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On the tectonics of the Neocomian Rio do Peixe Rift Basin, NE Brazil: Lessons from gravity, magnetics, and radiometric data

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Abstract

A geophysical perspective based on well-acquired gravity, magnetic, and radiometric data provides good insights into the basin architectural elements and tectonic evolution of the Rio do Peixe Basin (RPB), an Early Cretaceous intracontinental basin in the northeast Brazilian rift system, which developed during the opening of the South Atlantic. NW–SE-trending extensional forces acting over an intensively deformed Precambrian basement yielded a composite basin architecture strongly controlled by preexisting, mechanically weak fault zones in the upper crust. Reactivated NE–SW and E–W ductile shear zones of Brasiliano age (~0.6 Ga) divided the RPB into three asymmetrical half-grabens (Brejo das Freiras, Sousa, and Pombal subbasins), separated by basement highs of granite bodies that seem to anchor and distinguish the mechanical subsidence of the subbasins. Radiometric and geopotential field data highlight the relationship between the tectonic stress field and the role of a preexisting structural framework inserted in the final rift geometry. The up-to-2000 m thick half-grabens are sequentially located at the inflexion of sigmoidal-shaped shear zones and acquire a typical NE–SW-oriented elliptic shape. The Sousa Subbasin is the single exception. Because of its uncommon E–W elongated form, three-dimensional gravity modeling reveals an E–W axis of depocenters within the Sousa Subbasin framework, in which the eastern shoulders are controlled by NE–SW-trending faults. These faults belong to the Precambrian structural fabric, as is well illustrated by the gamma ray and magnetic signatures of the basement grain. Release faults were identified nearly perpendicular or oblique to master faults, forming marginal strike ramps and horst structures in all subbasins. The emplacement mechanism of Brasiliano granites around the RPB was partially oriented by the same structural framework, as is indicated by the gravity signature of the granitic bodies after removal of the gravity effect of the basin-filling deposits. The RPB major-fault occurrence along the releasing bend of a strong discontinuity – the so-called Portalegre Shear Zone – in addition to the configuration of a gentle crustal thinning, according to gravity field studies, suggests that a crustal discontinuity governs the nucleation of the RPB, followed probably by small displacement in deep crustal levels accommodating low-rate stretching during basin subsidence.

Keywords: Geophysics; Rift basin; Gravity modeling; Extensional tectonics

1. Introduction

Extensional tectonics is the most important mechanism responsible for the development of overall sedimentary-basin geometry, which affects and deforms the continental lithosphere (Keen, 1987; Ziegler, 1992; Roberts and Yielding, 1994; Ruppel, 1995; Ziegler and Cloetingh, 2003). Both upper crustal inhomogeneities and previous structural features also play major roles in the reorganization of the lithosphere to accommodate extensional strain (Nicolas et al., 1994). Studies of the relationships between these variables in the broader context of the crustal tectonic evolution

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are therefore important steps to understand how sedimentary basins settle on deformed crystalline basement.

A fundamental understanding of the relationship between extensional deformation, previous basement frameworks, and resulting rift architecture can be derived from gamma spectrometric and geopotential field (magnetic and gravity) data, especially if seismic reflection data and well drilling information are not available. The radiometric and magnetic signatures of the basement reveal a complex structural framework, including crustal blocks with lithostratigraphic units that differ in deformation intensity.

The Rio do Peixe Basin (RPB) is an intracratonic basin that is part of the northeast Brazilian rift system. The tectonothermal evolution of this system started in Early Cretaceous times, when a series of NE-trending rift basins nucleated (Fig. 1) (Matos, 1992; Françolin et al., 1994). During the Late Barremian, the extensional deformation moved north at the Equatorial Atlantic Branch, culminating in the continental breakup of South America and Africa and leaving behind, slightly extended, a few hundred kilometers of thinned crust.

The basement setting of the RPB is relatively complex, comprising three tectonostructural domains that were intensively deformed by ductile shear zones and intruded by synkinematic granites during the Late Proterozoic Brasiliano/Pan-African orogenic cycle (Neves et al., 2000). The main NW–SE-trending extensional motion, acting over this Precambrian basement, formed the RPB composite struc-

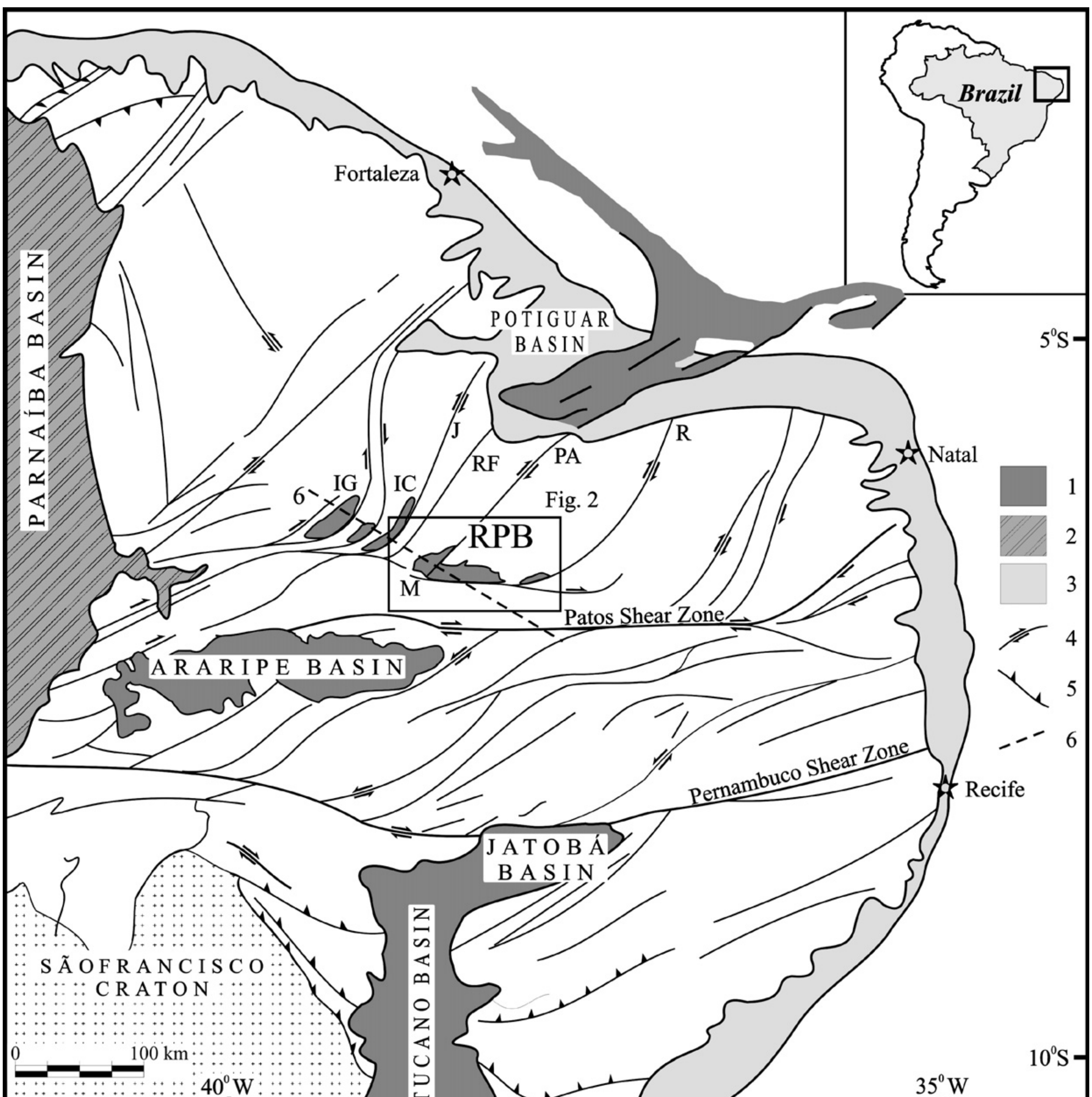

Fig. 1. Simplified geological map of the Borborema Province showing the distribution of sedimentary basins and major geologic features. (1) Cretaceous rift basins (IC, Icó; IG, Iguatu; RPB, Rio do Peixe); (2) Paleozoic sediments of the Parnaíba Basin; (3) coastal sediment cover; (4) shear zones (J, Jaguaribe; M, Malta; PA, Portalegre; R, Rio Piranhas; RF, Rodolfo Fernandes); (5) thrust zones; (6) gravity profile in Fig. 13.

ture in which three subbasins are separated by structural highs (Françolin et al., 1994).

Because of the scarcity of rift-related sediment outcrops in the eastern part of Borborema Province, the RPB plays a fundamental role in providing insights into the tectonostratigraphic record during the South America–Africa continental breakup. Most studies on rifting aspects focus on the subsurface features of marginal basins (e.g., rift stage of the Potiguar Basin), but little is known about the tectonic evolution of well-preserved intracratonic rift basins.

2. Geologic setting

2.1. Precambrian basement framework

The Rio do Peixe Basin (RPB) is inserted in a Precambrian lithostructural grain, named Borborema Province (BP), which partially corresponds to Neoproterozoic Brasiliano/Pan-African belts, as defined by Almeida et al. (1981) (Fig. 1). In a broader sense, the BP is a shield that consists of Paleoproterozoic inliers amalgamated along volcanosedimentary belts in which sedimentation and volcanism vary from Paleo- to Neoproterozoic in age (e.g., Neves et al., 2000). A widespread and pervasive low-angle foliation characterizes the BP, as does a network of steep continental scale, transcurrent ductile shear zones (e.g., Vauchez et al., 1995), both active during the Brasiliano/Pan-African orogenic cycle (0.8–0.5 Ga). During this period, the entire BP was intruded by many syn- to late-kinematic granite bodies (Almeida et al., 2000).

The complex network of NE–SW and E–W-trending shear zones is one of the outstanding structural features of the BP. Sigmoidal in shape, these shear zones occur along dozens to thousands of kilometers and are dozens of kilometers wide. Their structural textures vary from mylonitic to cataclastic. Patos and Pernambuco are the longest shear zones (Fig. 1) and seem to accommodate most of the ductile deformation (Françolin et al., 1994). A considerable number of these zones show brittle reactivation associated with Gondwana breakup in the Early Cretaceous. Kinematic studies by Françolin and Szatmari (1987) in the Patos shear zone suggest left-lateral, brittle-reactivated motion, revealing a reversal in the sense of shear, which in turn is consistent with fault movements observed in Cretaceous sedimentary rocks.

The Precambrian tectonostratigraphic setting, of which the RPB is part, encompasses three lithostructural domains north of the Patos shear zone (Fig. 2). The Orós-Jaguaribe domain forms two roughly parallel, NNE-trending linear belts (Arthaud et al., 2000). To the west, it bends to reach an E–W direction in the south. This inflection is the result of intense and continuous Brasiliano deformation essentially associated with NNE-trending transcurrent shear zones. A good example is the Portalegre shear zone, which marks the geologic contact between the Orós-Jaguaribe and Rio Piranhas domains (Fig. 2). The latter consists of a complex lithostructural association, including orthogneisses and supracrustal metasedimentary sequences, intruded by Neoproterozoic granite suites (Cavalcante, 1999). In the southern boundary of the RPB, metavolcanic, and metasedimentary sequences form the Granjeiro domain, which was affected by Brasiliano aged, E–W-trending recumbent tectonics.

