the measurement point (Barbosa & Silva, 2005). This parameter is an indicator of the geometric shape of the anomalous source. Table 1 summarizes the structural indices of models with simple geometry for magnetic and gravity anomalies.

Table 1 – Structural indices for magnetic and gravity fields.

Structural index	Magnetic field	Gravity field
0	Contact	Sill/Dike/Fault
0.5	Fault (large step)	Fine dike
1	Sill/Dike	Horizontal cylinder
2	Horizontal cylinder	Sphere
3	Sphere	—

Although the structural index can be treated as an unknown, it is best to fix the value of n and calculate only the location of the causative source in x_0, y_0 and z_0 (Munis, 2009). Selecting the correct structural index is crucial to achieving success when applying the technique (Reid, 1995). Despite the fact that the Euler deconvolution displays good location for horizontal sources, an error in choosing the structural index can cause both inaccuracy in determining the depth of the sources (Ravat, 1996; Barbosa et al., 1999; Nogueira, 2008) and the dispersed solutions, associated with isolated anomalies (Silva et al., 2001).

GEOPHYSICAL DATA

The gravity data of the Potiguar Basin comprises data from several surveys conducted by universities, public agencies and private companies. This gravity database is described in detail by Osako et al. (2011). These data, already corrected for the non-geological effects in the gravitational field, were interpolated on a regular 500-m grid, using the kriging method. The residual component was separated from the regional field through a spectral filter with Gaussian distribution, with a cutout frequency of 0.02 cycles/m. Figure 3a shows the residual gravity anomalies map of the Potiguar rift.

The magnetic data are from the Potiguar Basin and the Northeast Continental Shelf projects, obtained from the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP). The Northeast Continental Shelf Project was conducted in the 1970s, along NE-SW, spaced 500 m lines, in a nominal fly height of 700 m. The original magnetic maps were digitized and provided by ANP in a regular 500 m grid. The data of the Potiguar Basin project were raised between 1986 and 1987, along N20°W trending lines, spaced 2 to 4 km and a nominal fly height of 500 m (MME/CPRM, 1995). The magnetic data were interpolated using a bi-directional method on a regular 500 m grid and upward continued to 700 m.

The magnetic maps of the two surveys show major discrepancies in the overlapping areas. These differences were mitigated using reduction to the pole of the two data sets separately before integration. Because it is a region of low magnetic latitude,

