Journal of South American Earth Sciences 88 (2018) 700–714

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Architectural framework of the NW border of the onshore Potiguar Basin (NE Brazil): An aeromagnetic and gravity based approach

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ARTICLE INFO

Keywords:
Potential field methods
Euler deconvolution
Basement heterogeneity
Brasiliano lineaments
Equatorial Margin

ABSTRACT

On the basis of qualitative and quantitative geophysical interpretations, studies on tectonostratigraphic evolution were carried out in NW onshore Potiguar basin. Airborne magnetic and terrestrial gravity data were acquired in order to investigate tectonostratigraphic relationships in a poorly studied area of this oil-bearing Early Cretaceous basin. The present integrated study determined the main geophysical lineaments, basin internal geometry and depth of intra-basement magnetic and gravity sources, characterizing geological domains in terms of lithostructural elements. The depth of geophysical sources was estimated using 2D and 3D Euler deconvolution. 2D forward gravity modeling was also performed along three transects. The results unravel crustal partitioning, characterized by NE-SW lineaments with local E-W to NW-SE inflexions. The geophysical patterns are directly related to basement grain, which is Brasiliano in age. In fact, the Jaguaribe shear zone, that is not clearly marked on the surface, appears much more pronounced in the various geophysical maps and gravity models. The Ponta Grossa and Fazenda Belém shear zones show similar geophysical signatures to the Jaguaribe shear zone and appear to limit a low-related gravity features. Another important magnetic lineament was revealed by 2D Euler deconvolution and was named Retiro shear zone. 2D gravity modeling shows the basin geometry in depth, which presents shallow depocenters that may be associated with hydrocarbon reservoirs to the east, such as the Fazenda Belém oil field. An evolutionary tectonic model of this reservoir is proposed comparing our results and previous geological studies. This study indicates that a few faults, which occur in the NW edge of Potiguar Basin and form depocenter boundaries, oblique to the main transform continental margin in NE Brazil, have the orientation, kinematics and geometry as the main rift faults. Thus, our final model suggests that the grabenlike depocenter could be the westernmost expression of the NE Brazilian Rift System that generated a series of rift basins along the Borborema Province in the Early Cretaceous. The still unknown deposition of rift-related sequences to the west of Fazenda Belém oil field is probably associated with raised area that remained active when the eastern sector of the Potiguar basin presented overall subsidence. It is likely this basement structural configuration is topographic highs and lows, keeping geodynamics relationships with strike-slip fault regimes installed in the Atlantic Equatorial Margin during Aptian.

1. Introduction

The Equatorial and South Atlantic opening was preceded by an extensive continental rifting in the NE-most South American platform (e.g., Chang et al., 1988; Heine et al., 2013). The Early Cretaceous extensional event led to a series of rift basins, named Northeast Brazilian Rift System (NEBRIS) by Matos (1992), inserted in the Precambrian Borborema Province and São Francisco Craton (Fig. 1). In Barremian, the extensional kinematics changed, moving the rifting east- and northwards to the current continental margin and leaving behind a roughly N-S, 1000-km long sequence of aborted rifts and small grabenlike basins. The onshore Potiguar Basin is the northernmost member

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https://doi.org/10.1016/j.jsames.2018.10.002
Received 30 July 2018; Received in revised form 28 September 2018; Accepted 3 October 2018

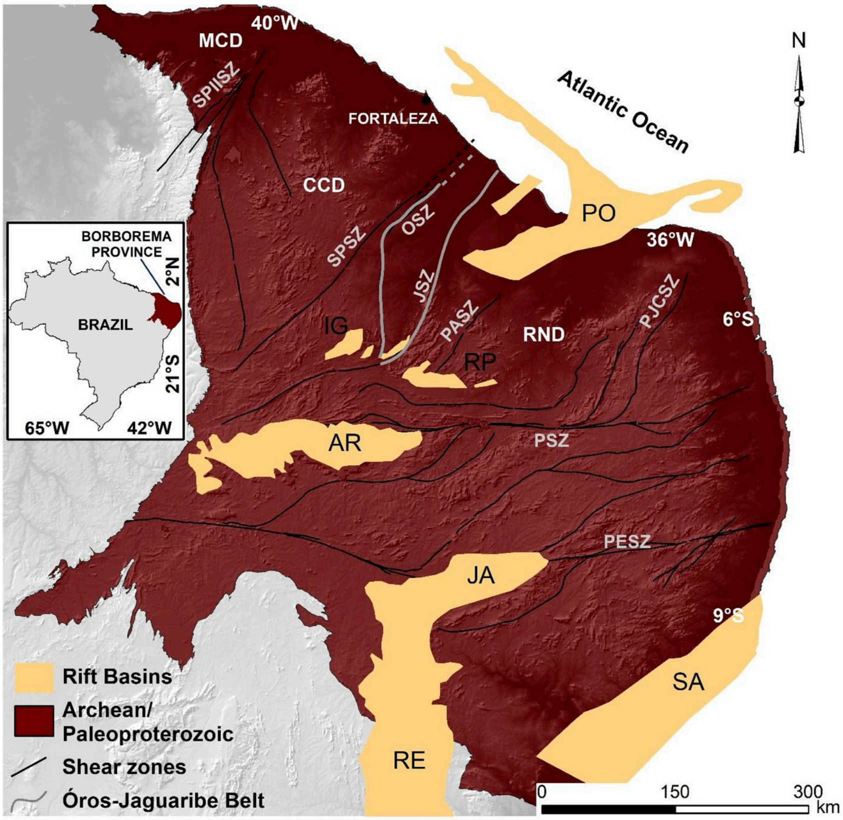


Fig. 1. The northeastern Brazilian rift system and its main Early Cretaceous rift basins (AR: Araripe, IG: Iguatu, JA: Jatobá, PO: Potiguar, RE: Recôncavo, RP: Rio do Peixe, SA: Sergipe-Alagoas). MCD: Médio Coreaú Domain; CCD: Ceará Central Domain; RND: Rio Grande do Norte Domain; SPIISZ: Sobral Pedro II Shear Zone; SPSZ: Senador Pompeu Shear Zone; OSZ: Orós Shear Zone; JSZ: Jaguaribe Shear Zone; PASZ: Porto Alegre Shear Zone; PJCSZ: Picuí – João Câmara Shear Zone; PESZ: Pernambuco Shear Zone; PSZ: Patos Shear Zone. Adapted from Matos (1992) and De Castro (2011).

of the NEBRIS and the unique that developed a second rift phase, which evolved to continental breakup (e.g., Matos, 1992; Lopes et al., 2018). A transgressive drift stage recovered the onshore rift with a vast Albian siliciclastic and carbonate platform (Vasconcelos et al., 1990), which is currently exposed in a ~50-km wide strip along the coastal region (Fig. 2), hiding the rift structures.

Despite the oil exploration started in the 1970's, the rift internal geometry of the onshore Potiguar Basin remains unknown. As an example, De Castro and Bezerra (2015) have only recently discovered new grabenlike structures in the SW edge of the onshore Potiguar Rift (5 and 6 in Fig. 2). In the NW portion of the onshore basin, the Fazenda Belém oil field is a good candidate to be another rift feature buried by the drift

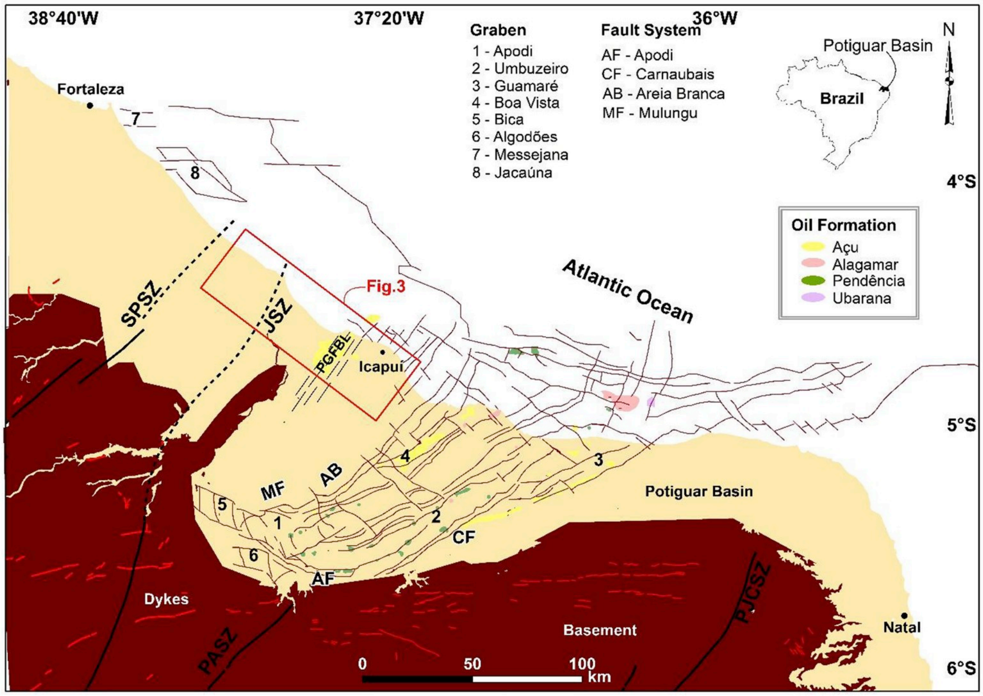


Fig. 2. Simplified geological map of the Potiguar Basin, showing the Potiguar Rift and the major border faults, with emphasis on formations containing hydrocarbons (modified from Bertani et al., 1990; De Castro and Bezerra, 2015). Shear zones: SPSZ: Senador Pompeu, JSZ: Jaguaribe, PASZ: Porto Alegre, PJCSZ: Picuí-João Câmara. PGFBL: Ponta Grossa-Fazenda Belém Lineament.

sequences. The up to 850-m thick sedimentary infill is located 50 km far from the onshore Potiguar Rift in the Aracati platform, whose local average thickness is around 300 m. Therefore, we analyzed magnetic and gravity data to find out if the Fazenda Belém oil field represents the NW-most expression of the NEBRIS in the onshore Potiguar Basin.

Potential field (magnetic and gravity) methods have been widely applied to study sedimentary basins, especially to determine the internal geometry and to identify structures that may hold (e.g., Telford et al., 1990; Reynolds, 1997). Magnetic susceptibility and density contrasts between less magnetized and less dense sedimentary basin infill and its basement generate potential field anomalies, that allow investigating the basin in depth. The Potiguar Basin, which is the subject of the present study, lends itself to use such methods because it still contains unknown areas in terms of the tectonostratigraphic framework. Traditionally, the most of the subsurface geophysical studies in the Potiguar Basin are concentrated in the rift region (Matos, 1992; De Castro, 2011; De Castro and Bezerra, 2015).

The present study focus on determining the internal geometry of the Fazenda Belém oil field in the NW portion of the onshore Potiguar Basin (Figs. 1 and 2) based on airborne magnetic and terrestrial gravity data. The analysis of the potential field anomalies is based on anomaly enhancement and semi-automatic source detection techniques, which defined three geophysical domains, two Precambrian basement units and Mesozoic grabenlike depocenters controlled by ancient shear zones. In addition, the magmatic origin of causative sources of short wavelength anomalies is discussed and an evolutionary model for the NW portion of the onshore Potiguar Basin is proposed.

2. Regional geological setting

The present tectonostratigraphic configuration of the study area is response to the deformation history along with the Equatorial Margin breakup, which was nucleated when the processes of Pangea disaggregation were triggered, governing the localization of depocenters near deep discontinuities within basement grain. More detailed information on the relationships between the two elements in the regional geologic framework, the Potiguar Basin and crystalline basement, will be described as follow.