2.2. The RPB tectonostratigraphic framework

2.2.1. Basin infill

Basin infill is continental in origin and consists of fluvial and lacustrine deposits. On the basis of field studies, the sedimentary deposits can be clearly separated into three stratigraphic units: Antenor Navarro, Sousa, and Rio Piranhas formations, from bottom to top (Albuquerque, 1970), as schematically indicated in Fig. 3. An exploratory well (LFst-1-PB) located at the Lagoa do Forno site (Fig. 2), as well as qualitative gravity data interpretation (Rand, 1984), enable Françolin et al. (1994) to estimate that the Neocomian basin filling deposits are up to 2000 m in the deepest depocenters.

The Antenor Navarro Formation consists of basal conglomerates and grits, passing into sandstones and mudstones, deposited in a fluviatile environment. Major exposures of this formation occur in the Brejo das Freiras Subbasin (Fig. 2), where it is less than 1000 m thick. In the Sousa Subbasin, it occupies the western portion with less than 250 m thickness or up to 86 m in the exploratory well (Lima and Coelho, 1987).

The 1000 m thick overlying Sousa Formation consists mainly of mudstones, with rare sandstones and marls. It was deposited by meandering rivers on floodplains or within shallow lakes. This stratigraphic unit outcrops in the central and eastern parts of the Sousa Subbasin. In the Brejo das Freiras Subbasin, the Sousa Formation lithologic types are restricted to the eastern-faulted basin margin. Lima and Coelho (1987) identify two stratigraphic sequences in the exploratory well. The lower unit is composed of siltic shale and siltstones with rare marls and claystone, whereas the upper unit consists of siltstones and mudstones interbedded with sandstones (Fig. 3).

The Rio Piranhas Formation consists of conglomerates and coarse sandstones, interspersed with sandy mudstones. This formation, 200 m thick, is widely exposed only in the southeastern part of the Sousa Basin near the Malta Fault (Fig. 2). Rio Piranhas Formation outcrops are absent in the Brejo das Freiras Subbasin (Sénant and Popoff, 1991), suggesting an eastward migration along the depositional history of the RPB.

2.2.2. Tectonic evolution

During the Late Jurassic to the Early Cretaceous, continental rifting processes associated with the South Atlantic opening yielded a sequence of several rift basins in northeastern Brazil (Fig. 1) and western Africa (e.g., Benue Trough, Niger Rift). Chang et al. (1988) assign three main synrift phases (I, II, and III) to the rift evolution of the

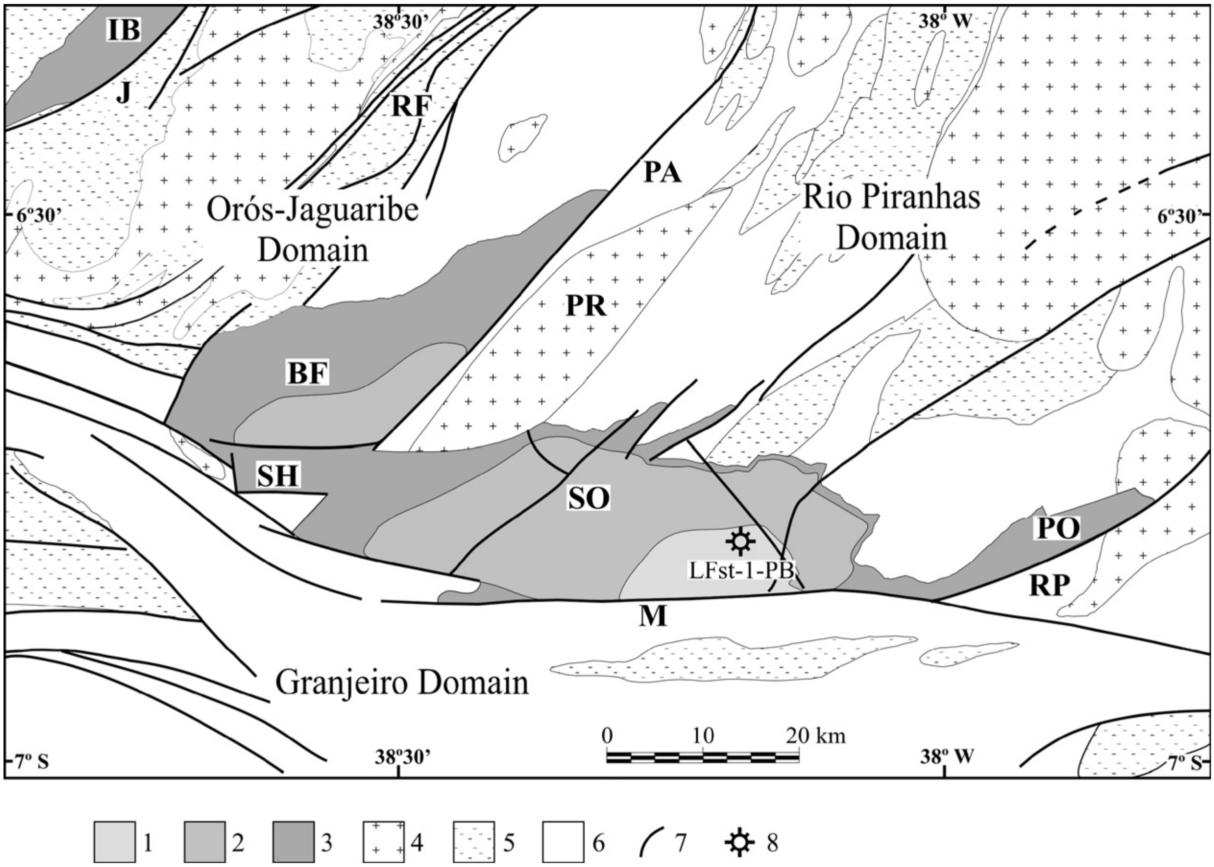

Fig. 2. Geology of the Rio do Peixe Basin (modified after Cavalcante, 1999), located at the intersection of three structural domains: Orós–Jaguaribe, Rio Piranhas, and Granjeiro. Early Cretaceous basins: Icó (IB) and Rio do Peixe (subbasins: BF, Brejo das Freiras; SO, Souza; PO, Pombal). (1) Rio Piranhas Formation, (2) Sousa Formation, (3) Antenor Navarro Formation; (4) Neoproterozoic granites (PR: Paraná Batholith); (5) Proterozoic cover sequences, (6) pre-Brasiliano basement; (7) faults (J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas); (8) exploratory well LFst-1-PB. SH, Santa Helena High.

South Atlantic. Matos (1992) has correlated the main rift phase of the BP basins to Synrift Phase II, when major rift valleys associated with widespread fracturing of the upper part of the crust developed. Deep shear zones, major faults, and lithotectonic unit boundaries controlled three main rift trends, of which the so-called Cariri–Potiguar rift system encompasses a series of northeast-trending intracratonic basins in the central portion of the BP (Fig. 1). Castro et al. (1998) point out that regional gravity data suggest localized crustal thinning below the Cariri–Potiguar trend (Fig. 4). The main extension took place along a NW–SE-trending axis, as indicated by overall surface geology and deep reflection seismic line (Matos, 1992). Preexisting upper crustal structures and NE–SW- and E–W-trending Neoproterozoic shear zones strongly influenced the rifting process in the extended upper crust.

The lithostratigraphic filling of the RPB represents a typical synrift deposit. The absence of pre- and postrift sequences in the RPB, as encountered along the onshore Potiguar and Iguatu basins, was probably caused by the rifting process, which prograded northward from the southern portion of the BP. The rifting kinematics, in turn, jumped to the north when rift sedimentation at Cariri–Potiguar ceased in the late Barremian. This event marked the beginning of Synrift Phase III in the Equatorial Atlantic Branch (Matos, 1992). Both pre- and postrift tectonic sequences are preserved in basins south of the Patos shear zone and offshore Potiguar Basin northward (Fig. 1). The erosive phase affected the whole northeastern Brazilian rift system (Fig. 3), with greater intensity north of the Pernambuco shear zone, where a large volume of sediments was removed during the late Neocomian. Backstripping studies based on exploratory well data estimate that up to 480 m of synrift sediments were eroded between 129 and 118 Ma in the Araripe Basin (Ponte and Ponte Filho, 1996). This interpretation is corroborated by fission track data (Morais Neto et al., 2000), which exhibit a pronounced widespread uplift event and concomitant erosion in the BP.

The RPB lithostratigraphy and faulting have been well described by Sénant and Popoff (1991) and Françolin et al. (1994). The whole RPB is composed of three subbasins – Brejo das Freiras, Sousa, and Pombal – separated by basement highs of three distinct structural domains (Fig. 2). Each subbasin can be classified as an asymmetric half-graben, with steep master faults on the southern (Sousa) and southeastern (Brejo das Freiras and Pombal)

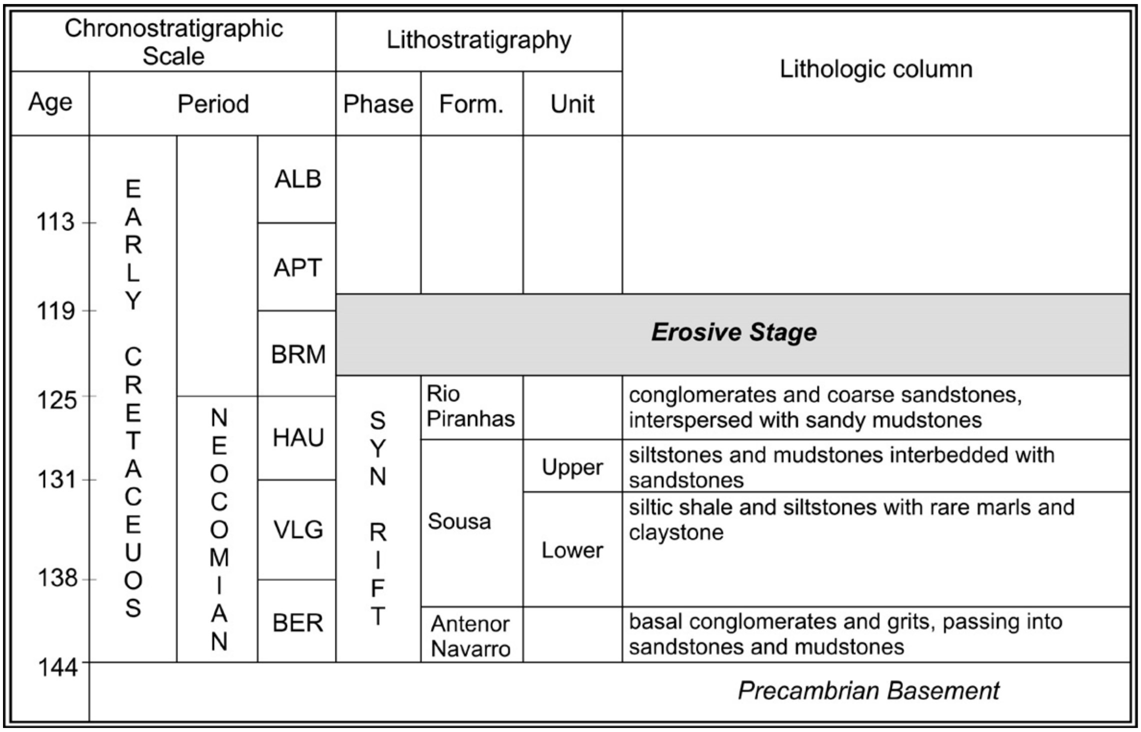

Fig. 3. Schematical chronostratigraphic chart of Rio do Peixe Basin (modified from Lima and Coelho, 1987).

edges. Their delineating master faults, known as Malta, Portalegre, and Rio Piranhas, respectively, formed at the expense of reactivated mylonitic shear zones in the basement. Fission track studies carried out on opposite sides of the Portalegre fault zone (Nobrega et al., 2005), *in loco*, where the Brejo das Freiras Subbasin is located, show that the western block moved downward in relation to the eastern block approximately 140 Ma ago, initiating the sedimentary filling process in the RPB. Sedimentary surface and core samples collected by Arai et al. (1989) yield Berriasian–Barremian ages, which are significantly similar to fission track data, indicating the main period of crustal activation tectonics when preexisting upper crustal weaknesses were reactivated along with the installation of rifting process in the RPB (Françolin et al., 1994).