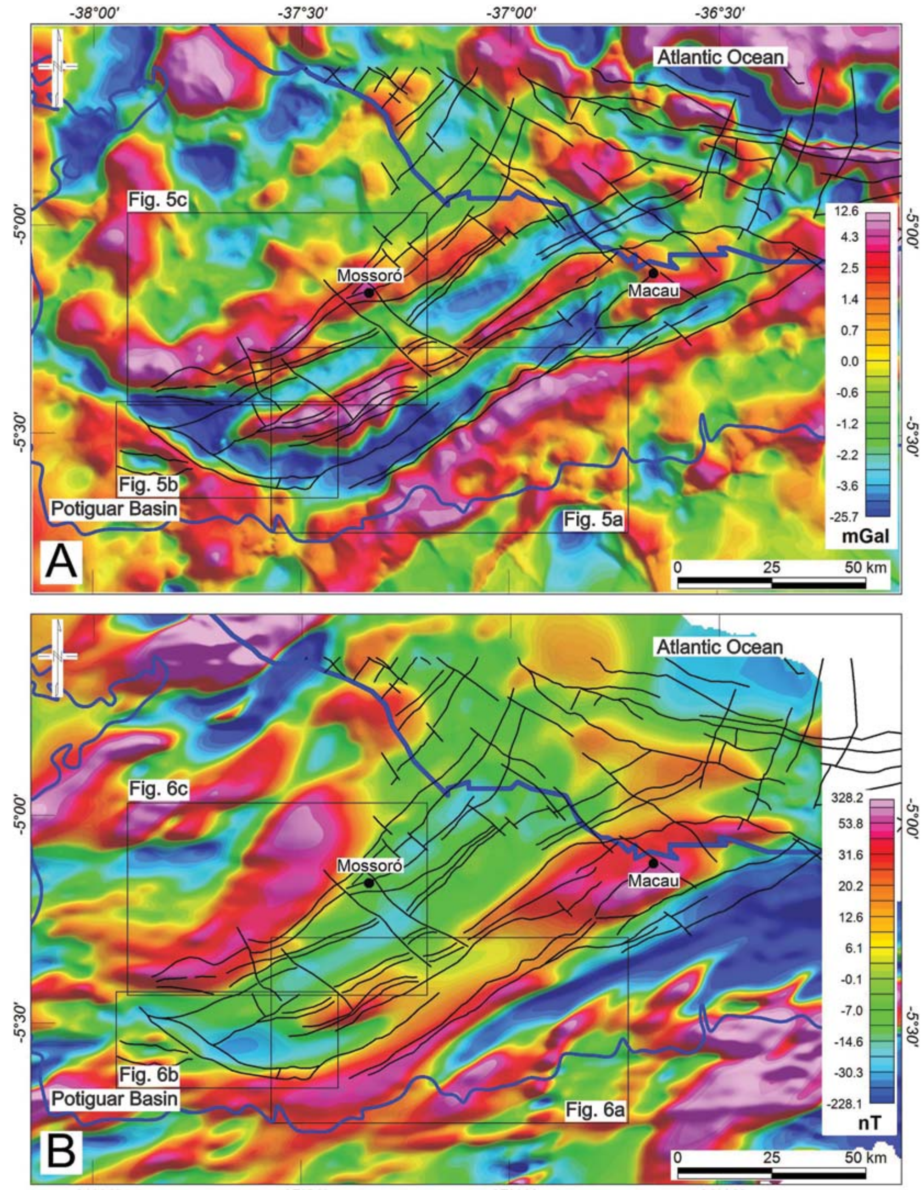

Figure 3 – Residual gravity (A) and reduced to the pole magnetic (B) anomalies maps, showing the structural features of the Potiguar rift.

the pseudo-inclination method was used to stabilize this operation in the frequency domain and eliminate the artifacts in the direction of magnetic declination (Blakely, 1996; Li, 2008). This operator does not fully reconstitute the amplitude of the magnetic signal, if it were obtained in the magnetic pole, but works properly in its phase, focusing the magnetic anomalies over their sources. And considering that the quantitative methods for magnetic sources detection, such as Euler deconvolution, act independently of the directions of magnetization and acquisition of the magnetic anomalies (Li, 2008), we chose to integrate the reduced to the pole (RTP) data from the two aeromagnetic surveys to a single database, generating a map of the total magnetic intensity reduced to the pole (Fig. 3b).

The 3D Euler deconvolution was then applied to the residual gravity and reduced to the pole magnetic anomalies of the Potiguar rift region (Fig. 4). In this study, the main objective of the Euler solutions is to enable the in-depth mapping of the faulting systems that define the faulted edges of the rift. Accordingly, the best combination of parameters to determine the Euler solutions was obtained for a structural index of zero for the residual gravity anomalies, and 0.5 for the reduced to the pole magnetic anomalies. These structural indices correspond to faults, as shown in Table 1. The spatial window size was chosen equal to 10 km, which is 20 times the spacing of the gridded data. This parameter is used to determine the area that should be used to calculate the Euler deconvolution. The maximum error tolerance chosen was 7% for both magnetic and gravity data. This limit provides solutions which are acceptable for the estimated geological context. Both the spatial window size and maximum error tolerance were chosen interactively by trial and error, analyzing the results generated for each variation of these parameters.

RESULTS AND DISCUSSION

The Euler solutions for the reduced to the pole and residual anomalies show clouds of the magnetic and gravity sources, respectively, concentrated along the major fault system of the Potiguar rift (Fig. 4). The rift borders are well marked by the alignment of Euler solutions, especially at the eastern (Carnaubais fault), southern (Baixa Grande and Apodi faults) and western (Mulungu fault and Areia Branca hinge line) limits (1 to 5 in Fig. 4), as well as major grabens, related to areas with a scarcity or absence of solutions (A to E in Fig. 4). The clusters of Euler solutions exhibit NE-SW trends, following the main direction of the Cariri-Potiguar rifting axis, described by Matos (1992).

Clouds of Euler Solutions

The main faults of the Potiguar rift edges over the clouds of gravity and magnetic Euler solutions are shown in Figure 4. At the eastern edge of the rift (1 in Fig. 4a, b), these maps reveal a set of NE-SW trending fault segments, which forms the Carnaubais fault system and limits the Umbuzeiro and Guamaré grabens (A and E in Fig. 4a, b). These are listric normal faults, with inflection in the SW segment, in addition to another group of faults, classified as ENE-WSW trending transfer faults. They correspond to previous transfer segments, which were reactivated as dextral transfer faults during the Brasiliano cycle (Bertani et al., 1990).