2.1. Precambrian basement

The Borborema Province (NE Brazil, Fig. 1) represents an orogenic system with a complex history of deformation, metamorphic, and magmatic events of the Brasiliano-Pan African orogeny, which is late Neoproterozoic-early Phanerozoic in age (Fetter et al., 2000). This Precambrian province represents the western part of a major branching system of Neoproterozoic fold belts that consist of Archean to Proterozoic inliers amalgamated along volcano-sedimentary belts (Caby, 1989; Santos et al., 2010). Furthermore, the whole Province is transected by a system of regional-scale anastomosing shear zones (Vauchez et al., 1995), which occasionally form the boundaries of different crustal domains and/or geological units (Brito Neves et al., 2000).

Considering only the northern sector of the Borborema Province where the study area is inserted, three crustal domains are divided by major tectonic shear zones: Rio Grande do Norte, Ceará Central, and Médio Coreaú (RND, CCD and MCD, respectively, in Fig. 1). The Médio Coreaú and Ceará Central domains are segmented by the so-called Transbrasiliano lineament, locally named Sobral-Pedro II shear zone, a continental-scale shear zone (Santos et al., 2008). The Ceará Central domain is separated, in turn, from Rio Grande do Norte domain by Senador Pompeu shear zone, consisting mainly of juvenile middle Paleoproterozoic gneisses and some Archean nuclei, both covered by Neoproterozoic rocks (Fetter et al., 2000, 2003). Situated between Patos and Senador Pompeu shear zones, the Rio Grande do Norte domain consists mainly of Paleoproterozoic gneisses and locally Archean and Neoproterozoic rocks (Van Schmus et al., 1995, 2008; Dantas et al., 2004).

The NNE-SSW trending Orós-Jaguaribe Belt (Fig. 1) comprises two supracrustal units (Orós to the west and Jaguaribe to the east), insulated by a Paleoproterozoic gneissic basement of Jaguaretama Complex (Arthaud et al., 2008). This complex is composed by tonalitic and granodioritic ortogneisses associated with remains of paraderived rocks of high grade metamorphic units and variable degree of migmatization, as amphibolites, quartzite, metaultramafics and calc-silicate rocks (Arthaud et al., 2008). To the east, the belt is limited by the Porto Alegre shear zone, and westwards by the Orós shear zone (Figs. 2 and 3). The Jaguaribe shear zone is another important crustal feature cutting the belt to the east. The main lithologic assemblage includes metavolcanic-sedimentary sequence, associated with orthogneiss (Caby and Arthaud, 1986; Mendonça and Braga, 1987; Sá and Bertrand, 1992; Parente and Arthaud, 1995). Al-rich schist, intercalated with a narrow strip of quartzite, as well as lenses of Ca- or Mg-rich marble, calc-silicate rocks, carbonaceous schist and quartzite, representing the metasedimentary rocks of Santarém Formation (Fig. 3).

2.2. The Potiguar Basin

The Potiguar Basin is a conjugate Early Cretaceous basin, evolving an onshore aborted rift and an offshore prototype of passive margin, in which a complete tectono-thermal evolution was well stablished (e.g., Matos, 1992; Lopes et al., 2018). The offshore basin is a typical case of a "steer head" geometric basin, in which basin-forming mechanisms (rift stage) were followed by flexural thermal subsidence (drift stage), both interspersed with a transitional sedimentary megasequence, as postulated by White and McKenzie (1988). The NE Brazilian rift system is hosted by the Precambrian basement of the Borborema Province along a north-south axis, which is inflected northeastward in the Potiguar Region, following NE-SW oriented shear zones. The internal geometry of this basin shows a preferential ENE-WSW direction, showing asymmetric grabens separated by internal basement highs. A system of intracontinental normal faults controlled the basin architecture, probably reactivating Brasiliano shear zones (650–550 Ma) (Matos, 1992). Structural framework of Potiguar Basin is a result of changes that occurred during evolution in rift and drift stages and recent magmatism (Bertani et al., 1990).

As part of a series of Cretaceous rift basins in northeastern Brazil (Fig. 1), the Potiguar Basin was nucleated during the first stages of the breakup between the South American and African plates in the Early Cretaceous, resulted from NW-SE-oriented extensional regime, which had a counterclockwise rotation, changing its direction to E-W during the final stage of rifting (Chang et al., 1988; Matos, 1992). The onshore sector comprises an area ~150 km long and ~50 km wide, with internal grabenlike features, which are bounded by NE-trending normal faults and NW-trending transfer faults, dipping to the NW-N, respectively (Fig. 2). The main depocenters reach maximum depths of 6000 m, and the basin infill was deposited in a typical continental environment (Araripe and Feijó, 1994). Besides, a few grabens occur away from the main depocenters. The best examples are the Jacaúna and Messejana grabens at the western part of Potiguar Basin. They are transtensional structures bounded by E-W-trending transfer faults and NW-trending normal faults (Matos, 1992).

In terms of basin infill, a basal sequence was deposited in the Early Cretaceous during the opening of the rift, consisting of lacustrine deposits, fluvial-deltaic and fan-deltaic units of the Pendencia Formation (Soares et al., 2003). The transitional sedimentary post-rift sequence is composed of fluvial-deltaic sedimentary units of the Alagamar Formation and was deposited during the Aptian-Albian (Vasconcelos, 1995). The last depositional sequences correspond to the drift stage, when a transgressive and regressive marine sequence were deposited from the Albian to recent (Vasconcelos et al., 1990). These units correspond to

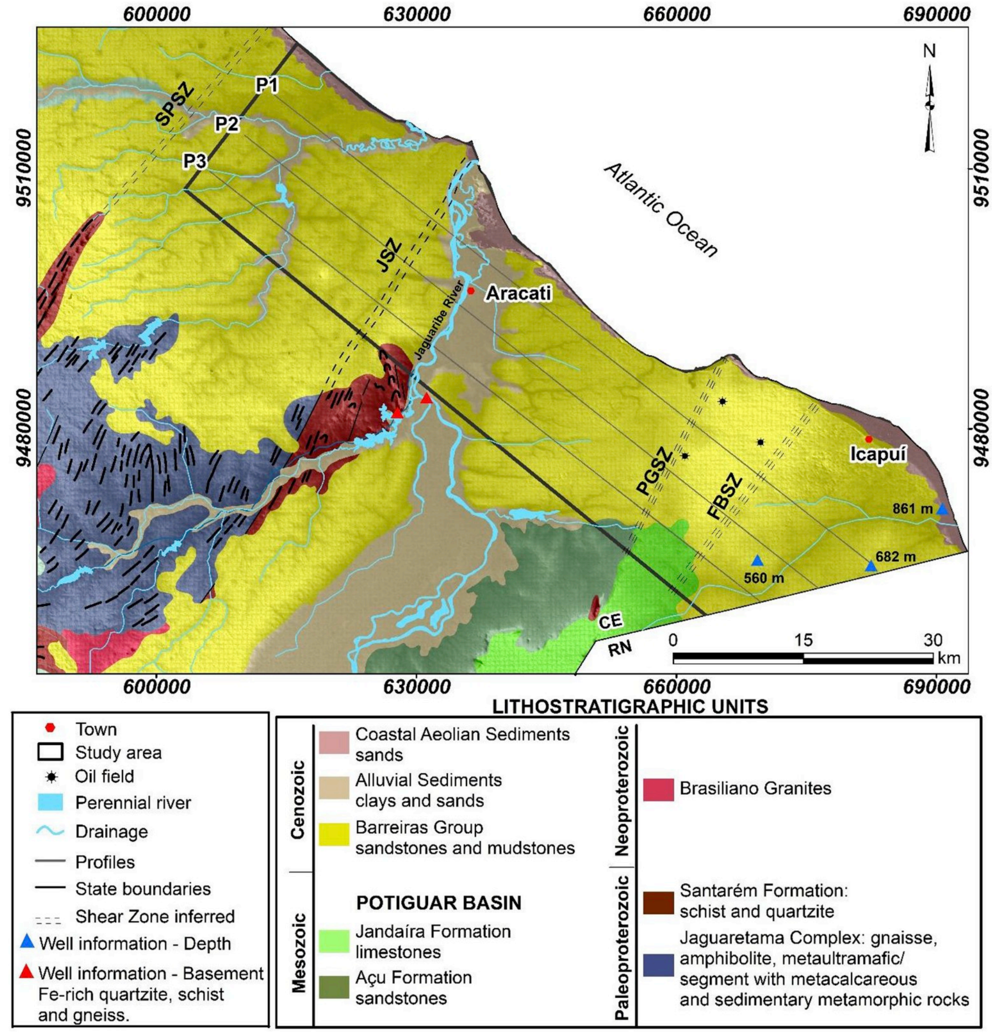


Fig. 3. Simplified geological map of the study area. SPSZ: Senador Pompeu Shear Zone; JSZ: Jaguaribe Shear Zone; PGSZ: Ponta Grossa Shear Zone; FBSZ: Fazenda Belém Shear Zone (Modified from Cavalcante et al., 2003).

river, platform, and deep slope facies of the Açu, Quebradas, Jandaíra, Ubarana, Guamaré and Tibau formations. Deposits of Barreiras Formation, which is characterized by sands and muddy sediments, with conglomerate facies occurring locally, completing the top of the stratigraphic column (Lima et al., 2006). According to Rosseti and Dominguez (2012), the Barreiras Formation was deposited in onlap on older rocks of Precambrian and Mesozoic, which occurred in association with relative higher sea level during the middle and lower Miocene.

Three separated igneous activities (Rio Ceará-Mirim Dike Swarm - EDCM; Cuó Suite - MC; Macau Suite - MM) are well-established, in tectonostratigraphic evolution of the Potiguar Basin (e.g., Oliveira, 1998). The oldest EDCM was geodynamically involved in the embrionary scenario of breaking up between Northeast Brazil and West Africa. This igneous event, which is extensively distributed in a strip of over 800 km from west Natal to east border of Paleozoic Parnaíba Sag Basin (Fig. 2), had a continuous activity ranging from 150 to 120 Ma in age. However, EDCM is represented by two main pulses of emplacement, roughly at 145 and 130 Ma. It is quite plausible that the more-localized dynamical mechanisms that drove the dike swarm generation and emplacement were associated with the evolution of a relatively “cold mantle plume”. The plume/lithospheric system resulting tectonic processes were able to nucleate and to control the Potiguar Rift opening (Oliveira, 1992). The MM is the most important igneous activity in Potiguar Basin and span age range between 45 and 25 Ma. Their exposure shapes vary from dikes, plugs, necks, floods to sills, and extends from basin offshore to the crystalline basement southwards, setting up a linear belt of 40 km width and trending N-S with 300 km in length. The generative and emplacement processes of Macau magmatic bodies have importance in developing the Potiguar thermal stage. In fact, Macau intrusion processes gave rise lateral adjustment inside the Potiguar Basin, resulting in a huge amount of shallow strike-slip faults with different magnitudes (Oliveira, 1998).