By using a simple model, Matos (1992) suggests that the tectonic evolution of the Cariri Valley rift basins (Fig. 4) was the result of NW–SE-trending extension along preexisting sigmoidal shear zones. Generally, these basins show half-graben type geometries, dipping to SE, with localized NW–SE-trending transfer faults. Françolin et al. (1994), in contrast, suggest a more complex tectonic evolution. They interpret the Cariri Valley rift basins as a zone of left-lateral wrenching along the E–W Malta fault. Wrenching attenuates along the fault, producing crustal thickening in the west Santa Helena High (SH in Fig. 2) and thinning further east. Alternatively, Peacock and Sanderson (1995) suggest that the Santa Helena High is a strike-slip relay ramp separating the Malta fault from an E–W-trending sinistral fault to the NW and allowing the antithetic Portalegre fault to extend beyond the strike-slip relay ramp.

The deformational pattern within the basin was controlled by E–W-trending sinistral transtension, involving NNW-trending extension (Françolin et al., 1994). The Malta fault forms the southern boundary of both the Brejo das Freiras and Sousa subbasins, whereas several NE-striking dextral faults, including the Portalegre and Rio Piranhas, mark the eastern boundary (Fig. 2). The latter faults, dominantly strike-slip in motion, acted as conjugate features with the Malta fault to generate half-graben subbasins. Exceptionally, the Sousa subbasin shows an anomalous graben geometry that extends to an E–W-oriented direction. Matos (1992) interprets this subbasin as a transtensional graben associated with a bend in the Patos shear zone (Fig. 1). A more detailed tectonic interpretation appears in the next sections based on radiometric, magnetic, and gravity data.

3. Airborne geophysical data

3.1. Data set and processing

The aerogeophysical survey, named the Iguatu Project, was carried out in the north central part of BP between 1976 and 1977 (Brasil. MME/CPRM, 1995). The 52,000 km^2 area was investigated with gamma ray spectrometry and magnetics, which yielded a 55,000 km line of survey data. The RPB lies at the southeastern corner of the Iguatu Project. The data set was collected on N45E-oriented flight lines, with a 1.0 km of spacing, a sample rate of 100 m, and nominal survey elevation of 150 m.

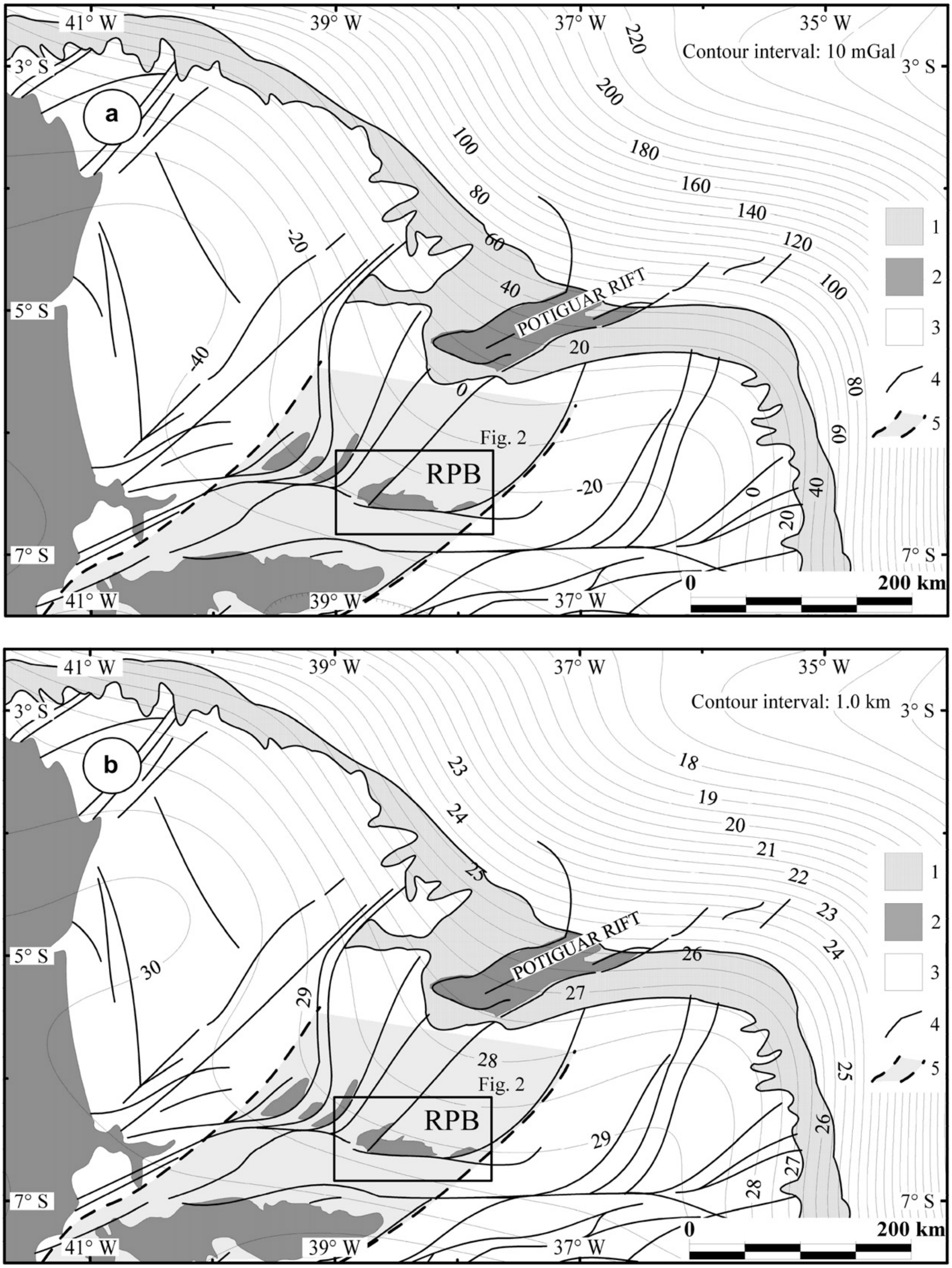

Fig. 4. (a) Regional gravity anomaly map of the northern part of the Borborema Province. (b) Depths to crust-mantle interface in km, obtained from gravity data modeling (modified from Castro et al., 1998). (1) Coastal sediment cover; (2) sedimentary basins; (3) Precambrian basement; (4) major faults; (5) Cariri rift system.

Airborne geophysical data were interpolated using the kriging method with 0.5 km regular spacing. Magnetic and radioelements abundance of K, Th, U, and total counts maps were filtered to eliminate high frequency noise related to the high sample rate along flight lines. The selected filter works in the frequency domain as a general directional cosine filter and rejects trends in a specific direction (Cordell et al., 1992). The selected direction of the filter is the same N45E-oriented flight lines. As a result, the high frequency noise was severely attenuated.

The magnetic anomalies were also reduced to the pole (RTP) to produce maxima over magnetic sources, regardless of the distribution of magnetization. The RTP computer program of the U.S. Geological Survey's potential field geophysical software (Phillips, 1997) was selected to reduce to the pole magnetic data from the RPB in a low latitude situation. The parameters of the geomagnetic field used in RTP were an inclination of $-8.0°$ and a declination of $-21.4°$.

In addition, the amplitude of the three-dimensional analytic signal of the magnetic field was obtained to improve an accurate delineation of the magnetic lineaments in both the RPB and basement domains. This technique, initially performed by Nabighian (1984), produces maxima over magnetic sources irrespective of their magnetization direction. The 3D analytic signal is the square root of the sum of the squares of the derivatives in the x, y, and z directions. The horizontal derivatives can be obtained with a spline interpolator, whereas the vertical gradient is computed using Fourier transforms.

3.2. Radiometric signature of the RPB

From the analyzed radioelement abundance of K, Th, U, and total count, the superficial distribution of U counts (Fig. 5) identifies the major geological features at the RPB. The Orós-Jaguaribe domain is characterized by a monotonous radiometric pattern with low U counts at the western sides of both the Jaguaribe and Portalegre shear zones. Radiometric maxima, which occur between the Jaguaribe and Rodolfo Fernandes shear zones, are associated with the NNE-SSW–oriented plutonic rocks. The U count lineaments have sigmoidal shapes, trending from E–W to NE–SW. To the east of the Portalegre shear zone, low U count values (<200 cps) characterize the radiometric response of the Rio Piranhas domain. This pattern is broken where granitic rocks of pre-Brasiliano and Brasiliano ages (>0.5 Ga) crop out with U count values of more than 300 cps (1 and 2 in Fig. 5). These radiometric highs seem to extend southward to the Malta shear zone beyond the RPB sedimentary rocks. This fact has significance for basin gravity analysis, as is addressed subsequently in this work.

The Granjeiro domain presents a uniform low U count distribution to the south, with just two anomalous areas represented by a supracrustal sequence at the southwestern portion of the area and a Brasiliano granitic body to the south of the Sousa Subbasin (3 and 4 in Fig. 5, respectively). Finally, the low U count values (<250 cps) of the RPB are a signature of basin infill terrigenous sediments. At the central and eastern parts of Brejo das Freiras and Sousa subbasins, radiometric minima are NE–SW oriented and parallel to the major prerift structures of the basement grain.

3.3. Magnetic signature of the RPB

The magnetic anomaly map reduced to the pole (Fig. 6) reveals a complex structural framework in the RPB area. A NE–SW-trending, magnetic lineament pattern that occurs to the north of the basin presents E–W-oriented inflexions in the western portion of the Orós-Jaguaribe domain. To the south, the magnetic alignments are E–W oriented in the central and eastern parts of the Granjeiro domain and NE–SW oriented to the west. E–W-trending lineaments are not clearly observed in the western border of the Brejo das Freiras Subbasin, where shear zones inflect to northwest (Fig. 2).

Between the Portalegre shear zone and the high U count domain (2 in Fig. 5), the magnetic data exhibit a negative magnetic zone, represented by the Rio Piranhas domain. In contrast with the positive magnetic response (>80 nT) of the granitic rocks in the northeastern portion of the area (2 in Fig. 6), the Paraná batholith located to the east of the Portalegre shear zone (1 in Figs. 5 and 6) is characterized by a NE–SW-trending negative magnetic anomaly, which denotes its distinct mineralogical composition.