The southern and southeastern boundaries of the rift are marked by a NW-SE oriented zone of Euler solutions, bending to NE-SW, at its eastern end. In this region, the Apodi Graben (B in Fig. 4a, b) is delineated by the Apodi and Baixa Grande faults (2 and 3 in Fig. 4a, b), trending to NW-SE and NE-SW, respectively (Bridges, 2005). Matos (1992) describes the combination of these two fault systems as an extensional triangular wedge, with the NW-SE segment of the Apodi fault characterized as a transfer fault to the tectonic efforts that formed the Potiguar rift (Hoerlle et al., 2007). In the magnetic Euler solutions map, the Apodi fault is represented by a segment sectioned by secondary normal faults, which were related to the presence of a crestal collapse graben by Hoerlle et al. (2007).

Likewise, the western boundary of the rift consists of a flexural edge (the Areia Branca hinge line – 5 in Fig. 4a, b), which can be identified by a sinuous narrow strip of NE-SW trending Euler solutions. This hinge zone is affected by ENE-WSW trending normal and dextral transfer faults. There is a shift westward in its SW portion, which is represented by the Mulungu fault (4 in Fig. 4a, b) that limits the northern Apodi Graben, according to Hoerlle et al. (2007).

The central graben of the Potiguar Basin rift (A in Fig. 4) is formed by indiscriminate normal faults, bending in the SW portion. The internal architecture of the rift results from the strong control of the Carnaubais fault in the development of the basin tectonic framework, coupled in the southern limit of the rift with extensive dextral transfer faults, the Baixa Grande and Apodi faults (Matos, 1992) (Fig. 2). These fault systems border the Umbuzeiro, Boa Vista Sul and Norte grabens (A, C and D in Fig. 4a, b), which represent the main depocenters of the onshore Potiguar basin. Additionally, the central graben of the rift can be individualized by the lack of magnetics Euler solutions (Fig. 4b). This response suggests a lack of significant faults in this region, which could generate solutions for the structural index related to fault geometry.

Analysis of Fault Dip

The behavior in subsurface of structural features can be investigated based on the Euler deconvolution for different depth intervals. In the Potiguar rift, the average dips of major edge faults are well represented by both gravity and magnetic Euler solution clouds (Figs. 5 and 6). The set of intervals between the 0.2 and 3.2 km depths best enhances the behavior of the major rift faults.

The Carnaubais fault shows a dip pattern predominantly NNW, smooth on the SW of the fault system and moderate towards NE (Figs. 5a and 6a). This difference is probably due to variations in the fault throw along its entire segment. According to the Euler deconvolution results, the throws are greater in the SW region of the fault, reaching depths of up to 6000 m.

In the southern limit of the Potiguar rift (Apodi and Baixa Grande faults), the Euler solutions describe a NNE dipping segment of the Apodi fault (Figs. 5b and 6b). The Baixa Grande fault has a SW dip, less pronounced toward its limit with the Carnaubais fault and Umbuzeiro Graben. In addition, the Figures 5c and 6c show the Euler solutions cloud for Mulungu fault and Areia Branca hinge line. These structures in the western edge of