3. Geophysical datasets

3.1. Airborne magnetic data

The aerogeophysical survey provided by the Brazilian Oil Agency (ANP) is named Potiguar Basin Project and was carried out onshore in northeastern Brazil by the Brazilian oil company (Petrobras). This dataset was acquired between 1986 and 1987, covering 44,600 km^2 in area with N70W flight lines spaced 2 km and N20E tie lines spaced 4 km (Fig. 4). With nominal flight height around 500 m and the sampling rate of 100 m, the database underwent quality control, when problems related to survey flight was solved. So, aeromagnetic data were corrected for diurnal variations and the main component of the geomagnetic field (International Geomagnetic Reference Field-IGRF). The magnetic data

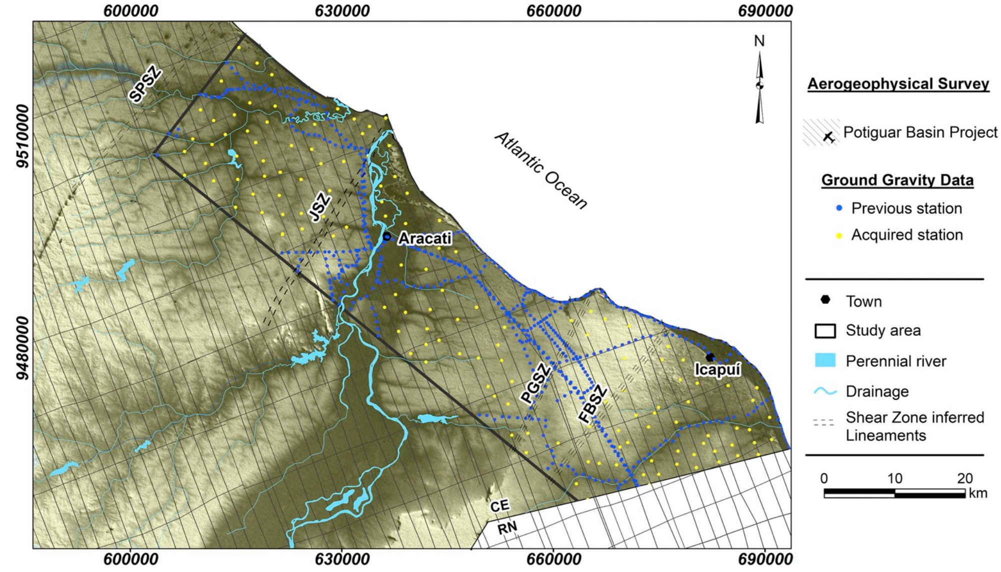


Fig. 4. Location of airborne magnetic data in the study area and distribution of previous gravity stations (blue dots) as well as the new stations acquired in the study area (yellow dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

were then interpolated into 500 m regular grid (1/4 of the spacing between flight lines) by the bi-directional method (BIGRID - Geosoft, 2014) to generate the total magnetic intensity map (TMI).

After this procedure, several filtering techniques were applied to improve the signal/noise ratio and to highlight specific features of the magnetic sources. Initially, a filter is used to eliminate high-frequency noise related to the high sampling rate along flight lines. The selected filter works in the frequency domain as a general directional cosine filter and rejects trends in a specified azimuth direction (Cordell et al., 1992). The filtered TMI anomalies were reduced to the pole (RTP) to center the anomalies on their respective sources. Fig. 5a shows the RTP magnetic signature of NW Potiguar Basin without the directional noise effect. Horizontal and vertical derivatives were used to produce the analytical signal amplitude (ASA) and tilt derivative (TDR) maps, whose main characteristic is to amplify and mitigate the short and long wavelengths of the magnetic signal, respectively, in the three orthogonal directions (Nabighian, 1984; Roest et al., 1992), thus enhancing the edges and contacts of geological features and faults (Fig. 5b). The vertical derivate and amplitude of the total horizontal gradient maps were also used for the interpretation (Fig. 5c).

3.2. Gravity data

The study area was already covered by 416 gravity stations, spaced every 500 m along roads, acquired by public universities and private exploration companies in Brazil (Fig. 4). In order to improve the distribution of gravity data in the entire studied area, 142 new gravity stations were acquired using a SCINTREX digital gravimeter model CG-5. The total of 558 previous and newly acquired gravity stations covers the studied area ($\sim 2037\ \text{km}^2$) with an average of 3.6 stations per km^2 or 1.8 stations in each 500-m size square cell.

The new acquired gravity data were corrected for tidal effects, instrumental drift and latitude, and the Free-Air and Bouguer anomalies were calculated. After integration with previous stations, the terrain effects were corrected for each station and the complete Bouguer anomaly map of NW part of the onshore Potiguar basin was interpolated using the kriging method (Geosoft, 2014) in a 500 m cell size. The regional and residual components of the gravity field were separated using a regional-residual separation filter, which is based on the Gaussian distribution of sources according to depth. The filter is a mathematical operator that acts as a low-pass or high-pass of chosen signal frequencies based on the radial power spectrum in the wave number domain. The Gaussian function standard deviation of 0.06 rad/km, representing the cutoff wavelength of approximately 16 km, was used. The regional gravity anomaly has a long wavelength (< 16 km), varying from −9.0 to 33 mGal (Fig. 5e). There is a slight increase in gravity values towards the Atlantic Ocean, due to the Moho rise associated with crustal thinning, typical of passive continental margins (De Castro et al., 1998). The residual anomalies map highlights the gravity response of shallower crustal heterogeneities (Fig. 5f). The residual gravity signature of the onshore Potiguar basin is marked by a sequence of positive and negative anomalies from short to long wavelengths (5–25 km), trending NE-SW, E-W and N-S and ranging from −6.3 to 6.4 mGal (Fig. 5f). The first vertical derivative of the residual gravity anomalies (Fig. 5g) outlines the main gravity alignments of the NW Potiguar basin. The lineaments have a preferred NE-SW trend, while 2nd order lineaments show NW-SE and E-W directions (Fig. 5h).

3.3. Euler deconvolution

Euler deconvolution is a powerful technique for magnetic and gravity source depth detection and analysis (Nabighian, 1972; Reid et al., 1990; Doo et al., 2007). The main advantage of using this technique is that it demands no *a priori* information about the source magnetization or density, and it assumes no particular geological model. Euler's method uses the potential field strength at any point in terms of gradient of the total magnetic or gravity values, expresses in Cartesian coordinates (Reynolds, 1997). These gradients are related to different causative sources by the structural index, which can be determined by observing the clustering of solutions for different index values. For a particular feature, the correct structural index yields a tight cluster (Dewangan et al., 2007).

The Euler deconvolution method (Thompson, 1982; Reid et al., 1990) was applied to both the magnetic and gravity data to investigate the depths of causative sources. Three important parameters regulate the results of the Euler solution: the structural index, the window size, and maximum depth error tolerance (Dewangan et al., 2007). The structural index indicates source geometry. It is an exponential factor

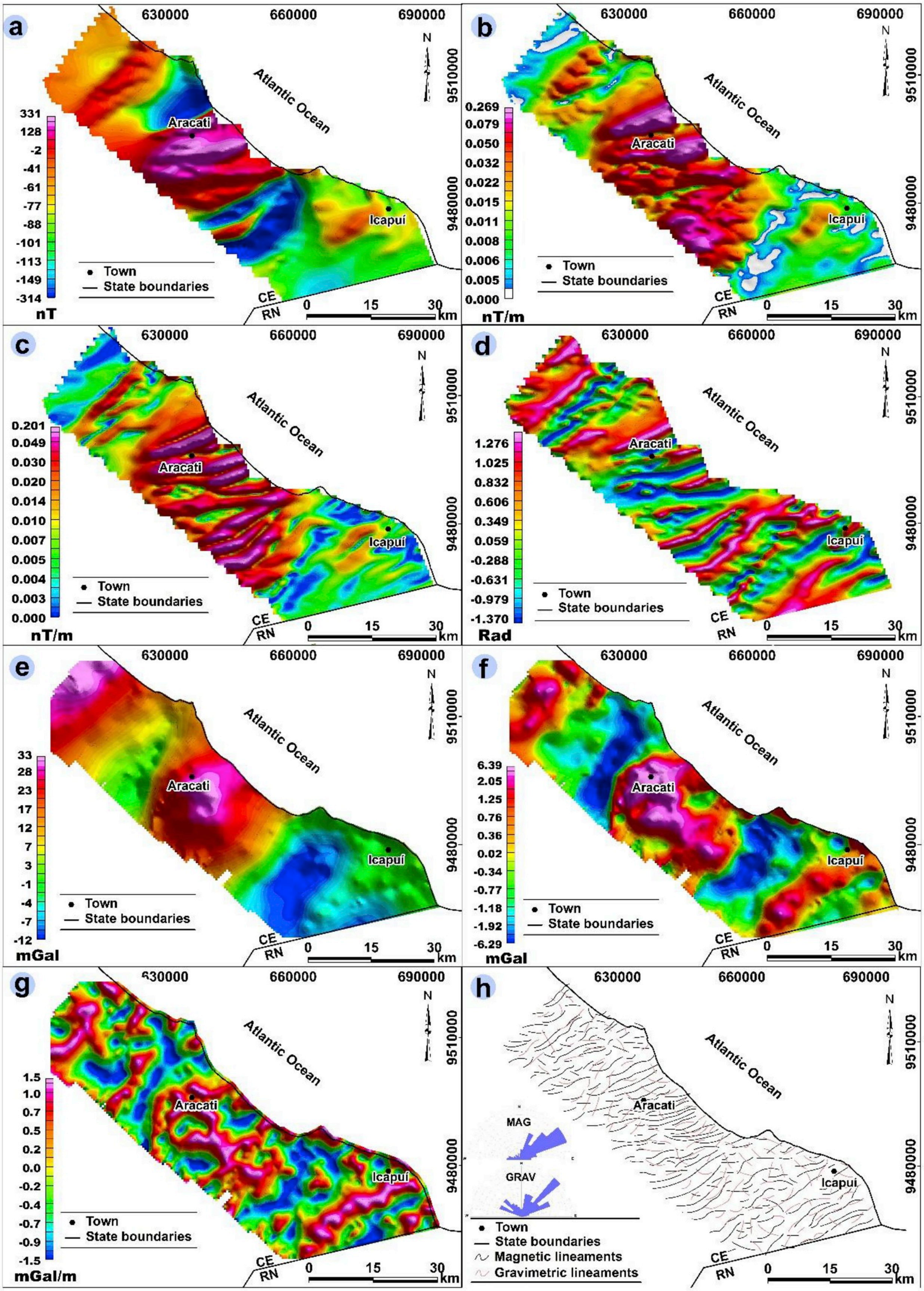


Fig. 5. Reduced to pole map (a); Analytic Signal Amplitude map (b); Tilt derivate map (c); Phase map (d); Complete Bouguer anomaly map (e); Residual map (f); First Vertical Derivate map (g) and magnetic and gravimetric lineaments. See location in Fig. 3.