The magnetic pattern of the RPB comprises a zone of NE–SW-trending, low to medium amplitude (−100 to 0 nT), negative anomalies with medium to high wavelength (Fig. 6). Exceptionally, positive anomalies are present at the eastern boundary of the Sousa Subbasin, which probably represents a horst-like feature in the basement grain. More than a variation in the magnetic content of the basin-filled sediments, such a magnetic array seems to reflect lithologic heterogeneities of the basement rocks, extending southward beneath the basin. Magnetic minima are concentrated in the northern limits of the subbasins, where the nonmagnetic sedimentary cover is thinner.

The magnetic patterns depicted in Fig. 6 are better emphasized in the 3D analytic signal map (Fig. 7). In general, shear zones are well marked by high amplitudes of the analytic signal, whereas supracrustal terrains, Brasiliano granitic bodies, and the RPB show very low amplitudes. In the eastern part of the Rio Piranhas domain, the outcropping Neoproterozoic rocks, which present unexpectedly high amplitudes, are composed mainly of an intrusive magmatic suite (2 in Figs. 5 and 6). Magnetic alignments are better observed with a preferential NE–SW orientation in the RPB. However, linear features show NW–SE-oriented trends in both subbasins, revealing details of their internal architecture, which we discuss together with the gravity results. The distribution of analytic signal also reveals WNW–ESE-trending magnetic

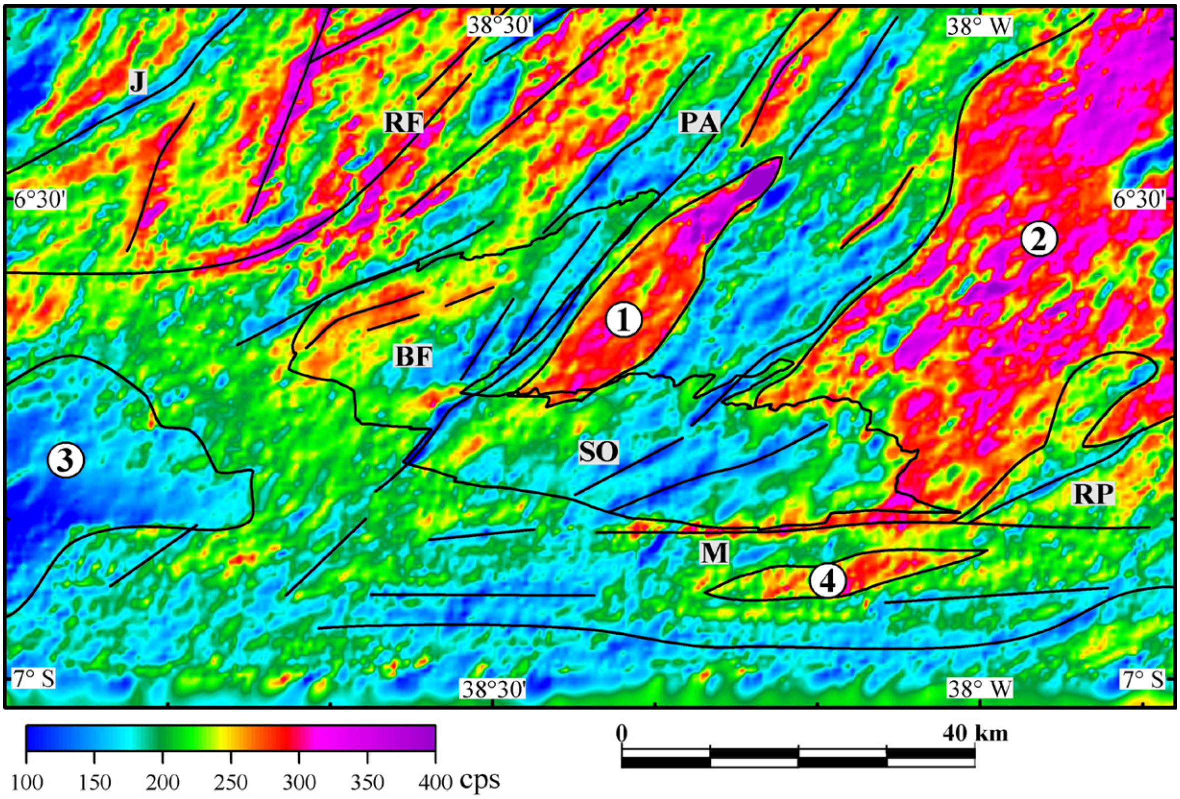

Fig. 5. Gamma ray U counts of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) with major radiometric domains – (1) Paraná batholith, (2) Neoproterozoic magmatic suite composed of granites, (3 and 4) Neoproterozoic supracrustal terrains in Granjeiro domain – and lineaments (J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas).

lineaments to west, which are slightly visible in the magnetic anomaly map (Fig. 6) and can be correlated with the SE inflexion of the structural features associated to the E–W-trending Patos shear zone.

4. Gravity data

4.1. Data acquisition and processing

A gravity survey was carried out by the Laboratory of Geophysics of Ceará Federal University in the region of the RPB in September 2001. The survey yielded 276 new gravity stations, which combined with gravity observation points from previous surveys (Bedregal, 1991; Castro et al., 1998; Castro and Castelo Branco, 1999), comprise a data set with 728 measurements, all shown together in the Bouguer anomaly map in Fig. 8. Each station was established with a Lacoste-Romberg Model G gravity meter, with precision of ±0.01 mGal. Geographic coordinates were determined using GPS, and elevations use either differential GPS or barometer arrays. Drift, latitude, free-air, and Bouguer reductions were applied, referring the data to the International Gravity Standardization Net 1971 (IGSN-71). The gravity maps were interpolated at 5400 equal spaced points with 1.5 km station intervals.

Because residual gravity data more clearly reflect shallow density distributions, a regional-residual separation filtering was applied to the RPB data set. The regional gravity field was estimated by applying the robust polynomial surface fitting method developed by Beltrão et al. (1991). The residual gravity component was obtained by subtracting the fourth-order, best-fit surface from the Bouguer anomaly. The residual gravity map (Fig. 9) shows a central, up to −25 mGal minimum, which closely corresponds to the geological boundaries of the RPB. Exceptionally, a negative anomaly ("1" in Fig. 9) extends to the north of the RPB's NW boundary, exactly where the slightly deformed Paraná batholith, mapped by Sénant and Popoff (1991), crops out. This porphyritic granite has well-defined radiometric and magnetic signatures (Figs. 5 and 6) and probably played an important role in the basin rifting process. Its negative gravity effect interferes with the negative anomalies of the basin deposits and must be taken into account during the gravity modeling.

The RPB basement structural domains present distinctive patterns of gravity anomalies (Fig. 9), which are well-subdivided by the Malta shear zone. To the south, the Granjeiro domain is characterized by positive anomalies, which extend as an E–W-trending feature, enlarging westward in the northwesternmost area and following the

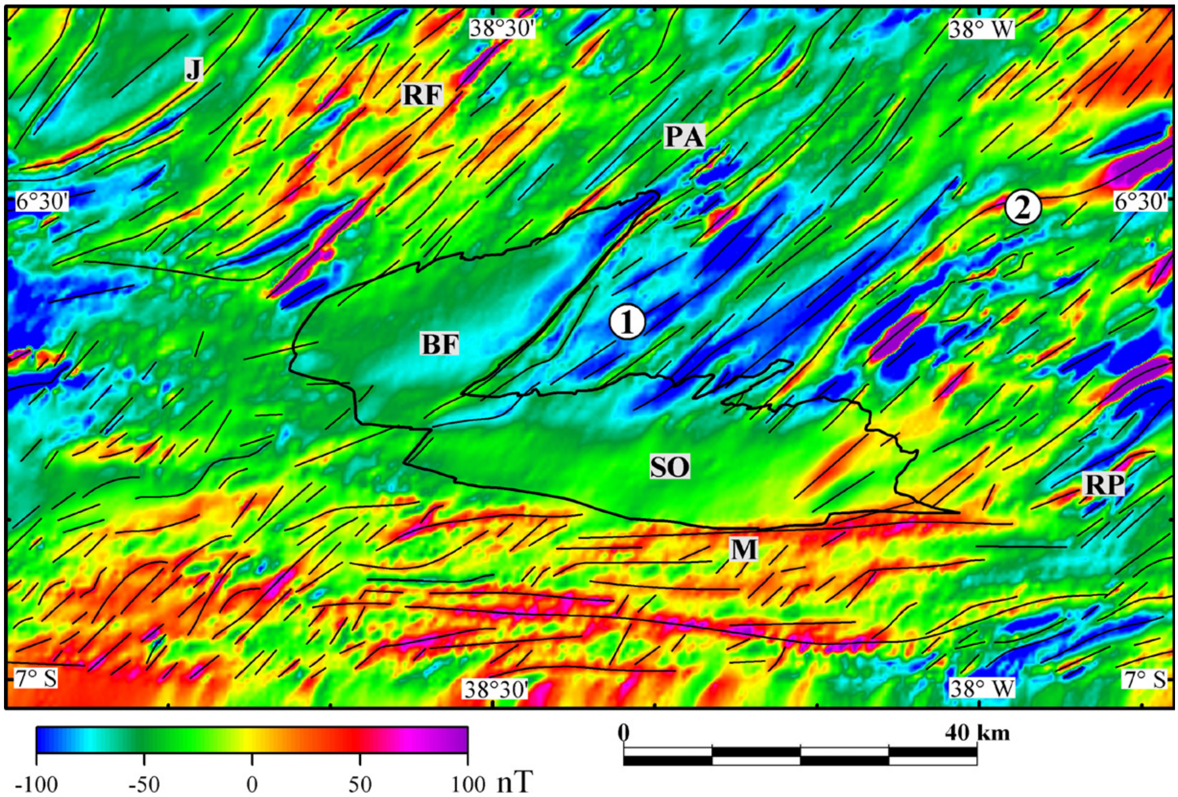

Fig. 6. Magnetic anomaly map reduced to the pole of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) with major magnetic lineaments (J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas). (1) Paraná batholith, (2) Neoproterozoic magmatic suite composed of granites.

NW inflexion of the shear zone, where the gravity field reaches values exceeding 15 mGal (3 in Fig. 9). In contrast, negative anomalies dominate to the north of the Malta shear zone, which is the result mainly of granite bodies and basin-filled sediments. These anomalies present a NE–SW trend, except for the Sousa Subbasin that shows an E–W-oriented anomaly.

4.2. Gravity modeling method

The heterogeneous nature of the basement revealed by geological and geophysical maps can easily violate the most common premise used in gravity-inverse methods. In many modeling procedures, the internal geometry of sedimentary basins is represented by an interface that separates two homogeneous media. However, severe errors can occur when the underlying basement rocks have significant density variations (e.g., Castro and Castelo Branco, 1999; Castro et al., 2002), especially in the RPB, as revealed by aerogeophysical and gravity data.