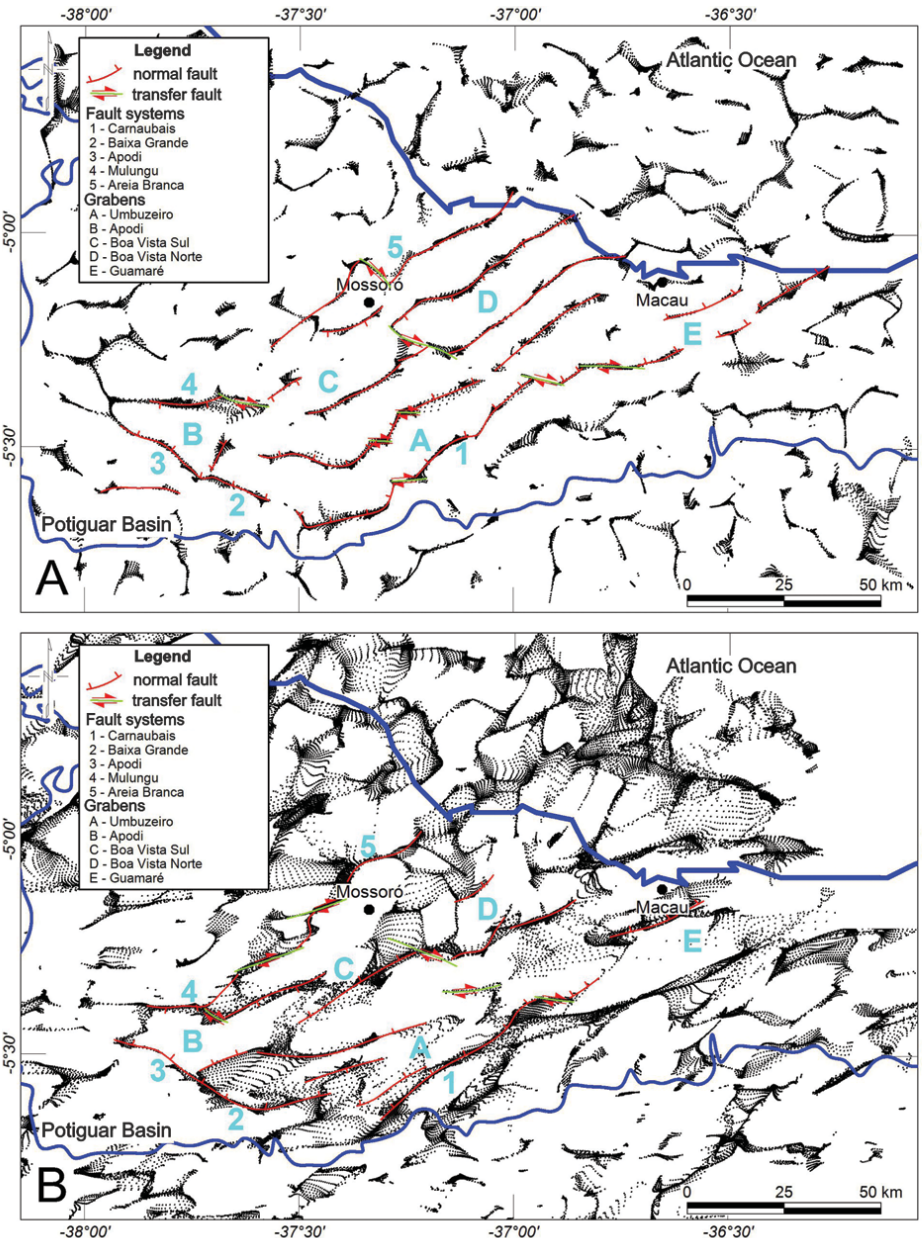

Figure 4 – Map of the Euler solutions for (A) residual gravity and (B) reduced to the pole magnetic anomalies of the Potiguar rift.

the Potiguar rift are characterized by moderate SW dips, along the central and northern segments. In the southern portion, it is gentler in the region of NE-SW transfer faults.

3D distribution of faults

The Euler solutions show that the Carnaubais fault reaches 7000 m deep (1 in Fig. 7), representing the thickest sedimentary infill of the onshore Potiguar Basin. In this portion of the Umbuzeiro Graben (A), the Euler solutions show synthetic faults related to the Carnaubais fault system. There is also an inflection in the SW portion, with throws of approximately 6700 m. The displacements decrease toward NE, and increase again in the transfer fault region. At this site, the throws of the faults system reach values of up to 5300 m.

Clouds of Euler solutions depict geometries of the Apodi and Baixa Grande faults in depth, which represent the southern rift edge (Fig. 8). The Apodi fault (3) shows a strong NW-SE to NE-SW inflection, with about 4500 m throw at the NW edge. The fault displacement decreases SW, towards the intersection with