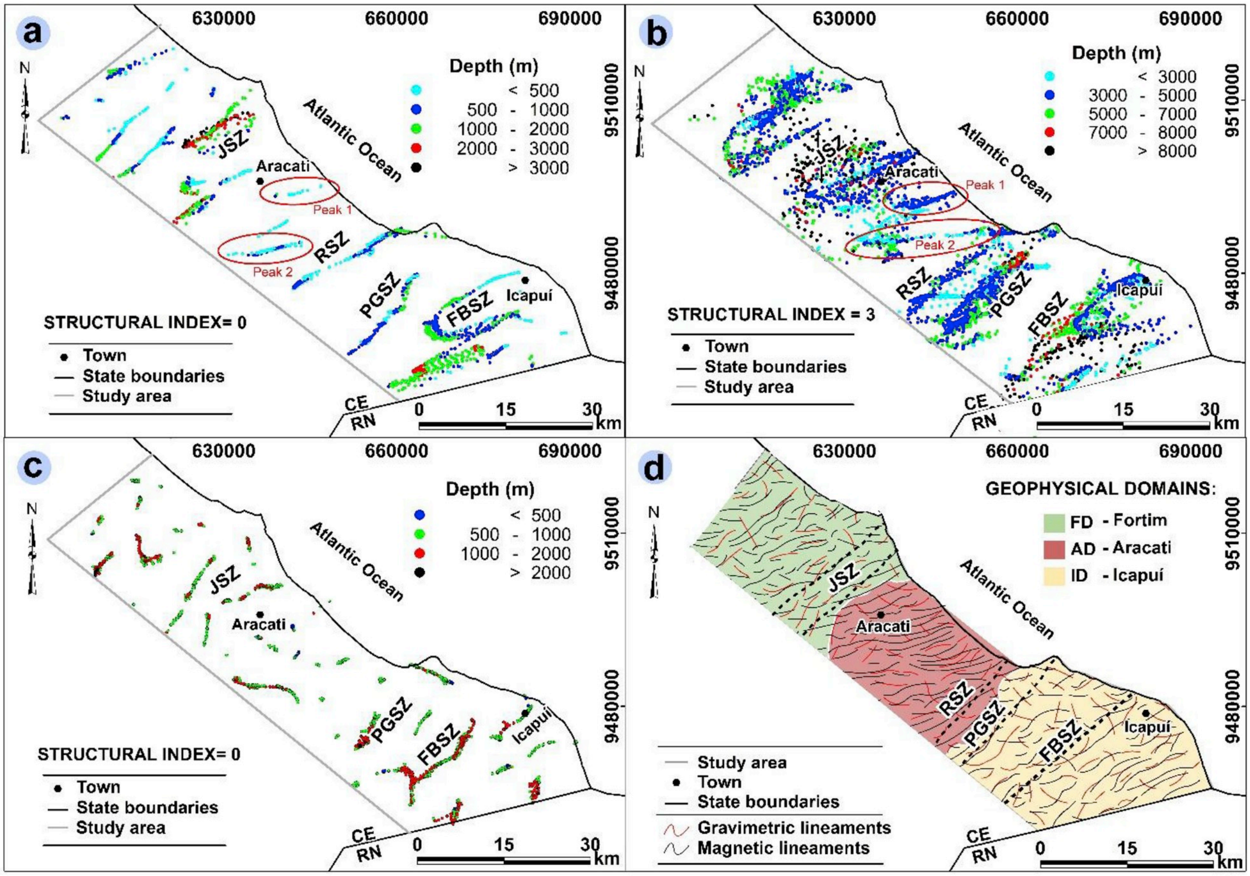


Fig. 6. 3D Euler deconvolution using structural index 0-magnetic data (a); 3D Euler deconvolution using structural index 3-magnetic data (b); 3D Euler deconvolution using structural index 0-gravity data(c) and geophysical domains and lineaments (d). Brasiliano shear zones: JSZ: Jaguaribe shear zone, RSZ: Retiro shear zone, PGSZ: Ponta Grossa shear zone, FBSZ: Fazenda Belém shear zone. See location in Fig. 3.

expressing the fall-off of the field strength versus distance from source (Barbosa and Silva, 2005). The complexity degree of the magnetic source geometry increases the structural index (SI), which varies from 0 to 3. The higher SI value, the higher is the tri-dimensionality of the source (Reid et al., 1990).

The structural indexes 0 and 3 were chosen for the magnetic data due to its relationship with linear features (faults) and three-dimensional bodies. The best results have been reached using a 5000 m spatial window and 10% maximum depth tolerance for structural index 0 and 15% maximum depth tolerance for structural index 3. The spatial window and maximum depth tolerance parameters were chosen interactively, by analyzing the results obtained when the parameters changed. The choice of parameters was based on the number and distribution of Euler solutions as well as on maximum and minimum values, average and standard deviation, to obtain representative data and avoid discrepancies.

The structural index 0 was also the best fit for the residual gravity anomalies, using a 500 m spatial window and 15% depth tolerance. The solutions for gravity data are scarcer compared with magnetic data, due to the fact that the residual gravity anomalies have medium to long wavelength and also due to irregular data distribution, with high sampling density on roads and low densities in other regions (Fig. 4). Fig. 6 shows 3D magnetic and gravity Euler solutions, which are discussed in Chapter 4.

In addition, 2D Euler depth solutions (Thompson, 1982; Reid et al., 1990) were computed along the magnetic and gravity profiles. Euler solutions were generated using structural indexes 0 and 1 in the three geophysical profiles (P1, P2 and P3) across the study area (Figs. 3 and 7). These indexes were used to obtain more linear Euler solutions, possibly associated with geological features such as contact, step, sill, dyke and ribbon (Reid et al., 1990). The magnetic and gravity solutions were obtained from the RTP and residual gravity anomalies (Fig. 5a and e, respectively), with 100 m sampling space. 2D Euler solutions were used to constrain the gravity modeling and are discussed in Chapter 4.

3.4. *2D gravity modeling*

The 2D gravity forward modeling was performed using the GM-SYS platform (GM-SYS, 2004) of the Oasis Montaj package from Geosoft, based on the algorithms developed by Talwani et al. (1959), Talwani and Heirtzler (1964) and Won and Bevis (1987). The interpreter defines the location and depth of one or more interfaces separating causative bodies, each one with specific density. The calculated gravity anomalies are compared to the observed anomalies, and adjustments are made to get the best fit between the observed and calculated anomalies.

Potential field modeling suffers from the well-known, non-unique determination of the source parameters from its field data (Fedi and Rapolla, 1999) just because several earth models can produce the same gravity and/or magnetic response. Moreover, many solutions may not be geologically realist. Therefore, because of this inherent ambiguity and nonlinear nature of the geophysical problem, the final result depends on the initial model. The surface boundaries of the exposed geological units as well as their densities are normally established from geological mapping to constrain the modeling process.

Three NW-SE trending, approximately 80-km long profiles (Fig. 3) were determined in the study area to analyze the 2D gravity sources, using Euler Deconvolution, as well as to perform 2D gravity modeling. The gravity profiles for 2D modeling were extracted from the residual

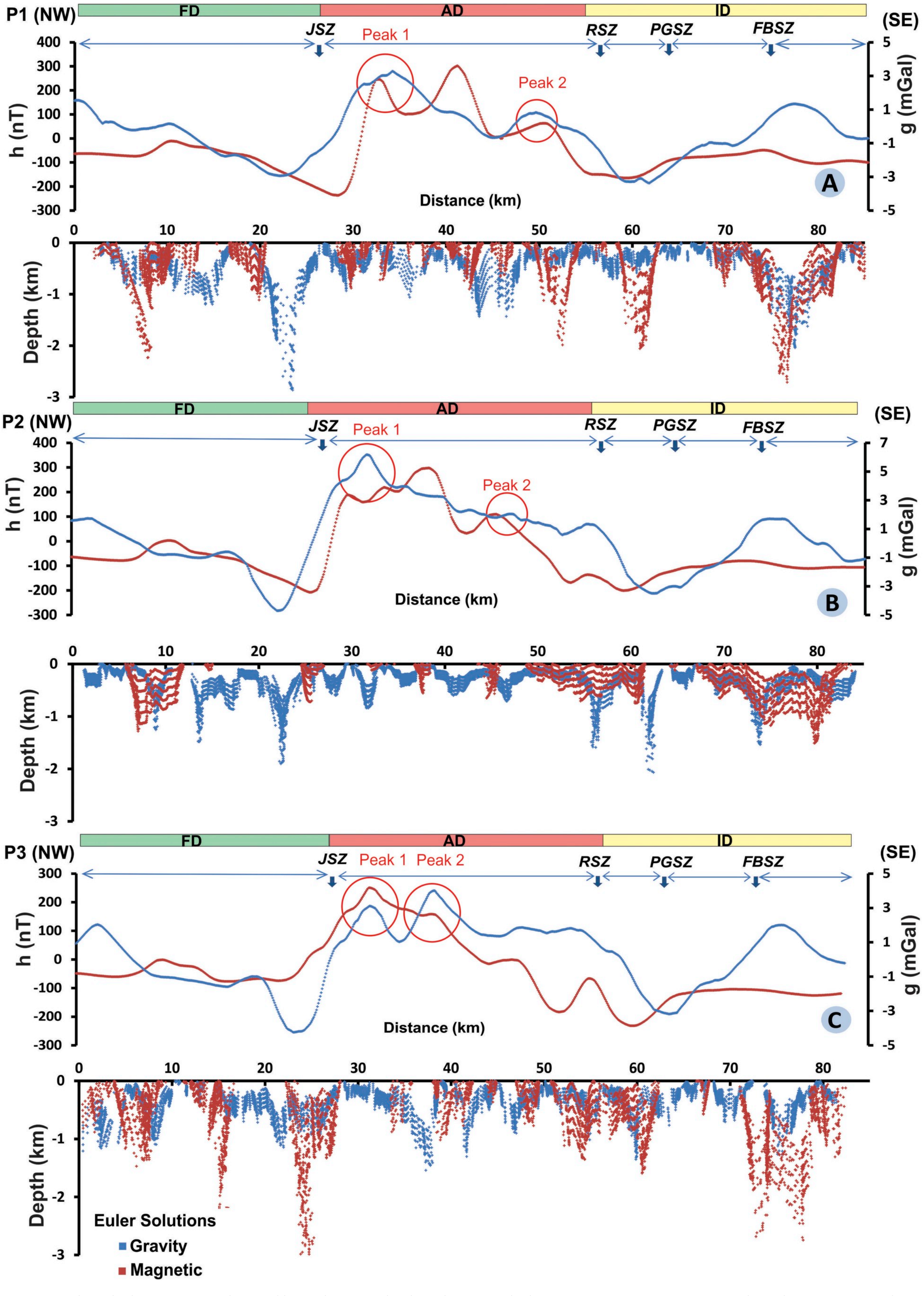


Fig. 7. Magnetic and residual gravity anomalies profiles at the top and Euler solutions at the bottom. section P1 (a); section P2 (b) and section P3 (c). The red circles are the possible locations of dykes in the region. See location of the P1, P2 and P3 profiles in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

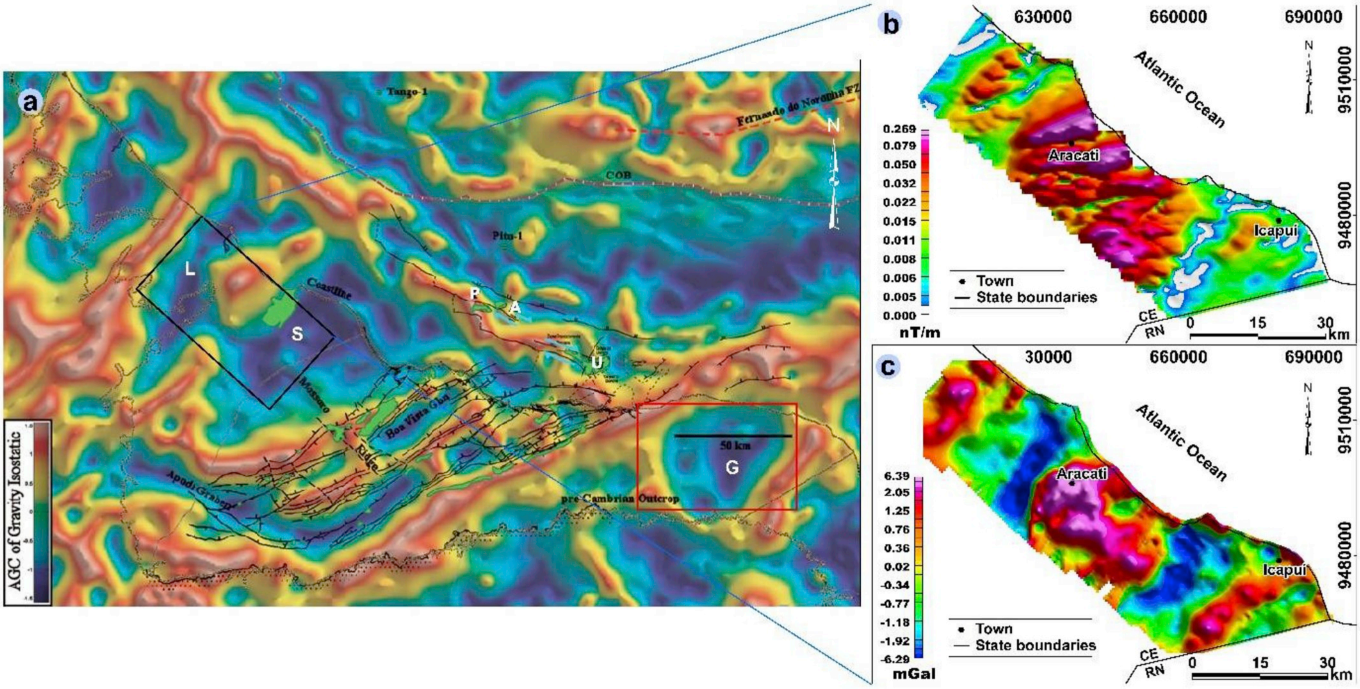


Fig. 8. Potiguar Basin setting with structural features (after Matos, 1993; Cremonini, 1996) with fields (green blobs) on gravity AGC of isostatic residual anomaly (Dickson et al., 2016) (a); Analytic Signal Amplitude map (b) Residual Gravity map (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

anomaly map (Fig. 5f), with a 100 m sampling space. We increased the gravity data along the profile to obtain more detailed geophysical models. However, we analyzed the interpolated anomalies to make sure that no artifacts have been included in the new 100-m spaced profiles. The initial models were created based on surface geological maps (Sousa, 2002), 3D and 2D Euler deconvolution (Fig. 7), and the depth of basement top from exploratory wells (Fig. 3). Each gravity model was divided in five layers: a) lower basement layer that comprises high-grade metamorphic rocks (Jaguaretama Complex); b) upper basement layer composed by metasedimentary sequences (Santarém Group); c) lower siliciclastic sequence of the Potiguar Basin (Açu Formation); d) upper carbonate sequence of the Potiguar Basin (Jandaíra Formation); and e) recent sedimentary cover (Barreiras Formation). The densities were established based on existing literature to the main lithostratigraphic units present in the area (Telford et al., 1990 and De Castro, 2011). The average densities of Jaguaretama Complex gneiss, amphibolites and metaultramafic rocks ranged from 2780 to 2800 kg/m^3. The densities of supracrustal metasedimentary sequences of the Santarém Group range from 2600 to 2700 kg/m^3. The sedimentary layers represent the intercalation of the Açu sandstones (2550 kg/m^3), and Jandaíra limestones (2558 kg/m^3), and Barreiras sandstones (2400 kg/m^3).