Three-dimensional gravity data inversion was performed using a procedure similar to the one developed by Jachens and Moring (1990). This method departs from others by taking into account the possibility that underlying basement rocks have variable density. It strives to separate gravity measurements into the component caused by the basin itself (g_d) and the component due to variations in density of underlying basement (g_b). The following steps are described in detail by Blakely (1995):

1. The first iteration assumes that g_b is defined by those stations located on basement outcrops and calculates a smooth gravitational surface across the entire study area. It constitutes the first approximation $g_b^{(1)}$ to the basement field but is a crude estimate because gravity values observed at basement stations still include the gravity effect of the nearby basin.
2. The first approximation to g_d is found by subtracting $g_b^{(1)}$ from the observed gravity. The new residual $g_d^{(1)}$ is used to find a first approximation of basement depth using the iterative procedure developed by Rao and Babu (1991). This method determines the shape, at depth, of an interface that separates two homogeneous media. This interface is modeled as a bundle of rectangular blocks that have variable density contrasts with respect to the surrounding basement. A quadratic function [$\Delta\rho\ (z) = a_0 + a_1 z + a_2 z^2$, where z represents depth, a_0 is the extrapolated value of density contrast at the surface in g/cm^3, and a_1 and a_2 are constants of the function] accounts for an increase in density with depth within the basin due to the compaction of the deposits.

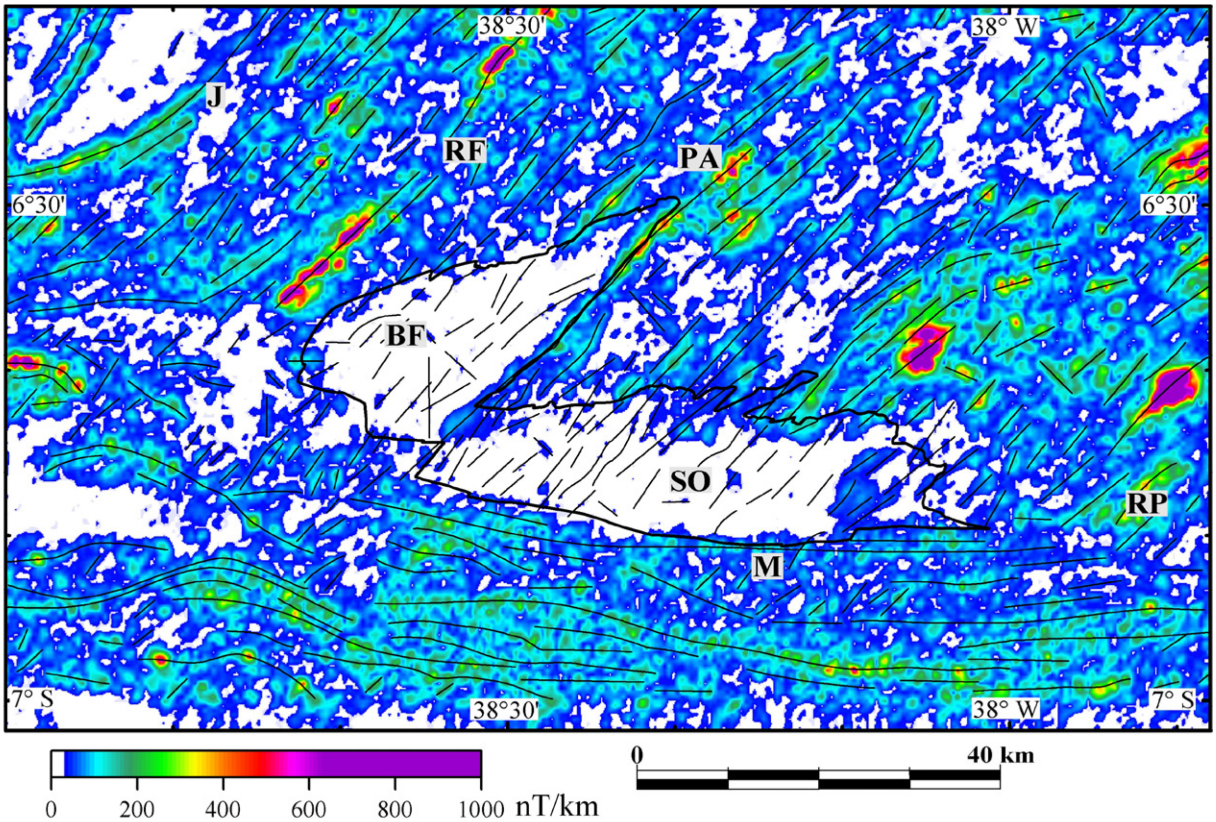

Fig. 7. Color image of the 3D analytic signal of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) with major magnetic lineaments (J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas).

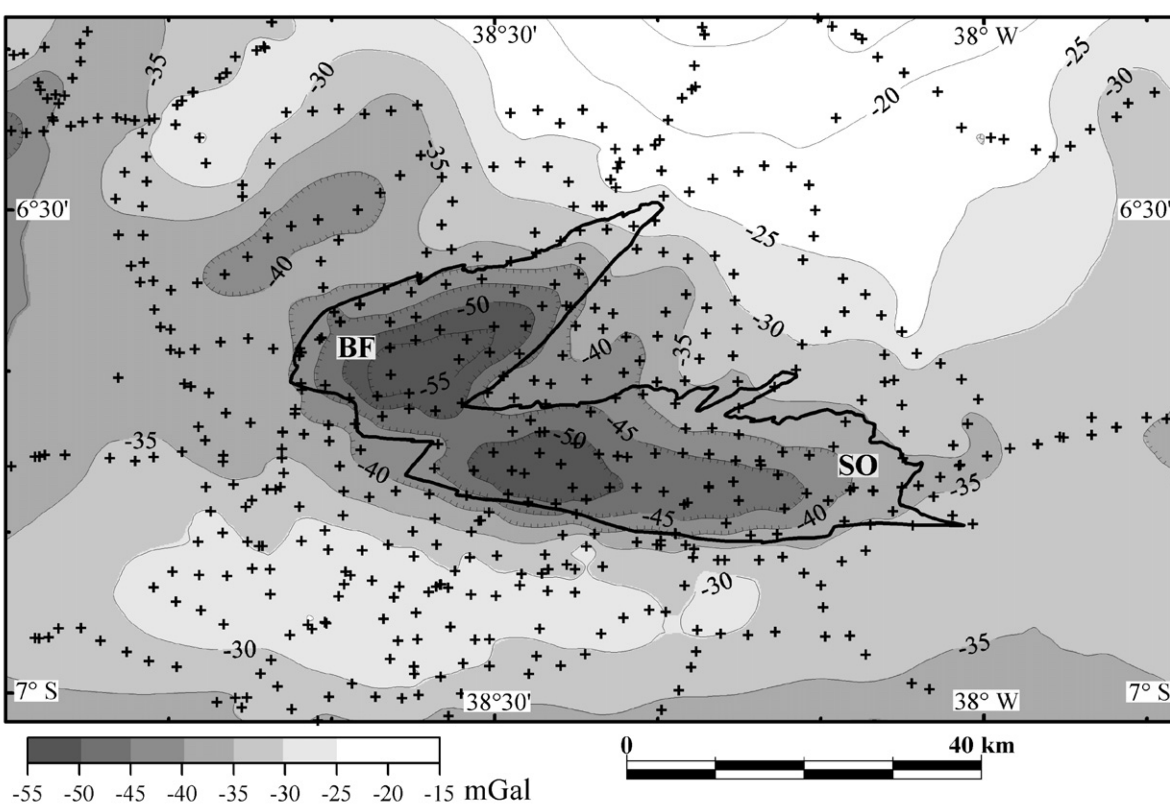

Fig. 8. Bouguer anomaly map of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) with the location of gravity stations.

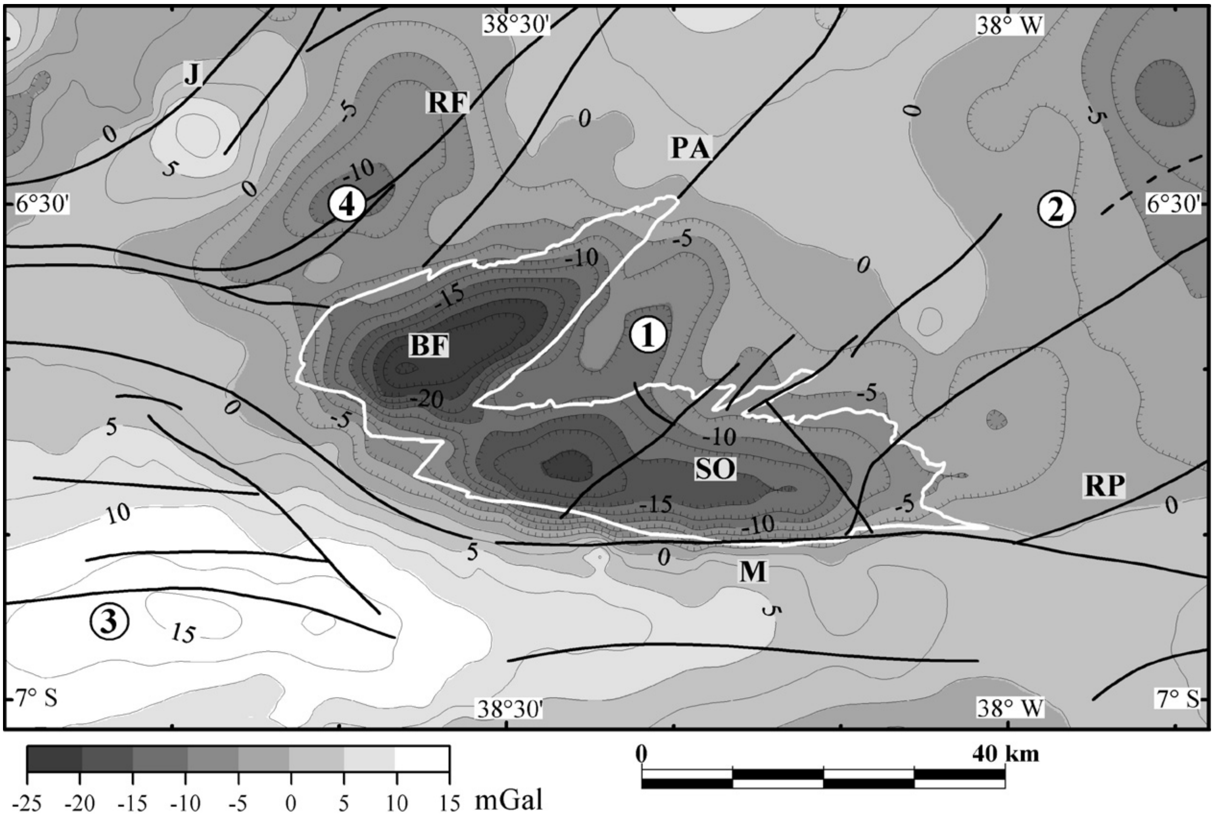

Fig. 9. Residual anomaly map of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) with major faults (J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas). (1, 2, and 4) Neoproterozoic granites, (3) Neoproterozoic supracrustal terrain in Granjeiro domain. The white line marks the basin boundary, and the dark lines mark major faults.

The gravitational effect of the basin is then calculated and subtracted from basement gravity stations to produce the next approximation for the basement gravity $g_b^{(2)}$ pattern. These steps are repeated until the solution converges to a satisfactory separation of basin and basement gravity. The shape of the low-density basin and the gravity field of the basement without the effects of the basin are the main results.