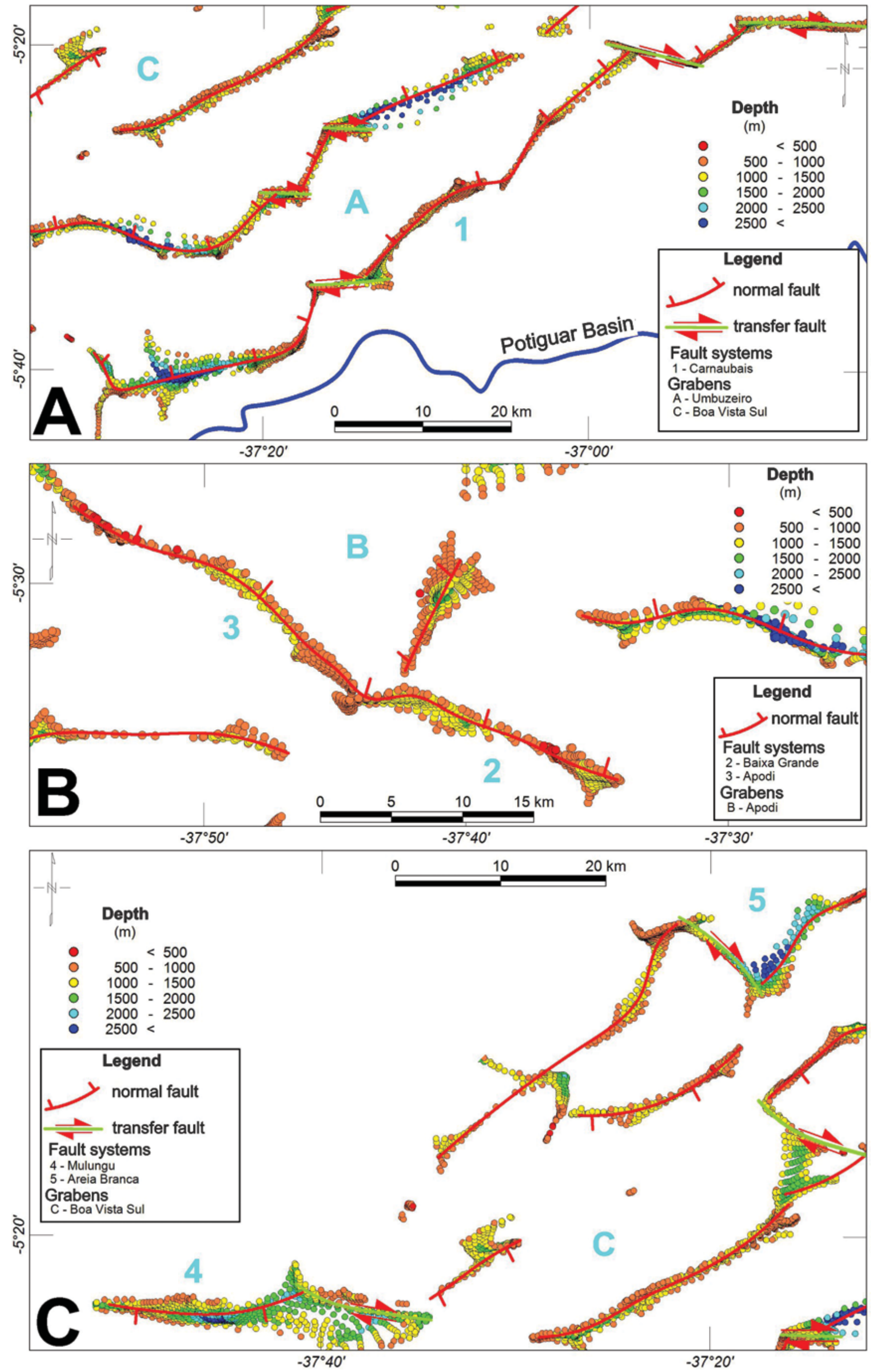

Figure 5 – Maps of structures associated to the Potiguar rift interpreted from gravity Euler solutions, showing major faults and grabens. A – Carnaubais fault; B – Baixa Grande and Apodi faults; C – Mulungu fault and Areia Branca hinge line.

the Baixa Grande fault. In this region, the Baixa Grande fault (2) has throws of 5200 m, with a SW dip. In the NE portion of the fault, the displacements are smaller, at the edge with Umbuzeiro Graben and Carnaubais fault. The decreasing throw of the Baixa Grande fault in this direction coincides with the increased displacement of the Carnaubais fault, which reaches 6700 m in the transfer fault area. Soares (2000) interprets this structural discontinuity as responsible for generating a large relayramp, dipping NE towards the center of the Umbuzeiro Graben (Fig. 9).