During the modeling process, the best fit between the observed and calculated anomaly profiles for gravity data were obtained modifying the shape of the assumed bodies. After, the iterative process consisted of performing incremental changes in body dimensions only because the physical property parameters are assumed to be established from *a priori* information. The geological units, the rock type and gravity properties of each block are shown in Fig. 9. The best root-mean-square (rms) misfits (in percentage) between observed and computed anomalies are 0.064%, 0.104% and 0.069% for profiles P1, P2 and P3, respectively. The final gravity models are shown in Fig. 9 and discussed in Chapter 4.

4. Results and discussions

4.1. Geophysical domains

Three geophysical domains could be distinguished in the NW onshore Potiguar Basin based on magnetic and gravity patterns, lineament trends and 3D Euler solutions (Figs. 5 and 6):

The Fortim Domain (FD) is located at the NW part of the studied area (Fig. 6d) and is characterized by a pair of magnetic and gravity high and low, with high amplitudes and NE-SW direction. The both magnetic and gravity anomalies are aligned in the NE-SW direction, associated with the Jaguaribe shear zone, which has no expression on surface, but follows the same trend, crossing the continent toward Equatorial margin (Fig. 2). A central ASA and TDR lineament (Fig. 5b and c) is associated to an intra-basement linear structure, revealed by NE-SW trending clouds of Euler solutions (Figs. 6 and 7). In the FD, the Euler solutions shows the deepest magnetic sources (over 3000 m). To the east, the -6.3 mGal gravity low indicates a less dense geological unit at the eastern FD domain border (Fig. 5f). We hypothesized two possible origins for this elongated gravity low: a) metasedimentary sequences of the Neoproterozoic Santarém Formation; or b) NW-most grabenlike structure of the onshore Potiguar Basin infilled by Early Cretaceous sedimentation, similar to the Fazenda Belém oil field at the eastern side of the Aracati Domain. Despite no direct evidence from boreholes, we assume the former option since Mesozoic sedimentary rocks partially crop out only at the eastern side of the Jaguaribe River (Fig. 2).

The Aracati Domain (AD) lies in the central sector of the study area (Fig. 5). It is associated with expressive magnetic ($\sim$330 nT) and gravity ($\sim$6.4 mGal) highs, high amplitudes of the analytical signal ($\sim$0.27 nT/m), and two sets of TDR lineaments oriented to E-W (to the west) and NE-SW (to the east) directions (Fig. 5c). Marinho et al. (1990) named this domain Aracati High, whose significant potential field

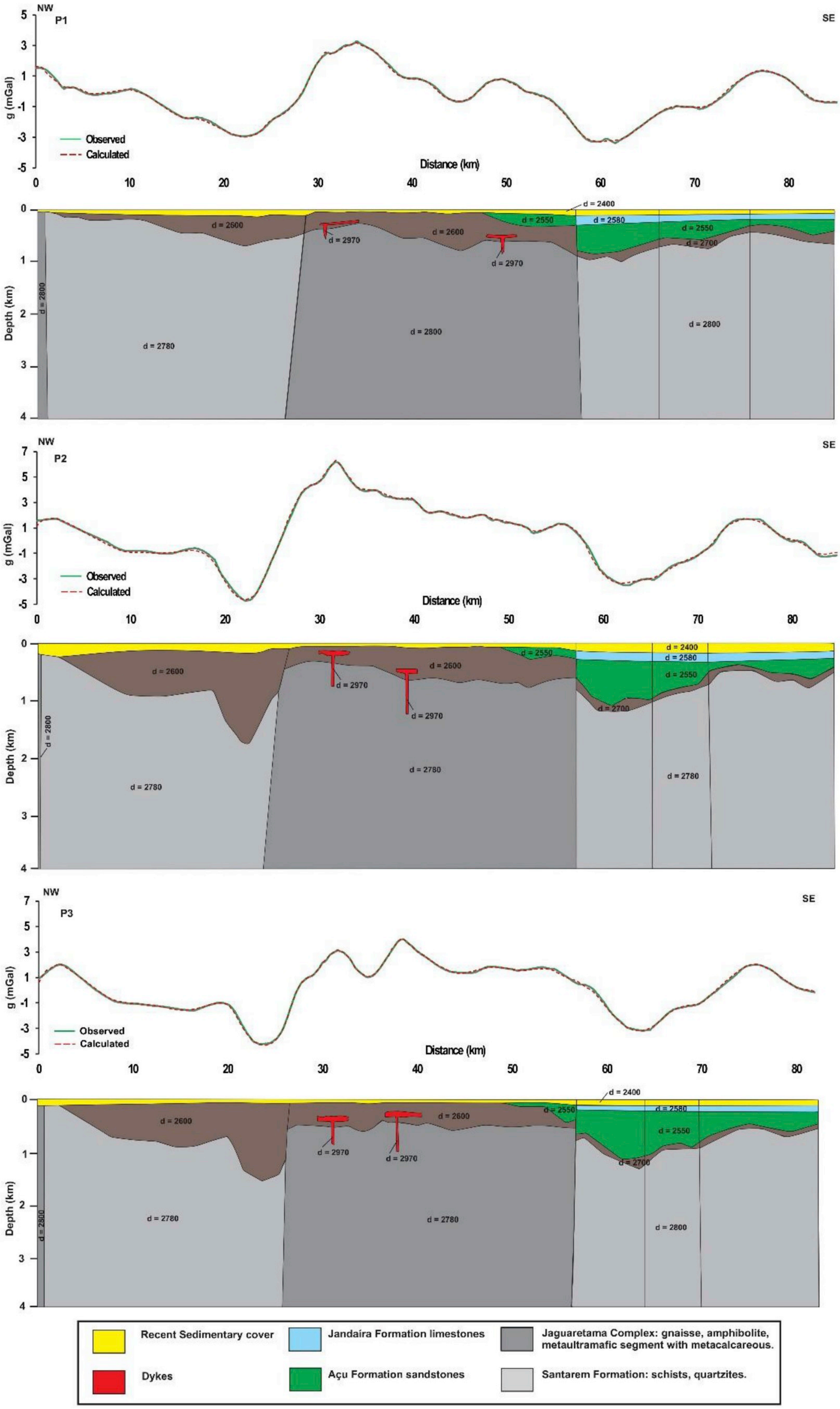


Fig. 9. 2D forward gravity modeling of three profiles: P1, P2 and P3. See location of the P1, P2 and P3 profiles in Fig. 3.

positive anomalies are certainly related with a relative more magnetized and denser geological unit deep in the Precambrian basement. In fact, 3D Euler magnetic solutions are spread throughout the Aracati High, especially along its boundaries and internal lineaments (Fig. 6). These solutions are concentrated in depths lower than 5000 m, suggesting a shallow nature of the geophysical source. However, Cenozoic to recent sedimentary cover prevents the direct recognition of the causative rocks, which is a manner of debate.

The Icapuí Domain (ID) occupies the eastern part of the study area (Figs. 5 and 6), exhibiting a pair of negative and positive magnetic and gravity anomalies limited westwards by the Aracati High. Low analytical signal amplitudes and sparse TDR lineaments indicate a more homogeneous geological setting in depth and/or a thicker sedimentary overburden. Three NE-SW oriented lineaments of magnetic 3D Euler solutions (Retiro - RSZ, Ponta Grossa - PGSZ, and Fazenda Belém - FBSZ) are separated by a central area without solutions (Fig. 6b), revealing the main depocenter of the Fazenda Belém oil field. The geophysical patterns suggest that this grabenlike structure is related to a gravity low and bounded by faulted basement highs. In this domain, Early Cretaceous sandstones (Açu Formation) and limestones (Jandaíra Formation) crop out partially overlaid by sedimentary rocks of the Cenozoic Barreiras Formation (Fig. 3).

In addition to indicating the boundaries of the geophysical domains, the 3D Euler Deconvolution also provides clusters of solutions aligned to ~E-W direction within the Aracati High (Fig. 6). To characterize them, a comparison was made between lineaments from the magnetic RTP and residual gravity anomalies (Fig. 5). Short wavelength (< 5 km) magnetic and gravity highs occur within the Aracati High (Figs. 5 and 7), showing NE-SW to ~E-W oriented lineaments of Euler solutions (Fig. 6). These causative sources can be associated with shallow magmatic features due to their high magnetic and gravity amplitudes and short wavelengths. In fact, Thurston and Smith (1997) described that the phase allows the estimation of the dip of the causative source and, consequently, the local contrast of susceptibility, in an extension of the signal theory complex initially presented by Nabighian (1972). It is easily observed a considerable number of linear sources in Fig. 5d and when comparing with Fig. 5b, we observe the coincidence of some negative values with the larger amplitude anomalies of the magnetic tilt derivate. This fact may indicate that the causative bodies have no dip, then we can infer the presence of dykes that are a good example to this relationship. In the NE Brazilian continental margin, two main magmatic events occurred in Mesozoic and Cenozoic ages. The former pulse is the ENE-WSW trending Ceará-Mirim dyke swarms that occurred in the early stages of the South America and Africa breakup (Oliveira, 1992). A more recent volcanic activity is the Macau Formation, which was restricted to a few small plugs in the NE boundary of the Potiguar Rift from 45 Ma to 6 Ma, related to the sea floor spreading of the South Atlantic (Mizusaki et al., 2002). The buried dykes in the Aracati High are certainly related to one of the both magmatic events.

4.2. Geological significance of gravity minima in the Potiguar Basin

Dickson et al. (2016) applied an AGC filter to isostatic residual anomalies of the Potiguar Basin (Fig. 8a). The aborted Potiguar Rift occurs in the central part of the basin, revealed by a series of positive and negative gravity anomalies oriented in NE-SW and NW-SE directions. Besides that, three large gravity lows are present in the opposite sides of the central rift (L, S and G in Fig. 8a). De Castro (2011) associated these gravity minima with Neoproterozoic metasedimentary sequences or granitic bodies, which may have the same gravity signatures as the rift grabens. To identify the geological origin of these gravity minima, a comparison with the magnetic and gravity patterns in the studied area was made (Fig. 8b and c). The low amplitude of magnetic analytical signal and negative gravity anomalies occupy the both NW and SE flanks of the Aracati High. These geophysical signatures are typical from low magnetized and less dense rocky materials. Based on the surface geology, the Neoproterozoic metasedimentary sequences of the Santarém Formation and the Mesozoic basin infill of the Potiguar basin are the primary candidates for causative sources of magnetic and gravity lows. The entire studied area is recovered by recent fluvial and coastal sedimentary layers, which hide the ancient geologic units, including the Aracati High. To the SE, exploratory wells drilled more than 800 m thick sedimentary sequences of the Potiguar basin according to ANP public database. On the other hand, no seismic and well data suggest Potiguar basin units deposited at the NW edge of the Aracati High. Furthermore, drilled wells for ground water exploitation are only few dozens of meters, not reaching rocks beneath the recent sedimentary cover.