The calculated thickness of basin-filling deposits depends critically on the density–depth function used in the modeling (Blakely et al., 1999). For the RPB, 35 density measurements were carried out on selected samples considered to represent both sedimentary and basement rocks. The averaged density contrast established in surface was -0.62 ± 0.05 g/cm^3. However, this superficial contrast does not reflect the increase of the density of the sedimentary package with depth. Because the petrophysical parameters of the Potiguar Basin (Figs. 1 and 4) are well known, as a result of intensive oil exploration since the 1970s (e.g., Mello, 1989) and the high similarity of both basins, we opt to use the density vs. depth data of the Potiguar Basin rift phase to achieve a more realistic density–depth distribution for the RPB in the inversion procedure. The dependence of the sediment density with depth, extracted from well-logging data in the Potiguar Basin (unpublished data from Petrobras; see also Milani and Latgé, 1987), is fitted to a quadratic function by least-squares, and the coefficients are estimated as follows: $a_0 = -0.297$ g/cm^3, $a_1 = 7.097 \times 10^{-5}$, and $a_2 = -8.836 \times 10^{-11}$.

4.3. Rift geometry and basin infill

On the basis of 3D gravity modeling, the internal architecture of the RPB, which encompasses three asymmetric half-grabens (Brejo das Freiras, Sousa, and Pombal), appears in Fig. 10. The Pombal Subbasin was not considered in the gravity study due to its poor gravity station cover. The stratigraphic well LFst-1-PB, near the depocenter of the Sousa Subbasin at its southeastern edge (Figs. 2 and 10), reached the crystalline basement at 990 m (Lima and Coelho, 1987). Our gravity modeling yielded a sedimentary cover 917 m deep, which represents a difference of 7.4% compared with borehole data. If this variation is extrapolated to the whole basin, we can assume good confidence obtained by the inverse method.

The Brejo das Freiras Subbasin is controlled by the NE–SW-trending Portalegre Fault, which dips to NW. The sedimentary sequence is up to 2400 m thick near its SW border. A basement high, whose NE–SW axial direction is 30° oblique to the master fault, divides the depocenter in two parts (Fig. 10). However, the E–W-trending Malta fault, a reactivated segment of the Patos shear zone, marks

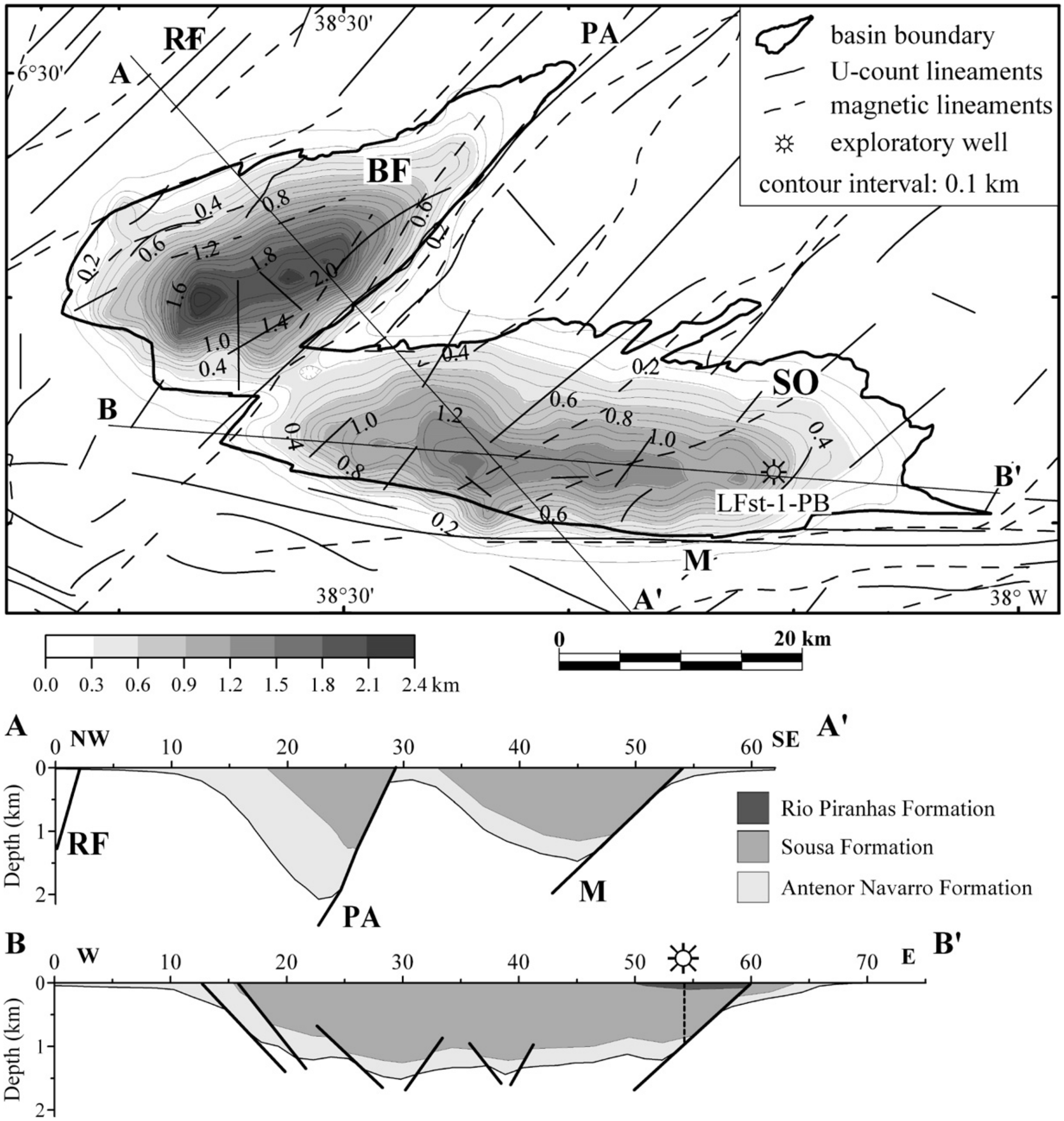

Fig. 10. Basement contour map of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa) derived from 3D gravity modeling with major magnetic lineaments (RF, Rodolfo Fernandes; PA, Portalegre; M, Malta). Geologic sections (A–A′ and B–B′) across Rio do Peixe Basin inferred from gravity modeling and surface geology.

the southern boundary of the Sousa Subbasin. A series of less pronounced depocenters is observed in the E–W-trending basin axis, which is filled with up to 1500 m of synrift sediments.

When seismic reflection sections are not available for the RPB, the sedimentary filling geometry of the Brejo das Freiras and Sousa subbasins was inferred from the gravity model (Fig. 10) and through extrapolation of surface data (Fig. 2), which is constrained by stratigraphic well data (LFst-1-PB). In this sense, the geological sections (A–A′ and B–B′ in Fig. 10) represent a schematic distribution of the sedimentary sequences in depth. According to our qualitative interpretation, the lowermost Antenor Navarro Formation is about 1600 m thick in the deepest Brejo das Freiras Subbasin depocenter and becomes much thinner (less than 500 m) in the Sousa Subbasin. The overlying Sousa Formation shows an apparently uniform thickness (about 1250 m) in both subbasins. Its sedimentary rocks are limited by basement highs, which form strike ramps at the northern and southern borders of the Brejo das Freiras Subbasin (Fig. 10). The uppermost Rio Piranhas Formation is recorded only in the Sousa Subbasin with a thickness of 200 m. This stratigraphic framework suggests that tectonic activity was initially more intense at the Brejo das Freiras Subbasin and migrated eastward (Françolin et al., 1994).

The proposed stratigraphic distribution at depth is supported by apatite fission track data, which indicate that the western block in the Portalegre fault zone experienced a 3–4 km downward movement before 140 Ma. Thus, the opposite eastern block was exhumed and eroded, which would provide the source for sediment infilling in the Brejo das Freiras Subbasin (Nobrega et al., 2005). After 140 Ma, the whole region was buried by an extensive cover that linked the Potiguar Basin to the Cariri basins along the Portalegre fault zone.

Furthermore, Fig. 10 shows the structural control of the basin internal geometry, which was revealed by the superposition of the basin model derived from gravity, radiometric counts (Fig. 5), and magnetic lineaments of the 3D analytic signal (Fig. 7). Coincidence of magnetic and gravity features is consistent with the assumption that the basin architecture is strongly influenced by the preexisting upper crustal structures.

The Portalegre and Malta steep master faults (PA and M in Fig. 10) mark the southern and southeastern margins of the RPB, whereas NE–SW-trending minor structures apparently control the relief of the basement surface beneath the basin. Although the Sousa Subbasin has an elongated E–W-trending shape axis, the structures evidenced both by aerogeophysical lineaments and gravity modeling suggests a NE–SW-trending tectonic control of its internal geometry.

Release faults, as defined originally by Destro and Masiero (1993), occur nearly perpendicular or oblique to the Portalegre and Malta master faults, forming marginal strike ramps in both subbasins and a central horst structure in the Brejo das Freiras Subbasin (Fig. 11). These secondary faults die out within individual hangingwalls and are responsible for the rough basement relief beneath the RPB. Such cross-faults are geometrically required to accommodate variable displacements along the strike of a normal fault (Destro, 1995).

In the southern border of the RPB, the Santa Helena High has been interpreted as either crustal thickening by Françolin et al. (1994) or a strike relay ramp by Peacock and Sanderson (1995). However, the basin geometry derived from gravity modeling (Fig. 11) suggests that this basement high probably represents a strike ramp, over which an important release fault formed.

In addition, another product provided by the gravity modeling is the gravitational attraction of the basement rocks without the effect of the overlying basin. Comparing the residual anomalies map (Fig. 9) with the gravity map subtracted from basin effect (Fig. 12), we observe a very satisfactory attenuation of gravity lows related to less dense basin-filling sediments. In the RPB region, the resulting negative values of the gravity field relate to a series of granite bodies that intruded the boundary region between three structural domains (Fig. 2). The gravity signature of the Paraná batholith at the northwestern border of the Sousa Subbasin is especially interesting. The gravity low ("1" in Fig. 12) reveals the actual magnitude of this granite beneath the basin, which comprises the top of the basement in the northern part of the Brejo das Freiras Subbasin, as well as the western part of the Sousa Subbasin. Its eastern side seems limited by a NE–SW-trending fault, which also marks the limit of the deepest depocenters of this subbasin (Fig. 10). The granite played an important role in the tectonic development of the rift geometry, as discussed subsequently.

5. Discussion

5.1. Geodynamic scenario of the northeast Brazilian rift system

The Rio do Peixe Basin is part of the southern segment of the so-called Cariri Potiguar rift system (Matos, 1992, 1999), which encompasses other rift structures such as the

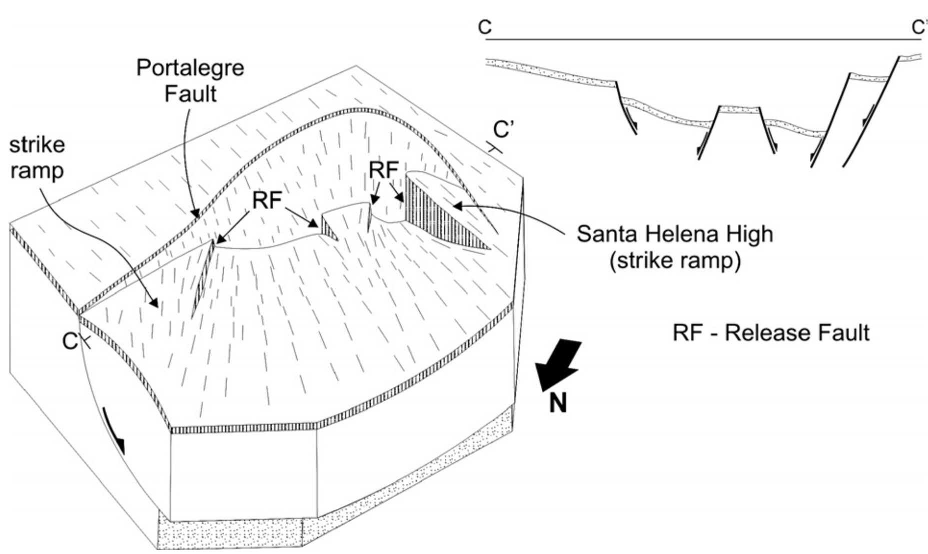

Fig. 11. Block diagram and cross-section showing the internal geometry of the Brejo das Freiras Subbasin. Release faults control the structural framework of the basin in response to varying throws along the strike of the Portalegre fault.