The cloud of Euler solutions at the Areia Branca hinge line

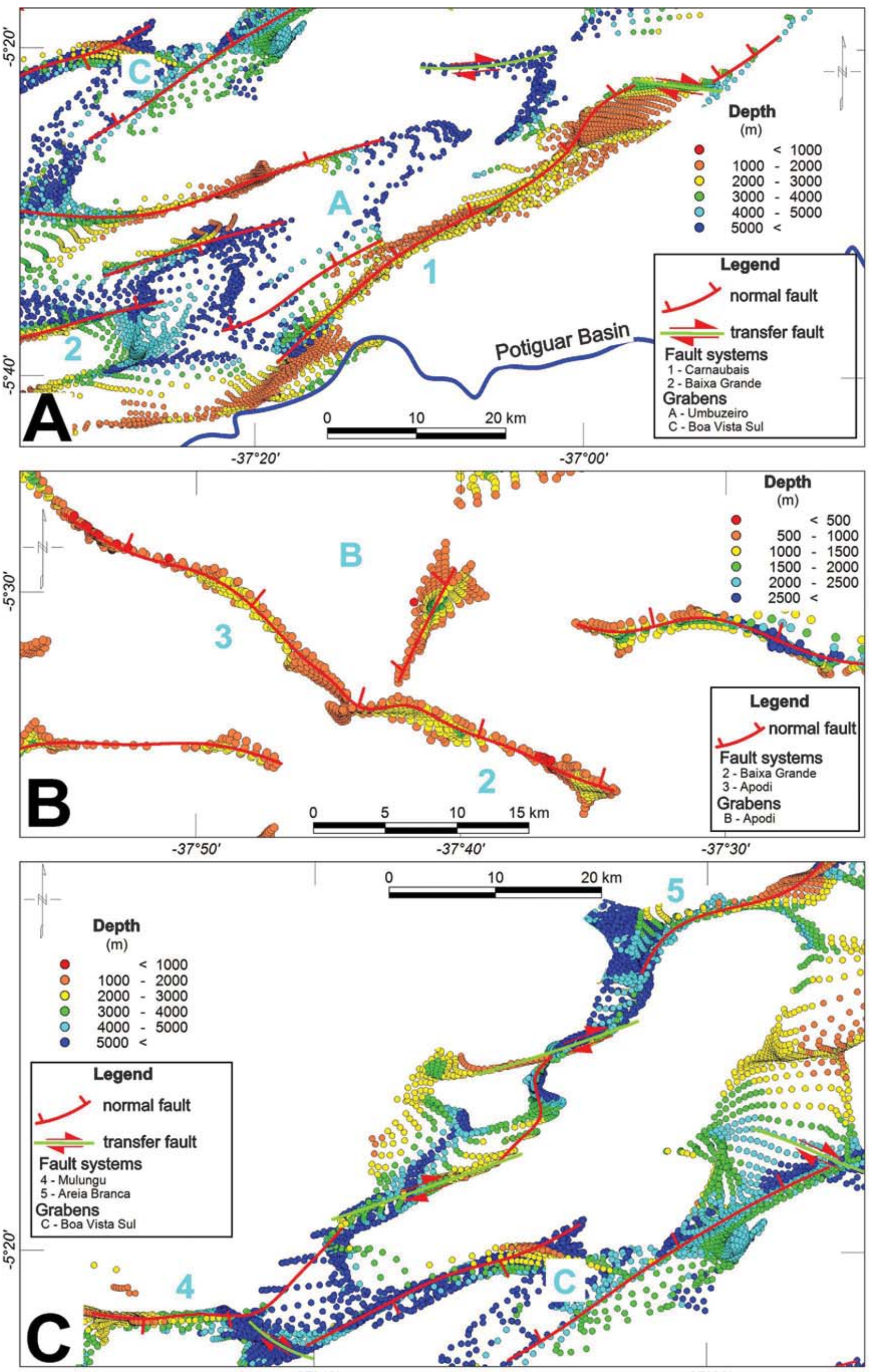

Figure 6 – Maps of structures associated to the Potiguar rift interpreted from magnetic Euler solutions, showing major faults and grabens. A – Carnaubais fault; B – Baixa Grande and Apodi faults; C – Mulungu fault and Areia Branca hinge line.

(5 in Fig. 10) reveals throws of up to 6800 m in the central area, where the transfer faults are observed. The fault displacement decreases NE and increases SE, and extends up to 6600 m at the Mulungu fault (4). In this region, two segments can be identified, with inflections to either NE or SE. The last segment is an antithetic fault.

In the central rift zone, encompassing Boa Vista Sul and Norte grabens (C and D in Figs. 4 to 6), the clouds of Euler