4.3. 2D gravity modeling

The three geophysical profiles (location in Fig. 3) show positive magnetic and gravity anomalies of the Aracati High flanked by potential field lows (Fig. 7). These negative anomalies indicate less magnetized and less dense metasedimentary and sedimentary sequences around the Aracati High. Furthermore, short-wavelength maxima occur within the Aracati High, possibly unraveling a quite rugged paleorelief of the Paleoproterozoic Jaguaretama complex or shallow-seated magmatic bodies emplaced in the Precambrian basement. The distribution of magnetic and gravity 2D Euler solutions (Fig. 7) shed light in the structural setting of the NW border of the onshore Potiguar Basin, indicating at least four main shear zones (JSZ, RSZ, PGSZ and FBSZ in Fig. 7) that delimited crustal domains and controlled the basin faulted geometry.

Relatively deeper Euler solutions (~3.0 km) are observed between stations 20–30 km and 70–80 km along the profiles (Fig. 7), while the central part has shallower solutions (< 1.5 km), which may explain the presence of sources related to basaltic dykes or structural discontinuities in the basement. It is noteworthy that the extension of the Jaguaribe (JSZ), Ponta Grossa (PGSZ) and Fazenda Belém (FBSZ) shear zones, characterized on surface (Fig. 2), are well pronounced by solution clouds and reach depths of up to 3.0 km. The JSZ coincides in part with the boundary between the geophysical domains FD and the AD, while the RSZ marks the boundary between the geophysical domains AD and ID (Figs. 6d and 7). There is another interpreted lineament, which displays similar characteristics of the JSZ, PGSZ and FBSZ, is indicated by clouds solutions ranging 1.5–2 km deep and sub-vertical dip, here and after called Retiro shear zone (RSZ) (Fig. 7).

The shallower alignments located in the SE portion of the profiles are interpreted as faults or intra-basin discontinuities (Fig. 7), which may represent brittle reactivations of the main shear zones extending in the studied area. These regions are important from the point of view of oil and gas exploration on the NW edge of the onshore Potiguar basin, as these features may in the basal sedimentary deposits behave as structural traps. In addition, knowledge of intra-basin faults helps in the production of oil and gas if we take into account the geomechanical model of the exploration field.

The final 2D gravity models are shown in Fig. 9. In the profiles P1, P2 and P3 the maximum thickness of the sedimentary sequences on the NW edge of Potiguar Basin reaches ~1000 m. In general, the residual gravity anomaly varies between −4.5 and 6.3 mGal, where the most pronounced gravity lows reach −4.5 and −3.8 mGal in Profile P2. The three profiles contain a central maximum anomaly and two lateral minimums anomalies. The two negative anomalies occur at 22 and 60 km and are separately by a positive anomaly called Aracati High by Marinho et al. (1990). In the P2 the gravity low located at 22 km (−4.5 mGal) is more pronounced than the low gravity in the western edge of the Potiguar Basin (−3.0 mGal) (Fig. 9). In the P3 the Aracati gravity high still separates the two low gravity but is less pronounced in this section that the sections shown above (Fig. 9). Supracrustal rocks of the Santarém Formation is less pronounced below in westward of Potiguar Basin, acquiring more expression in adjacencies of JSZ. The

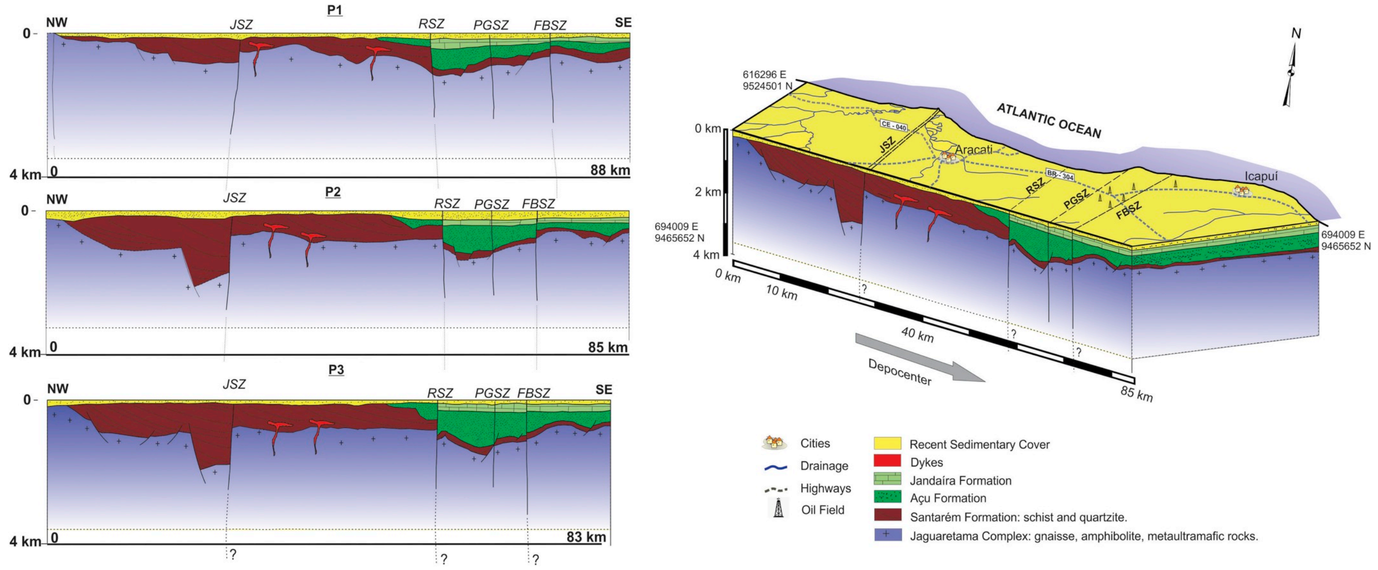


Fig. 10. Geological models obtained from three gravity profiles and a diagram block for the structural framework of the western edge of the Potiguar Basin.

Paleoproterozoic basement has less expression of gravity values near JSZ and has increased from Aracati high to the east.

4.4. Interpretative geological model

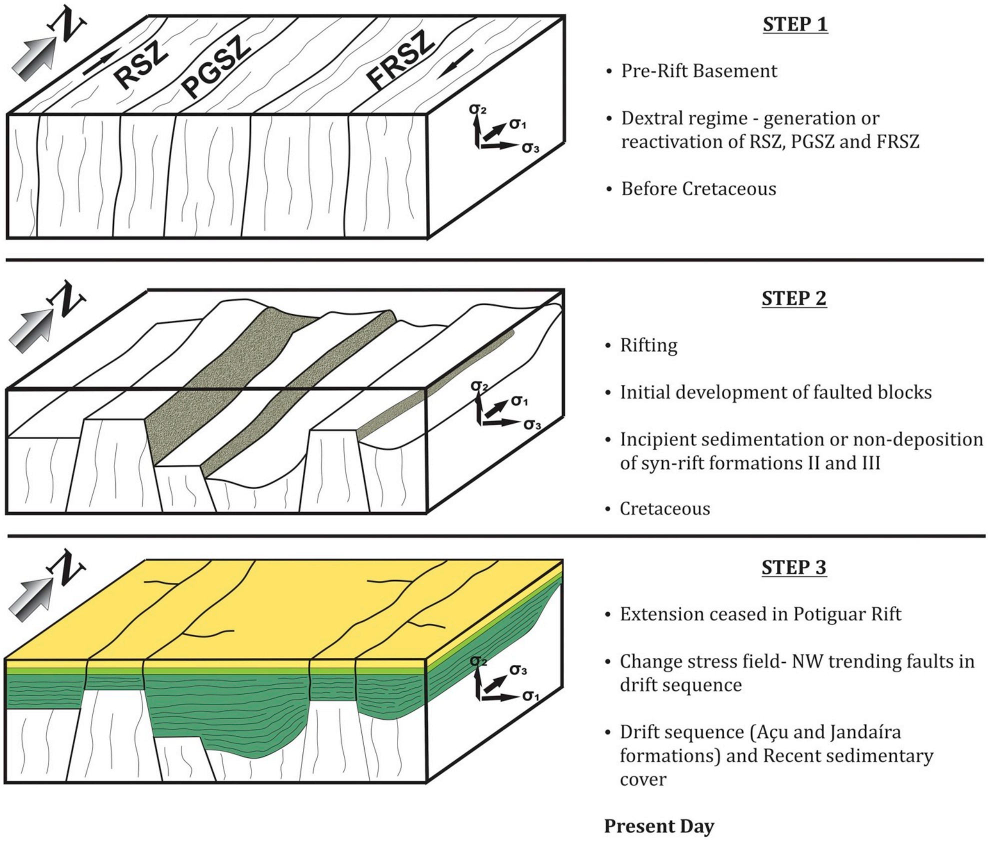
The gravity models unravel the internal geometry of the NW edge of the onshore Potiguar basin and heterogeneities in the Precambrian basement (Fig. 10). The presence of more dense rocks in the basement is closed correlative with magnetic and gravity positive anomalies of the Aracati High in central portion of the studied area (Figs. 5, 7 and 9). These anomalies were modeled and interpreted as belonging a more pronounced Paleoproterozoic basement of the Jaguaretama Complex overlapped by supracrustal rocks of the Santarém Formation, as suggested by regional geologic maps (Cavalcante et al., 2003). The supracrustal rocks are less thick underneath the Potiguar basin when compared to the western portion of the study area (Fig. 10). A possible grabenlike structure is identified at the eastern side of the Aracati High, limited by the Retiro (RSZ) and Fazenda Belém (FBSZ) shear zones. The faulted feature was infilled by tectono-depositional units of the Potiguar Basin. If the rift phase sediments have been deposited in this structure is still a matter of debate due to a lack of geological data from exploratory wells in the Fazenda Belém oil field. At the western side of the Aracati High, the Jaguaribe shear zone (JSZ) becomes more pronounced in the basement, showing a deeper magnetic signature, and may have anchored an ancient grabenlike structure infilled by supracrustal sequences of the Santarém Formation in the Neoproterozoic. In addition, Euler source solutions indicate that deep seated discontinuities divided the Precambrian basement in crustal blocks with subtle density contrasts (Figs. 6, 7 and 9). On the other hand, high amplitude and short wavelength anomalies and pervasive lineaments of Euler solutions with ~E-W orientation (Fig. 6) reveal at least two magmatic features, which can be associated to the Mesozoic Rio Ceará-Mirim dyke swarms or the Cenozoic Macau volcanic Formation.

The sedimentary package has a maximum thickness up to 1.0 km close to the Aracati High (Figs. 9 and 10). The Potiguar Basin increases in depth from profiles P1 to P3, as it moves away from the coast. The shallower alignments located in the SE portion of the profiles are interpreted as intrabasin faults or discontinuities, which could represent reactivation of the main shear zones extending in the study area. The sub-vertical reactivated Retiro, Ponta Grossa e Fazenda Belém shear zones controlled the sedimentary deposition in depocenters favoring the accumulation and trapping of hydrocarbons. These faults are of great importance to the petroleum system of Fazenda Belém oil field, because they can act either as conduits or barriers for hydrocarbon migration.