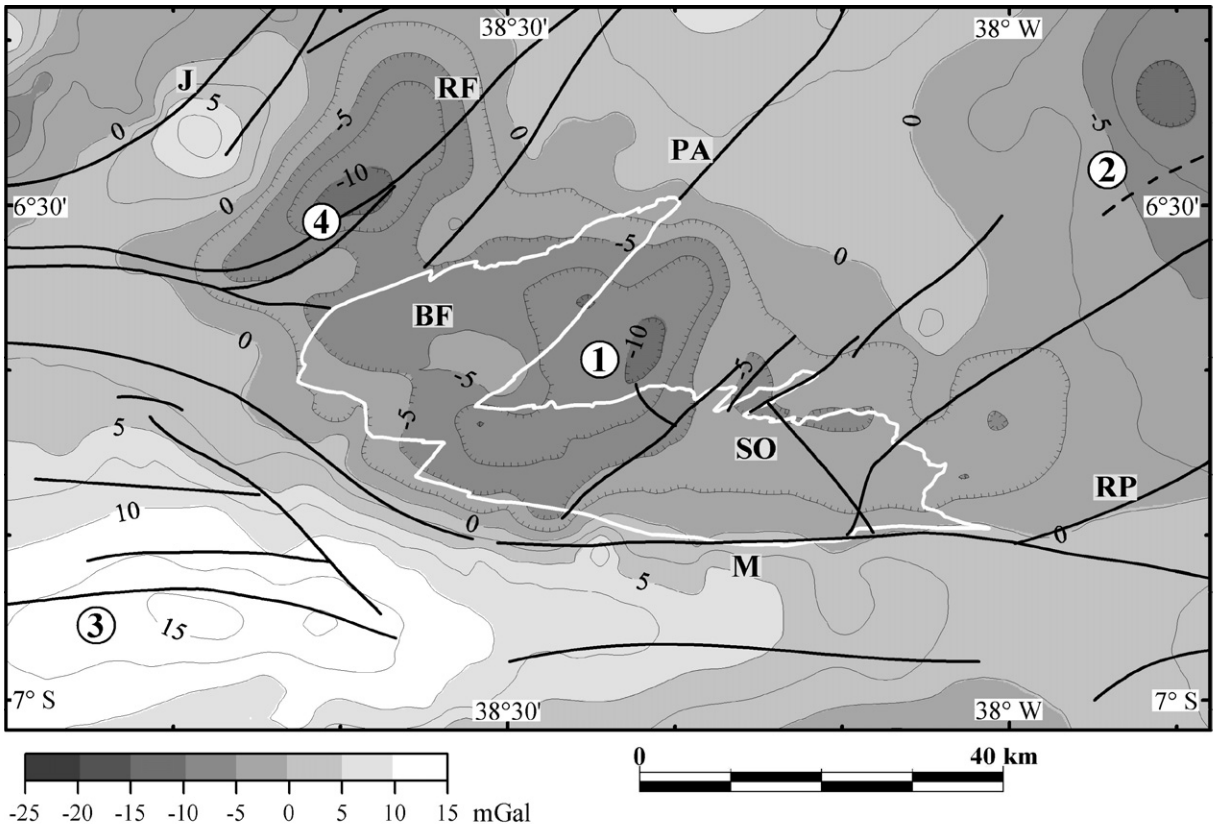

Fig. 12. Residual anomaly map of the basement without the gravity effect of the Rio do Peixe Basin (subbasins: BF, Brejo das Freiras; SO, Sousa). Faults: J, Jaguaribe; RF, Rodolfo Fernandes; PA, Portalegre; M, Malta; RP, Rio Piranhas. (1, 2, and 4) Brasiliano granitic bodies, (3) Neoproterozoic cover terrain in Granjeiro domain.

Potiguar, Araripe, and Iguatu basins (Fig. 1). A regional crustal picture beneath these tectonic elements, constructed by Castro and Medeiros (1997) and Castro et al. (1998), consists of 500 km of a well-defined NE–SW-oriented gravity high aligned in the northeastern portion of the Borborema Province (Fig. 4). Many anomalies can be correlated directly with geologic features observed in the Precambrian framework along this trend, which is the most important aspect in basin-forming processes. But many other anomalies do not correspond to known basement geological features and may be caused by density variations within the crust. Our attention focuses on these geophysical signatures that most closely reflect the tectonic and structural character of the basement grain.

In a complete view, the major sedimentary events within the BP can be broadly understood with the proposal of two development phases (Chang et al., 1992). The first phase, the rifting or Synrift Phase II, consists of taphrogenetic movements initiated during the Early Cretaceous. Assuming that the isostatic equilibrium was maintained during uniform extension, some mechanical subsidence would be produced during the rifting phase (e.g., Keen, 1987; Ziegler, 1992), resulting in the accumulation of a faulted sequence of sediments (e.g., Ziegler and Cloetingh, 2003). The second phase consists of a gradual regional subsidence that resulted in the formation of a huge marine sedimentary wedge. Cooling of the lithosphere, its resulting contraction, and loading effects may explain this gradual regional subsidence phase (e.g., Ruppel, 1995). The presence of the broad gravity maximum (Fig. 4) in closed geographic correspondence with a high heat flow anomaly (>100 mW/m^2; Hamza and Muñoz, 1996) could favor the interpretation that the mass excess in depth is responsible, at least in part, for the regional subsidence phase (Castro et al., 1998). This last stage is absent in the Rio do Peixe area (Françolin, 1992). According to Matos (1992) and Ponte and Ponte Filho (1996), the major synrift phase was prematurely aborted in the Rio do Peixe, Iguatu, and onshore Potiguar basins. In contrast, the Araripe and offshore Potiguar basins remained active during the second phase, which affected the NE Brazilian rift system in Late Barremian, named Synrift Phase III by Chang et al. (1988), which received sediments from far west at the Equatorial Branch. The E–W-oriented extensional forces caused the reactivation of older Precambrian mylonitic zones at the rifting onset.

5.2. Tectonic implications of the RPB

By comparing local and regional basement elements with tectonostratigraphic aspects of the RPB, using aeromagnetic, gravity, and radiometric data, as well as structural features of the basement grain, we suggest a complex geodynamic scenario, in which both deep and shallow structural effects in the adjoining basin area are recorded. Initial analysis has determined the gamma ray and geopotential field signatures of key features, such as compositional variations in crustal blocks and regional fault patterns. Next, the role of regional deep shear zones, such as Portalegre, was investigated to access insights into the whole basin geodynamic evolution.

In the surrounding basement grain, the consistent geographic association of gravity and magnetic anomalies are best explained by a crustal source. The Precambrian terrains adjoining the RPB consist of metasedimentary rocks and high-grade migmatitic inliers, intensively intruded by granites (Fig. 2). Both magnetic and gravity maps (Figs. 6 and 9) have high amplitude positive and negative anomalies in this area, reflecting the wide variation in physical rock properties, whereas the U counts map (Fig. 5) reveals high concentrations in granite intrusions in the Rio Piranhas and Granjeiro domains and the central part of the Orós-Jaguaribe domain. All geophysical data have strong NE–SW- to E–W-trending fabric, which mimics the orientation of the major tectonic features of the rift border.

On a smaller scale, the regional component of the gravity field is dominated by a relatively weak positive gravity anomaly over the graben structures (Figs. 4 and 13), indicating near-isostatic equilibrium. A simple estimation of the gravity effect caused by sedimentary thickening from 1 to 2 km in the graben area would result in anomalies from at least −15 to −25 mGal. These high values also indicate the existence of soft topographic effects (less than 0.4 km) on the uplift of the Moho surface beneath the graben (Figs. 4 and 13).

The shapes and trends of the subbasins with respect to the faults (Figs. 10 and 11) clearly indicate that the origin of the subbasins is the result of overstepped divergent directional faults. The fault traces step left, forming areas of tension, where the RPB was nucleated following the major E–W-trending crustal discontinuity (Fig. 14). The whole RPB consists of three easterly tilted subbasins with half-graben geometry separated by uplifted Precambrian blocks. The very striking NE–SW-trending negative gravity anomaly (Figs. 9 and 12) separates the RPB into two basinal compartments, likely ascribed to push-up and uplift of the internal high and probably due to isostatic equilibrium of the Paraná batholith in the basement framework. This intrusive body is well identified in the U count map of Fig. 5. The emplacement of this body probably made the upper crust more resistant, anchoring and deviating the mechanical subsidence. The whole dimension of this granite beneath the basin is well illustrated in Fig. 12. Its eastern border seems consistent with a NE–SW-trending fault, which limits the deepest depocenter of the Sousa Subbasin (Fig. 10). It could be important evidence of previous structural control on the rift development.

Upper levels of the basement grain are considered to have a structure based on crustal blocks bounded by faults with varying depths of penetration, as is reflected both on gravity and magnetic anomaly maps. Some of these faults are confined to the upper levels of the crust, whereas others reach the mantle. Anomalies representing these NE–SW-oriented deep anisotropies change gradually to an E–W direction, with the amplitude of transcurrent displacements ranging from slight dislocations to dozens of kilometers (Figs. 1 and 4). Reactivation of these structures as normal faults occurred in the Early Cretaceous during a period of extension and mechanical subsidence (Françolin and Szatmari, 1987; Françolin et al., 1994). The basin is further compartmentalized by a second minor orthogonal fault family composed of transfer elements, which dissect the Precambrian grain, as shown in Figs. 2, 7, and 10.

When an E–W-trending Malta shear zone interferes with NE–SW-oriented segments of shear zones (e.g., Portalegre), releasing stress zones develop and, as a consequence, nucleated mechanical subsidence patterns emerge. West of the corresponding gravity model (Fig. 10), the fault array in the internal geometry of the Sousa Subbasin is more consistent with growth faults, which were active in the early stages of its development. Furthermore, the regional gravity transect (Fig. 13) shows a slightly thinner crust beneath the RPB. Crustal extension during the period of rift climax resulted in progressive uplift of the central block, separating the whole basin in two half-grabens and generating subsidiary internal NNW–SSE-trending faults inside the eastern subbasin and NW–SE-oriented faults in the western one, both of which acted as release faults governed by the reactivation of the underlying basement fabric. Major release faults were formed over marginal strike ramps, which controlled the Sousa Formation at the northern and southern borders of the Brejo das Freiras Subbasin (Fig. 11). The Santa Helena High represents the most pronounced strike ramp of the RPB, also described as a relay ramp by Peacock and Sanderson (1995).