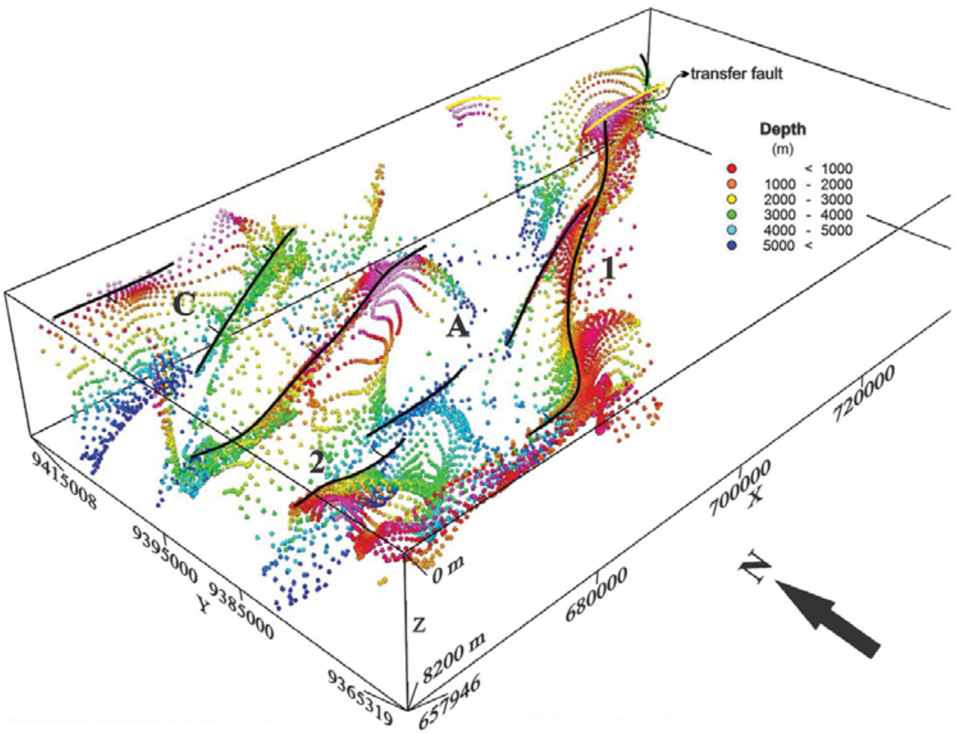

Figure 7 – Distribution of the magnetic Euler solutions at the eastern edge of the Potiguar rift. (1) Carnaubais fault; (A) Umbuzeiro Graben; (C) Boa Vista Sul Graben. Coordinates UTM: SAD69, MC-39°.

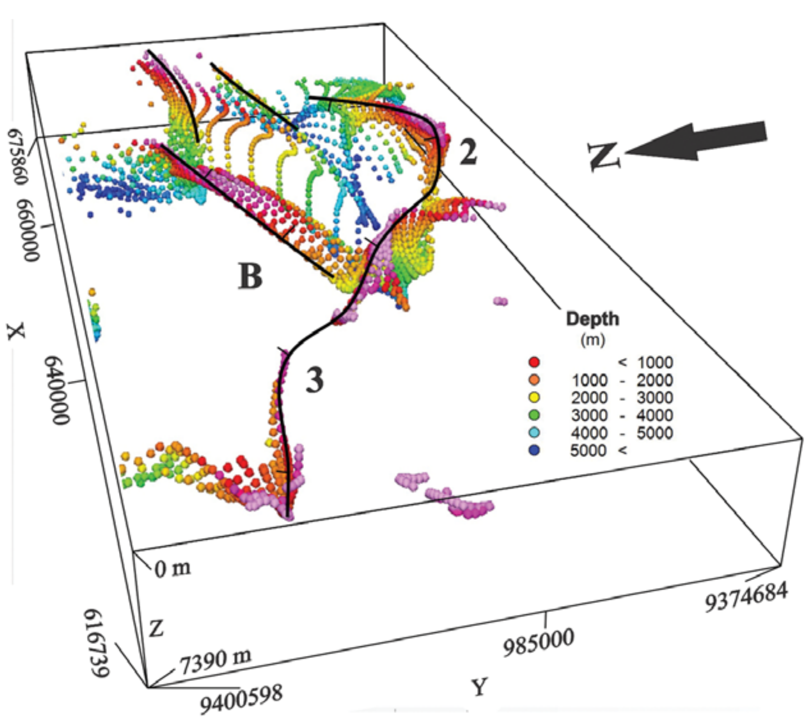

Figure 8 – Distribution of the magnetic Euler solutions at the southern boundary of the Potiguar rift. (2) Baixa Grande fault; (3) Apodi fault; (B) Apodi Graben. Coordinates UTM: SAD69, MC-39°.

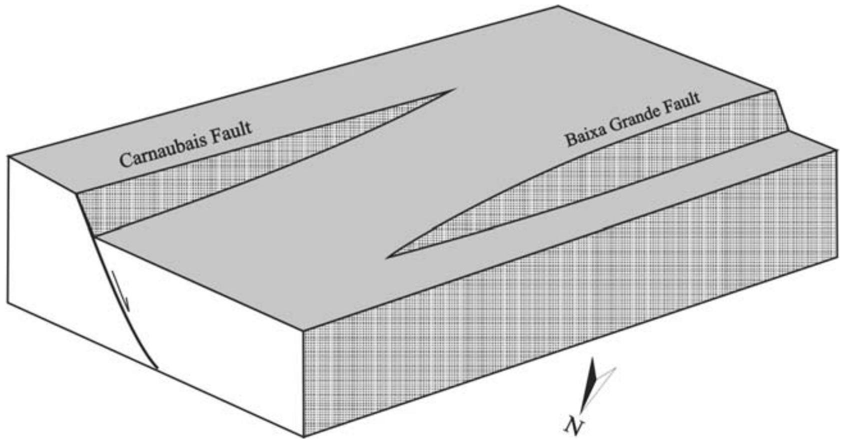

Figure 9 – Schematic model of the relay ramp formed between Carnaubais and Baixa Grande faults.