5. New insights on tectonic setting of the Fazenda Belém oil field

In order to explain the evolution of this grabenform feature, which is situated ~50 km NW of the Potiguar Rift, the role of Brasiliano shear zones in generating depocenters should be emphasized. The extension of this structure in depth (Euler 2D) and to the interior of the continent, affecting different lithostratigraphic units, suggest strong influence of these large structures in the development of the Potiguar Basin, from the Precambrian to the Recent. The crustal anisotropies, which extend from the African continent, such as the Senador Pompeu (SPSZ) and Jaguaribe shear zone (JSZ) (Figs. 1 and 2), concentrating distensional deformation and being decisive in generating and/or reactivating other zones of weakness with the same orientation and kinematics in neighboring regions, such as Retiro (RSZ), Ponta Grossa (PGSZ) and Fazenda Belém (FBSZ) shear zones. Regionally, NE-trending Brasiliano directional shear zones operated on dextral regime during Cretaceous (Fig. 11), when Potiguar rift system onshore and at the continental margin followed a complex, polyphasic evolution (Matos, 1999, 2000; Melo et al., 2016). The role of the PGSZ and FBSZ in the tectonic evolution of this sector of the Potiguar Basin was determinant in nucleating faulted blocks (Fig. 11). The rheological stratification of the Borborema province associated with NE-SW trending Proterozoic transcurrences conditioned differentiated deformational responses of large portions of the crust, making Neocomian fragmentation with heterogeneous signature. It is possible to notice that, in the central portion of the Borborema province, where a greater density of Brasiliano folded belts is concentrated (Fig. 1), the Neocomian rift structures were installed when oriented along an extensive northeastern zone (Matos, 1992). Taking into account a WNW crustal stretching efforts in the Neocomian, this important rheological characteristic provided the distribution of the rifts along an extensive NE belt, where the Araripe, Iguatu, Icó, Rio do Peixe and Potiguar basins were implanted (Fig. 1).

In the Potiguar Basin, the syn-rift II stage included the deposition of the Pendência Formation in the Potiguar rift, during the Neocomian, when reactivated faults along the PGSZ and FBSZ, with distensional kinematics (Fig. 11). In this scenario the investigated area could be protected from the distensional strain-bearing area, in which a long main rift structure was installed, remaining in as positive platform



STEP 1

- Pre-Rift Basement
- Dextral regime - generation or reactivation of RSZ, PGSZ and FRSZ
- Before Cretaceous

STEP 2

- Rifting
- Initial development of faulted blocks
- Incipient sedimentation or non-deposition of syn-rift formations II and III
- Cretaceous

STEP 3

- Extension ceased in Potiguar Rift
- Change stress field- NW trending faults in drift sequence
- Drift sequence (Açu and Jandaíra formations) and Recent sedimentary cover

Present Day

Fig. 11. Illustration of the main remnants of the Brasiliano shear zones of the Potiguar Basin. Geodynamic model showing the evolution and current configuration of the architecture of the westward Potiguar Basin – Fazenda Belém oil field.

called Aracati Platform. From the Upper Barremian to the Aptian, the opening of the Atlantic Equatorial Margin, in a dextral transcurrent regime (Zalan et al., 1985; Azevedo, 1991; Castro, 1992; Matos, 2000), generated major faults with E-W or NW-SE directions and was accompanied by deposition of the Pescada and Alagamar formations in the offshore sector of the basin (stage III). The Açu and Jandaíra formations were deposited in the subsequent stage of thermal subsidence (drift stage) between Albian and Santonian. The deposition of the Açu formation was then locally controlled by the topographic high and valleys already developed in the basement. The Fazenda Belém region has no direct register and markers of the syn-rift sequences II and III. Such absence can be caused by the existence of thick, but not laterally extensive, sedimentary piles deposited very rapidly during certain periods of time, together with areas where no or little sedimentation occurred during the same time, typical case of oblique-slip regime (Reading, 1980). In such areas certain blocks subside very quickly while others are uplifted and eroded. In the subsequent phases reversal movements are common.

In the interval of time between late Barremian and Albian, the oblique rifting and the subsequent deformation in this sector of the Equatorial Margin (Potiguar and Ceará basins) were conditioned by NW contraction and NE distension. E-W faults deformed the platform, as example of the pull apart Jacaúna graben, SE Fortaleza (Matos, 1999). Equivalent structures are indicated by gravity data in the Ponta Grossa region (Fig. 8a). Normal or oblique NW-trending faults were observed in the Açu Formation, being recognized on the southern edge of the Potiguar Basin (Fig. 11) (Jardim de Sá, 2001) or in crystalline basement outcrops in the western coastal region (Costa et al., 2001). This kinematic regime must have reactivated pre-existing structures, such as PGSZ and FBSZ, with sinistral contractional/transpressional kinematics regime, where high angle structures with antithetical to the dextral E-W movement can be observed in the larger area (Sousa, 2002).

6. Conclusions

The qualitative interpretation of magnetic and gravity data allowed a geophysical recognition of three domains in the NW border of the onshore Potiguar basin. The spatial arrangement of geophysical domains is related to the distribution of deep crustal lineaments, which are associated with the continuity of the main Brasiliano shear zones. JSZ coincides, in part, with the boundaries between Fortim and Aracati geophysical domains, while RSZ marks the boundary between Aracati and Icapuí geophysical domains. The FD shows low intensity magnetic anomalies, whereas locally the amplitude of the magnetic analytic signal is close to zero, and gravity field is marked by a pair of NNE-SSW trending positive and negative anomalies. High magnetization anomalous zone is associated with JSZ. The AD, in turn, is characterized by high amplitude anomalies of the analytical signal and by significant gravity high, with features trending to NE-SW orientation, while 2nd order lineaments oriented to E-W direction. These anomalies are associated with high density basement features such as amphibolites and metaultramafic rocks of Jaguaretama Complex and/or buried magmatic features. The ID is characterized by locally low amplitude analytical signal and high intensity magnetic anomalies, likewise to the gravity pattern in the same domain, all of them possibly are related to basement high.

The JSZ is not well marked on the surface, but appears well pronounced on the subsurface as shown in geophysical maps and models. The PGSZ and FBSZ, in turn, present similar characteristics and seem to limit possible grabenlike structures in the NW-most edge of onshore Potiguar basin. Another lineament with expression and depth similar to others presents well marked by 2D Euler deconvolution northwest of the PGSZ and was named Retiro shear zone. The JSZ and heterogeneous basement variation also changes from coast to inner continent side as shown in 2D gravity models, denoting a deeper character for JSZ and suggesting more pronounced deformation of supracrustal rocks of the Santarém formation. Furthermore, the central positive gravity anomaly was interpreted as the Aracati High, constituted by denser gneisses and amphibolites of the Jaguaretama Complex.

Geophysical indications of buried volcanic dykes possibly associated with Mesozoic Rio Ceará-Mirim or Cenozoic Macau magmatic events are indicated by 3D magnetic and gravity Euler solutions and by high amplitude and short wavelength gravity anomalies with E-W trends. 2D gravity modeling in the three profiles points out the geometry of NW edge of the onshore Potiguar basin, which could be grabenlike structures, with implications on the westward continuity of the Fazenda Belém petroleum system.

The crystalline basement of the entire study region proves to be quite heterogeneous. The shallower alignments located in the SE sector are interpreted as faults or intrabasin discontinuities, which may represent reactivations of the main shear zones. Fazenda Belém oil field is bounded by important NE-SW-trending shear zones (Ponta Grossa and Fazenda Belém). Another shear zone (Retiro) with the same characteristics was clearly recognized to the west of this oil field. A block diagram perspective view of geological models shows that such depocenters and lineaments are larger and deeper in the south of study area.

An evolutive tectonic model for the faulted blocks westward of the Fazenda Belém was consolidated from the analysis of the data of the potential methods and previous works. Such model suggests this possibly depocenter is coeval to the aborted Potiguar main rift. The still unknown deposition of rift-related sequences to the west of the Fazenda Belém oil field is probably associated with raised area that remained active when the eastern sector of the Potiguar basin presented full subsidence. It is likely this basement grain structural configuration is topographic highs and lows, keeping geodynamics relationships with strike-slip fault regimes installed in Equatorial Margin during aptian times. Such conditions seem to have acted more intensively on the Aracati platform than the other regions of the Potiguar Basin.

Acknowledgements

The authors are grateful to the Brazilian National Petroleum Agency (ANP) for the concession of geophysical data and to Brazilian Geological Survey (CPRM) for the software license. DLC thanks CNPq for his PQ grants.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2018.10.002.

References

Araripe, P.T., Feijó, F.J., 1994. Bacia potiguar. Bol. Geociencias Petrobras 9 (1), 127–141.

Arthaud, M.H., Caby, R., Fuck, R.A., Dantas, E.L., Parente, C.V., 2008. Geology of the northern Borborema province, NE Brazil and its correlation with Nigeria, NW Africa. In: In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., de Wit, M.J. (Eds.), West Gondwana: Pre-cenozoic Correlations across the South Atlantic Region, vol 294. Geological Society of London, Special Publications, pp. 49–67.

Azevedo, R.P., 1991. Tectonic Evolution of Brazilian Equatorial Continental Margin Basins. University of London, Imperial College, London, pp. 455p PhD dissertation.

Barbosa, V.C.F., Silva, J.B.C., 2005. Deconvolução de Euler: passado, presente e futuro - um tutorial. Rev. Bras. Geofís. 23 (3), 243–250.

Bertani, R.T., Costa, I.G., Matos, R.M.D., 1990. Evolução tectonosedimentar, estilo estrutural e habitat do petróleo na Bacia Potiguar. In: Gabaglia, G.P.R., Milani, E.J. (Eds.), Origem e evolução de Bacias Sedimentares. Petrobrás, Rio de Janeiro, pp. 291–310.

Brito Neves, B.B., Santos, E.J., Van Schmus, W.R., 2000. The tectonic history of the Borborema province. In: In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), International Geological Congress, Rio de Janeiro, Tectonic Evolution of South America, vol 31. pp. 151–182.

Caby, R., 1989. Precambrian Terrane of Benin-Nigeria and Northeast Brazil and Proterozoic Atlantic Fit Barks. Geological Society of America, pp. 145–158 Special paper, 230.

Caby, R., Arthaud, M.H., 1986. Major precambrian nappes of the brazilian belt. Ceará, northeast Brazil. Geology 14, 871–874.

Castro, A.S., 1992. Arcabouço estrutural e evolução tectônica da sub-bacia de Icaraí, Bacia do Ceará. Universidade Federal do Ouro Preto. Dissertação de Mestrado 109p.

Cavalcante, J.C., Vasconcelos, A.M., Medeiros, M.D.F., Paiva, I.G., 2003. Mapa Geológico Do Estado Do Ceará. escala 1:500.000.

Chang, H.K., Koswmann, R.O., Figueiredo, A.M.F., 1988. New concepts on the development of East Brazilian marginal basins. Episodes 11 (3), 194–202.

Cordell, L., Phillips, J.D., Godson, R.H., 1992. US Geological Survey Potential Field Geophysical Software Version 2.0. USGS, Open File Report 92-18.

Costa, P.R.C., Almeida, C.B., Jardim de Sá, E.F., Antunes, A.F., Arthaud, M.H., 2001. Estruturas nos quartzitos da Reião de Jericoacoara, NW do Ceará: registros do Ciclo Orogênico Brasiliano e da evolução da margem continental Meso-cenozoica. In: SBG/Núcleo Nordeste, Simpósio de Geologia do Nordeste, 19, Natal. Boletim, pp. 324–325.

Cremonini, O.A., 1996. Evolução tectônica da área de Ubarana, porção submersa da Bacia Potiguar. Bol. Geociencias Petrobras 10, 81–97.

Dantas, E.L., Van Schmus, W.R., Hackspacher, P.C., Fetter, A.H., Brito Neves, B.B., Cordani, U., Nutman, A.P., Williams, I.S., 2004. The 3.4e3.5 Ga São Jose do Campestre massif, NE Brazil: remnants of the oldest crust in South America. Precambrian Res. 130, 113–137.