Sénant and Popoff (1991) attribute faulting and basin formation to an episode of crustal thinning with NNW extension (large black arrows in Fig. 14). Although Françolin et al. (1994) agrees with the NNW–SSE extension direction, they claim that left-lateral wrenching was the main mechanism of deformation in the RPB (Fig. 14). A simple shear basin-forming mechanism is clearly indicated by not only dip-slip throw from reactivated crustal anisotropies into the basin but also strike-slip motion along the RPB edge (Bedregal and Chemale, 1992; Françolin et al., 1994).

The close correlation between magnetic and gravity data justify modeling the gravity data transecting the whole basin (Fig. 13). This model also provides an opportunity to test the compatibility of the geometries and thicknesses of the sediment columns obtained from modeling procedures. Previously, we used magnetic and radiometric profiles to make this comparison with near-surface geology around the basin. As mentioned previously, the regional

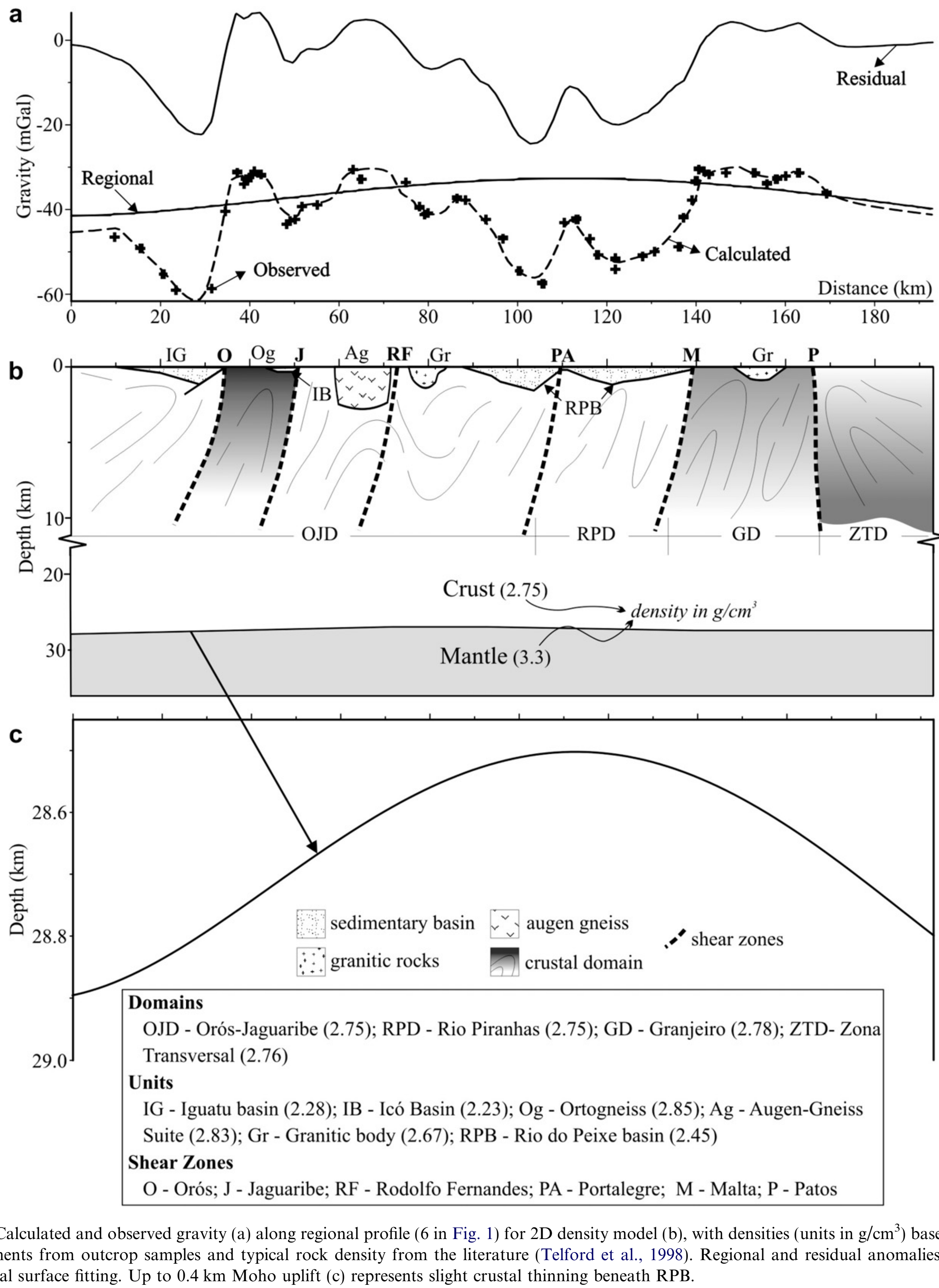

Fig. 13. Calculated and observed gravity (a) along regional profile (6 in Fig. 1) for 2D density model (b), with densities (units in g/cm^3) based initially on measurements from outcrop samples and typical rock density from the literature (Telford et al., 1998). Regional and residual anomalies obtained by polynomial surface fitting. Up to 0.4 km Moho uplift (c) represents slight crustal thinning beneath RPB.

gravity anomaly basically reflects the variation in crustal thickness across the RPB. Vertical tectonic movements during rifting cannot be explained by lithospheric flexure, because the isostatic equilibrium is too local and the wavelength of the tectonic movement is too short. It is more plausible to interpret the mechanical subsidence as a response of deep reactivation of crustal discontinuities, as shown in the 2D modeling of Figs. 4 and 13. The same mechanism of mechanical subsidence was invoked by Dunbar and Sawyer (1989) and Braun and Beaumont (1989) to

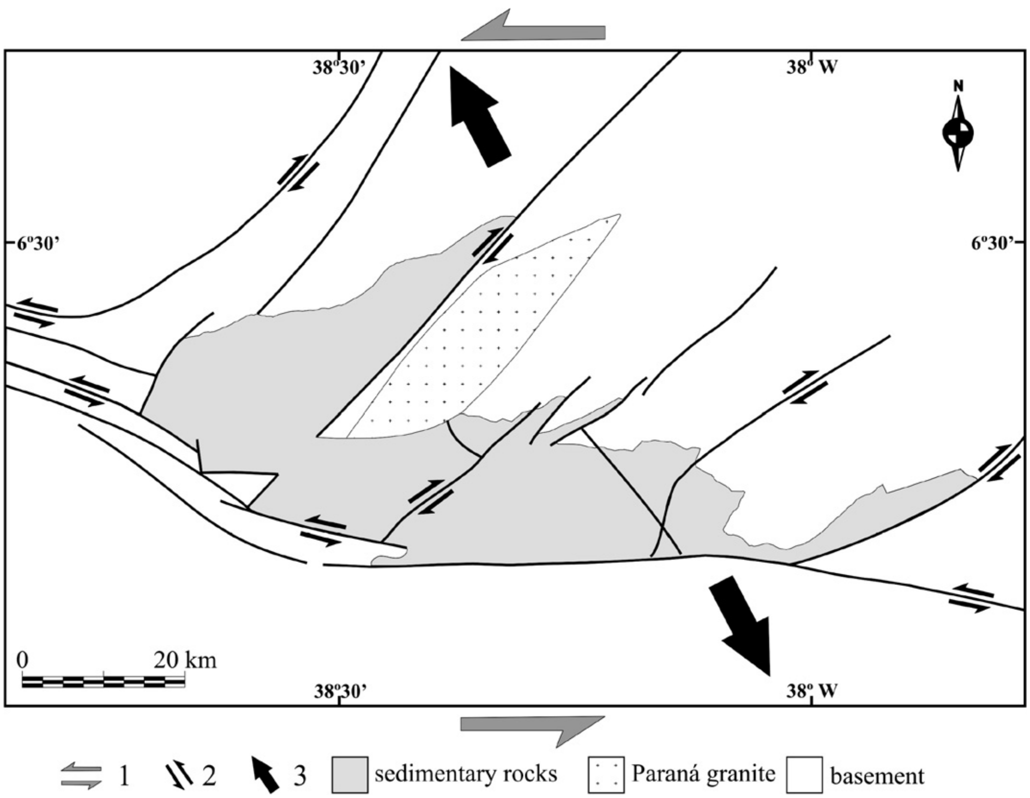

Fig. 14. Tectonic setting of the Rio do Peixe Basin. Arrows: (1) model of left-lateral wrenching (Françolin et al., 1994) with strike-slip senses on master faults (2); and (3) model of NNW–SSE-trending extension (Sénant and Popoff, 1991; Matos, 1992).

explain rifting in environments dominated by preexisting crustal weaknesses and low rates of continental stretching. Results of thermomechanical simulation indicate that narrow localized grabens, like the Cariri rift system, depend basically on the existence of low-strength areas along deep discontinuities (e.g., releasing bend), where the discontinuities can be reactivated, nucleating rift structures and extensional strain can be partitioned, and generally decoupling of the crust bottom from the mantle can occur. The major-fault bordering RPB to the east coincides with a releasing bend of the Portalegre shear zone, enabling graben formation. The probable absence of lithospheric stretching below the RPB suggests that extensional forces would be dissipated horizontally in the crust bottom.

6. Conclusions

Gamma ray, geopotential field data, and structural evidence enables us to establish the relationship between the predeformed Precambrian basement and the extensional mechanism that formed the complex rift architecture of the RPB of NE Brazil. During the Early Cretaceous, the Neoproterozoic BP was subjected to a NW–SE-oriented extension that formed a series of intracratonic rift basins, which preferentially developed where preexisting mechanically weak zones were present in the upper crust. The Rio do Peixe rift opened at the intersection of three Precambrian tectonostratigraphic domains, strongly deformed by shear zones and intruded by granitic rocks of Neoproterozoic age. The residual component of the gravity field reveals a strong coincidence between gravity lows and the area that concentrates the rift basins, suggesting that the upper crust composed of low density supracrustal sequences and granites offers minor tensile strength to the extensional deformation. The Paraná batholith acted in the basin-forming process to anchor the Brejo das Freiras Subbasin at the NE–SW-oriented Portalegre fault and deviate the mechanical subsidence of the Sousa Subbasin eastward along the E–W-oriented Malta Fault Zone. These two families of faults represent the reactivation of Brasiliano ductile shear zones, which played a definitive role in the structural control of the final rift architecture.

The sequence of small basins in this region is located at the inflection of sigmoid-shaped extensive shear zones. The Brejo das Freiras Subbasin is the deepest, up to 2400 m in sediment thickness. The Sousa Subbasin has an uncommon E–W-elongated shape and is relatively shallow in depth ($\sim$1600 m). Furthermore, there is no evidence of major NE–SW normal fault bounding of this subbasin to the east. In contrast, overstepped secondary release faults accommodate variable displacements along-strike of the Portalegre and Malta master faults and mark the eastern limits of the depocenters with tilted blocks dipping to the SE. These basement highs strongly restrict Sousa Formation sedimentation in the Brejo das Freiras Subbasin and western part of the Sousa Subbasin. The Pombal Subbasin has a narrow shape accompanying the Rio Piranhas shear zone and probably represents an embryonic rift stage infill. Again, the strong NE–SW-trending fabric in the northern structural domains influenced the entire final rift geometry, as is revealed in the magnetic lineaments beneath the basin and by 3D gravity modeling.

Acknowledgments

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