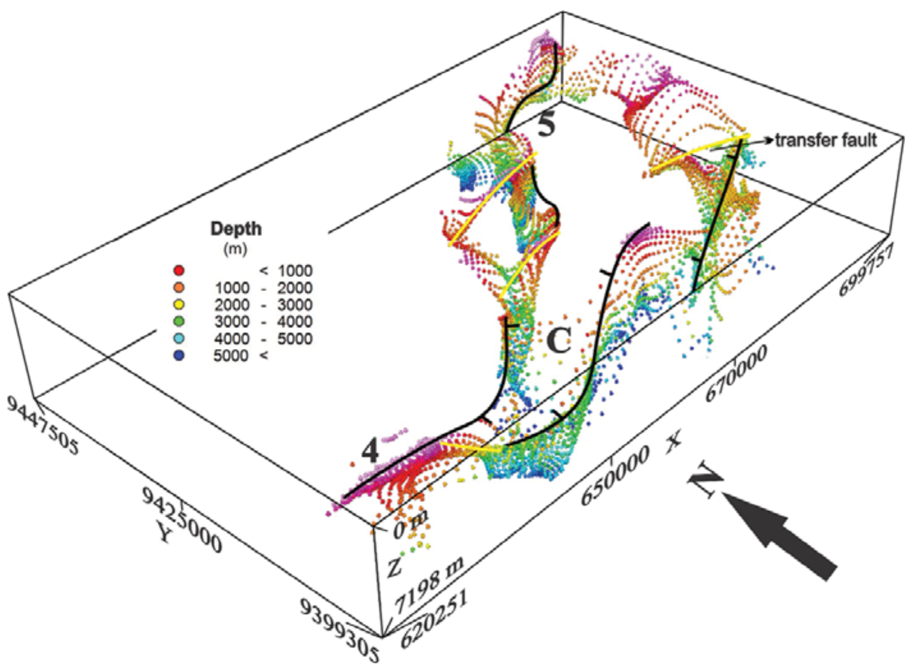

Figure 10 – Distribution of the magnetic Euler solutions at the western boundary of the Potiguar rift. (4) Mulungu fault; (5) Areia Branca hinge line; (C) Apodi Graben. Coordinates UTM: SAD69, MC-39°.

solutions present throws up to 6050 m in the western portion of the rift (Fig. 7). Further east, displacements of 4200 m are observed, along the NE-SW trending normal fault, which bends to west. On the other hand, in the NE limit of the normal fault, the displacements are more modest, reaching up to 200 m.

CONCLUSIONS

The Euler deconvolution method applied to gravity and magnetic data was effective to identify faults of the Potiguar rift in subsurface. Based on the spatial distribution of clouds of Euler solutions, it was possible to analyze the behavior of the rift main limits, such as the Carnaubais fault system, comprising a set of segments with NE-SW trending faults. This system is formed by listric normal faults, bending westward in the SW portion, and by dextral transfer faults with gentle to moderate NNW trending dip. Euler solutions suggest displacements greater than 6000 m in the Umbuzeiro Graben that decrease towards NE. This graben is the deepest depocenter of the Potiguar Basin, whose southern boundary is formed by an extensive dextral transfer fault with throws up to 6050 m.

At the southern boundary of the Potiguar rift, the Euler deconvolution reveals NW-SE and NE-SW trends for the Apodi and Baixa Grande faults, respectively, with strong, predominant NNE dips. The maximum displacements are of the order of 4000 and 5000 m for the Apodi and Baixa Grande faults, respectively. Additionally, it is observed that the Apodi fault is sectioned by secondary normal faults, possibly related to the presence of a crestal-collapse graben, as previously interpreted in seismic sections. The decreasing throw in the Baixa Grande fault towards NE coincides with increasing displacement in the Carnaubais fault, thus forming a relay ramp with NE dip.

The Areia Branca hinge line, which represents the flexural boundary of the Potiguar rift, shows a NE-SW trend according to Euler solutions. This result indicates the presence of normal (Mulungu fault) and dextral transfer faults with gentle SW dips. In the region of the transfer faults, the dip angles are relatively gentle, with the throws reaching depths greater than 5000 m, decreasing toward NE.

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