De Castro, D.L., 2011. Gravity and magnetic joint modeling of the Potiguar rift basin (NE Brazil): basement control during Neocomian extension and deformation. J. S. Am. Earth Sci. 31, 186–198.

De Castro, D.L., Bezerra, F.H.R., 2015. Fault Evolution in the Potiguar rift termination, equatorial margin of Brazil. Solid Earth 6, 185–196.

De Castro, D.L., Medeiros, W.E., Jardim de Sá, E.F., Moreira, J.A.M., 1998. Mapa gravimétrico do Nordeste Setentrional do Brasil e margem continental adjacente: interpretação com base na hipótese de isostasia. Braz. J. Genet. 16 (2/3), 115–131.

Dewangan, P., Ramprasad, T., Ramana, M.V., Desa, M., Shailaja, B., 2007. Automatic interpretation of magnetic data using Euler deconvolution with nonlinear background. Pure Appl. Geophys. 164, 2359–2372.

Dickson, W., Schiefelbein, C.F., Odegard, M.E., Zumberge, J.E., 2016. Petroleum Systems Asymmetry across the South Atlantic Equatorial Margins. vol. 431. Geological Society, London, Special Publications, pp. 219–233.

Doo, W.B., Hsu, S.K., Yeh, Y.C., 2007. A derivative-based interpretation approach to estimating source parameters of simple 2D magnetic sources from Euler deconvolution, the analytical-signal method and analytical expressions of the anomalies. Geophys. Prospect. 55, 255–264.

Fedi, M., Rapolla, A., 1999. 3-D inversion of gravity and magnetic data with depth resolution. Geophysics 64 (2), 452–460.

Fetter, A.H., Van Schmus, W.R., Santos, T.J.S., Nogueira Neto, J.A., Arthaud, M.H., 2000. U-Pb and Sm-Nd geochronological constraints on the crustal evolution and basement architecture of Ceará State, NW Borborema Province, NE Brazil: implications for the existence of the Paleoproterozoic Supercontinent “Atlantica”. Braz. J. Genet. 30, 102–106.

Fetter, A.H., Santos, T.J.S., Van Schumus, W.R., Hackspacher, P.C., Brito Neves, B.B., Arthaud, M.H., Nogueira Neto, J.A., Wernick, E., 2003. Evidence for neo-Proterozoic continental arc magmatism in the Santa Quitéria batholith of Ceará state, NW Borborema Province, NE Brazil: implications for the assembly of West Gondwana. Gondwana Res. 6, 265–273.

Geosoft, 2014. Oasis Montaj How- to Guide. Complete Workflow for Oasis Montaj. Geosoft Incorporated, Toronto, Ontario, Canada, pp. 260.

GM-SYS, 2004. Gravity/magnetic Modeling Software: User's Guide Version 4.9. NGA Inc., pp. 101.

Heine, C., Zoethout, J., Müller, R.D., 2013. Kinematics of the south atlantic rift. Solid Earth 4, 215–253.

Jardim de Sá, E.F., 2001. Tectônica cenozóica na margem equatorial brasileira da Província Borborema, Nordeste do Brasil (A contribuição da geologia estrutural no continente). In: SBG/Núcleo Nordeste, Simpósio Nacional de Estudos Tectônicos, 8o, Recife, Boletim de Resumos Expandidos, pp. 25–28.

Lima, C.C.U., Vilas Boas, G.S., Bezerra, F.H.R., 2006. Faciologia e Analise Tectônica Preliminar da Formação Barreiras no Litoral Sul do Estado da Bahia, Brasil. Geol. Usp. Série Científica 6, 71–79.

Lopes, J.A.G., de Castro, D.L., Bertotti, G., 2018. Quantitative analysis of the tectonic subsidence in the Potiguar Basin (NE Brazil). J. Geodyn. 117, 60–74.

Marinho, J.M.L., Castelo Branco, R.M.G., Vasconcelos, S.M.S., Maia, L.P., 1990. Reconhecimento Geofísico da Região Costeira entre Aracati e Beberibe, Ceará. Projeto Reconhecimento Global dos Sistemas Deposicionais Costeiros do Ceará. Technical report agreement SECIRM/FCPC/LGPSR/UFC.

Matos, R.M.D., 1992. The northeast Brazilian rift system. Tectonics 11, 766–791.

Matos, R.M.D., 1993. Resolução Sísmica versus modelos geológicos na bacia potiguar emersa. In: Conferencias Sociedade Brasileira de Geofísica, Rio de Janeiro, 7–11 November, 1993, pp. 147–151.

Matos, R.M.D., 1999. History of the northeast Brazilian rift system: kinematic implications for the break-up between Brazil and West Africa. In: In: Cameron, N.R., Bate, R.H., Clure, V.S. (Eds.), The Oil and Gas Habitats of the South Atlantic, vol 153. The Geological Society, London, pp. 55–73 Special Publications.

Matos, R.M.D., 2000. Tectonic evolution of the equatorial South Atlantic. Geophysical Monography AGU 115, 331–354.

Melo, A.C.C., de Castro, D.L., Bezerra, F.H.R., Bertotti, G., 2016. Rift fault geometry and evolution in the Cretaceous Potiguar Basin (NE Brazil) based on fault growth models. J. S. Am. Earth Sci. 71, 96–107.

Mendonça, J.C.G.S., Braga, A.P.G., 1987. As faixas vulcano-sedimentares de Orós e Jaguaribe: um greenstone belt? Rev. Bras. Geociencias 17, 225–341.

Mizusaki, A.M.P., Thomaz-Filho, A., Milani, E.J., Césero, P., 2002. Mesozoic and Cenozoic igneous activity and its tectonic control in northeastern Brazil. J. S. Am. Earth Sci. 15 183e198.

Nabighian, M.N., 1972. The analytical signal of two-dimensional magnetic bodies with polygonal cross-section: its properties and use for automated anomaly interpretation. Geophysics 37, 507–517.

Nabighian, M.N., 1984. Toward a three-dimensional automatic interpretation of potential field data via generalized Hilbert transforms: fundamental relations. Geophysics 49, 780–786.

Oliveira, D.C., 1992. O papel do enxame de diques Rio Ceara Mirim na evolução tectônica do Nordeste Oriental (Brasil): implicações na Formação do Rifte Potiguar. UFOP, pp. 172 Master Thesis.

Oliveira, D.C., 1998. Evolução magmática da Bacia Potiguar, Anais 40º Congresso Brasileiro de Geologia, abstracts. pp. 102.

Parente, C.V., Arthaud, M., 1995. O Sistema orós-jaguaribe no Ceará, NE do brasil. Rev. Bras. Geociencias 25, 197–306.

Reading, H.G., 1980. Characteristics and recognition of strike-slip fault systems. In: Balance, P.F., Reading, H.G. (Eds.), Sedimentation in Oblique-slip Mobile Zones. vol. 4. Special Publication: International Association of Sedimentologists, pp. 7–26p.

Reid, A.B., Allsop, J.M., Granser, H., Millet, A.J., Somerton, I.W., 1990. Magnetic interpretation in three dimensions using Euler deconvolution. Geophysics 55, 80–91.

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics. John Wiley & Sons, pp. 796.

Roest, W.R., Verhoef, J., Pilkington, M., 1992. Magnetic interpretation using the 3D analytical signal. Geophysics 57 (1), 116–125.

Rossetti, D.F., Dominguez, J.M.L., 2012. Tabuleiros Costeiros. Paleoambientes da Formação Barreiras. In: In: Barbosa, J.S.F. (Ed.), Geologia da Bahia: Pesquisa e Atualização, vol. 2. CBPM, Salvador, pp. 365–393.

Sá, J.M., Bertrand, J.M., 1992. Transpressão dextral no sudeste do Estado do Ceará. Província Borborema. In: Congresso Brasileiro de Geologia 37, São Paulo. Boletim de Resumos Expandidos. Sociedade Brasileira de Geologia, pp. 368–370.

Santos, T.J.S., Fetter, A.H., Hackspacher, P.C., Van Schmus, W.R., Nogueira Neto, J.A., 2008. Neoproterozoic tectonic and magmatic episodes in the NW sector of Borborema Province, NE Brazil, during assembly of Western Gondwana. J. S. Am. Earth Sci. 5, 271–284.

Santos, E.J., Van Schmus, W.R., Kozuch, M., Brito Neves, B.B., 2010. The Cariris Velhos tectonic event in northeast Brazil. J. South Am. Earth Sci. 29, 61–76.

Soares, U.M., Rossetti, E.L., Cassab, R.C.T., 2003. Bacia sedimentares brasileiras - bacia potiguar. Phoenix 5 (56), 1–6.

Sousa, D. do C., 2002. Litoestratigrafia e deformação cenozoica na região de Icapuí, Ceará, e implicações para a estruturação de campos de petróleo na borda ocidental da Bacia Potiguar. Universidade Federal do Rio Grande do Norte Ph.D. thesis.

Talwani, M., Heirtzler, J.R., 1964. Computation of magnetic anomalies caused by two dimensional bodies of arbitrary shape. In: In: Parks, G.A. (Ed.), Computers in the Mineral Industries, Part 1, vol. 9. Stanford University Publications, Geological Sciences, pp. 464–480.

Talwani, M., Worel, J.L., Landisman, M., 1959. Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. J. Geophys. Res. 64, 49–59.

Telford, W.M., Geldart, F.E.M., Sheriff, R.E., 1990. Applied Geophysics, vol. 2. Cambridge University Press, USA, pp. 62–64 3.

Thompson, D.T., 1982. EULDPH: a new technique for making computer assisted depth estimates from magnetic data. Geophysics 47, 31–37.

Thurston, J.B., Smith, R.S., 1997. Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the SPI(TM) method. Geophysics 62 (3), 807–813.

Van Schmus, W.R., Brito Neves, B.B., Hackspacher, P., Babinski, M., 1995. U-Pb and Sm-Nd geochronological studies of eastern Borborema Province, northeastern Brazil: initial conclusions. J. S. Am. Earth Sci. 8, 267–288.

Van Schmus, W.R., Oliveira, E.P., Da Silva Filho, A., Toteu, S.F., Penaye, J., Guimarães, I.P., 2008. Proterozoic links between the Borborema Province, NE Brazil, and the central African fold belt. In: In: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., De Wit, M.J. (Eds.), West Gondwana: Pre-cenozoic Correlations across the Atlantic Region, vol 294. Geological Society, London, pp. 69–99 Special Publications.

Vasconcelos, E.P., 1995. O evento CPT (Camadas Ponta do Tubarão) Aptiano da Bacia Potiguar. Dissertação de Mestrado, UFRGS, pp. 198.

Vasconcelos, E.P., Lima Neto, F.F., Roos, S., 1990. Unidades de correlação da Formação Açu, Bacia Potiguar, Anais 36º Congresso Brasileiro de Geologia 1. pp. 227–240.

Vauchez, A., Neves, S.P., Caby, R., Corsini, M., Egydio da Silva, M., Arthaud, M.H., Amaro, V., 1995. The Borborema shear zone system, NE Brazil. J. S. Am. Earth Sci. 8, 247–266.

White, N., McKenzie, D., 1988. Formation of the "steer's head" geometry of sedimentary basins by differential stretching of the crust and mantle. Geology 16, 250–253.

Won, I.J., Bevis, M., 1987. Computing the gravitational and magnetic anomalies due to a polygon: algorithms and Fortran subroutines. Geophysics 52, 232–238.

Zalan, P.V., Nelson, E.P., Warme, J.E., Davis, T.L., 1985. The Piauí Basin: rifting and wrenching in an Equatorial Atlantic transform basin. In: In: Biddle & Blick (Ed.), Strike-slip Deformation, Basin Formation and Sedimentation, vol 37. Society Economist Paleontologist and Mineralogist (SEPM), Special Publications, pp. 177–192.