Mapping the basement architecture using MT data across a coastal part of Borborema Province, NE Ceará-Brazil.

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Abstract

The Borborema Province is a key area in the amalgamation of West Gondwana by continental collision during the Brasiliano/Pan-African orogenies, it consists of a complex rock mosaic composed mainly by Proterozoic metasedimentary belts that amalgamate Archean-to-Paleoproterozoic gneiss-migmatite complexes.In this work we present the interpretation of 21 magnetotelluric (MT) and time domain EM (TDEM) soundings carried out along a 100 km profile in northeast of Borborema Province. Dimensionality analysis shows that a 3D electrical structure predominates in the subsurface and thus 3D inversion was carried out. The final geoelectric model allows delineating the geometry and variation in physical properties of different lithospheric blocks bounded by major electrical discontinuities. The interpretation was based on a 3D model obtained from the inversion of the MT data with validation of a 2D model inversion. The result allows, for the first time, the characterization of: 1) the uppermost structures correlated to the Mesocenozoic sedimentary formations and groundwater reservoirs, 2) a deeper Precambrian framework denoted by lithotypes of the Ceará Central and Rio Grande do Norte crustal tectonic domains and 3) distinctive anomalies corresponding to the Senador Pompeu, Orós and Jaguaribe Neoproterozoic shear zones.

Introduction

The major tectonic reactivation of the Brazilian shield is linked to the structures developed during the Brazilian Orogenic cycle (750 to 550 Ma) during the Precambrian. Since Almeida *et al.* (1981), the Borborema Province (BP) has been considered as a large crustal segment where Neoproterozoic tectono-thermal events reworked Archean-Paleoproterozoic basement and generates new tracts of Meso and Neoproterozic supracrustal rocks (Brito Neves *et al.* (2000), Van Schmus *et al.* (2008). Together with the counterpart located today on the African continent, BP is an important member of west-Gondwana (Arthaud *et al.* 2008; Van Schmus *et al.* 2008).

The geology at the southeastern coast of the Ceará State depicts very well this scenario, where the sedimentary record (Tertiary to Quaternary) covers more than 5.000 km^2. From the coast, this cover extents up to 60 km onshore, putting a lack in the regional Precambrian lithostructural pattern that occur between the Borborema Province and West-African counterpart. The detection and visualization of buried structures with a proper geophysical survey represents a goal in applied geophysics in that region. In order to better constrain the further geophysical interpretations, regional geologic synthesis needs to be addressed.

With a view to fill this gap, MT and TDEM surveys have been conducted in the year 2003 in BP northeast region, NE of Ceará. In order to understand the actual articulation of the crustal blocks and the role of large transcurrent lineaments in bringing these blocks together. There are a considerable number of segments in the BP with their own geologic characteristics, grouped into the various domains and sub-domains proposed for the province. Although they are reasonably well-known and delimited on the surface, the true nature of their limits at depth has still not been established, especially when represented by important and extensive shear zones.

Regional Geological Context

The Borborema Province (Almeida *et al.* 1981; Brito Neves *et al.* 2000; Van Schmus *et al.* 2008) covers a central part of a large late Neoproterozoic orogenic system resulting from the convergence and collision of the São Luis-West-Africa and São Francisco-Congo Kasai cratons. The province has different tectonic domains (Fig. 1), which contain variable volume of Archean to Paleoproterozoic basement gneissic-migmatitic rocks, Proterozoic supracrustals rocks, an expressive volume of Neoproterozoic granitoids and Phanerozoic covers. The tectonic domains limits are always defined by regional shear zones (Transbrasiliano, Senador Pompeu, Patos and Pernambuco) that depict a continental-scale network of transcurrent shear zones (Vauchez *et al.* 1995). In this context, the study area comprises a regional transect located where Senador Pompeu (boundary of Ceará Central and Rio Grande do Norte tectonic domains) and Jaguaribe shear zones occur, mainly overlearned by Tertiary sedimentary rocks and Quaternary sediments (Figure 1).

Geophysical Datasets

TDEM Data

Due to logistic reasons the profile was carried out a few km away from the coastline. Ten time-domain electromagnetic soundings (TDEM), using the TEM FAST48 equipment, were realized at the MT sites in order to correct probable static-shift effects over the MT data and to have a preliminary and rough image of the uppermost layers of the area. The TDEM soundings were acquired with a coincident loop scheme using 100m-sided loop. In general the recorded data were of good quality and highly repeatable over the band-width 7.0 to 500µs (up to 10^4µs at a few sites).

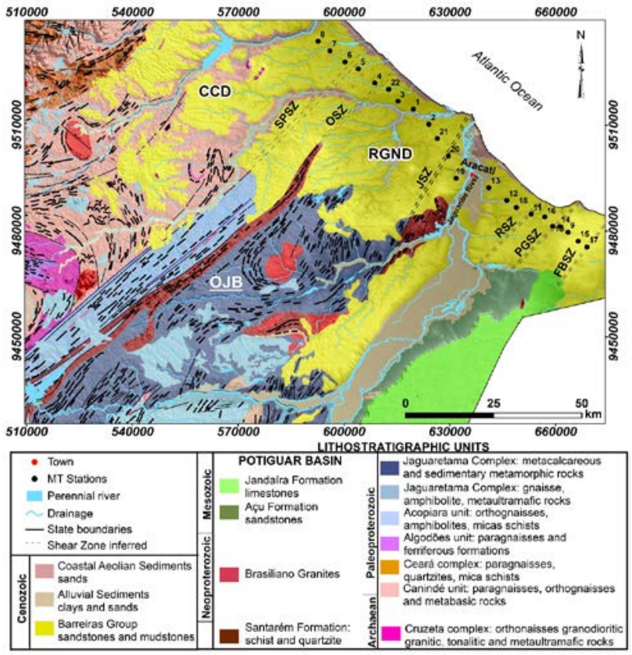

Figure 1: Geological map of northeastern Ceará State, southeast coast and adjacent continental lands. Tectonic domains (Ceará Central-CC and Rio Grande do Norte-RGND from Brito Neves et al. (2000) and Van Schmus et al. (2008). Neoproterozoic shear zones Senador Pompeu (SPSZ), Orós (OSZ), Jaguaribe (JSZ), RSZ: Retiro Shear Zone, PGSZ: Ponta Grossa Shear Zone; FBSZ: Fazenda Belém Shear Zone and main lithotectonic units constructed in part considering Cavalcante (2003).

MT data

The MT survey comprised 21 soundings spaced 5-10 km approximately, along a profile that runs roughly NW-SE (Figure 1). The MT profile is approximately sub-parallel to the ocean coast (10 km southwards). The measurement directions of the horizontal fields were N-S and E-W. The vertical magnetic component was recorded at 12 sites. Measuring times spanned 16 to 24 hours per site. The data were acquired in a period range 0,004-1000s using the ADU06-Metronix instrument.

Dimensionality of the measured impedances was studied by WALDIM code that uses a series of invariant rotations classifying from I1 to I7 and Q. The invariants I1 and I2 are dimensionless, and serve to normalize the remaining invariants that provide 1D information of the resistivity and geoelectric phase Martí et al. (2010).

Figure 2 shows the result obtained at each site for the entire period band. The dimensional complexity of the geoelectric structures beneath this profile is clear, with predominance of undetermined structures and 3D dimensionality. From center to east of profile there is an increase of 1D cases only concentrated at short periods, being associated to Potiguar basin. Long periods at sites over Rio Grande do Norte domain are dominated by undeterminated structures, this can be an indicative that data errors propagate into the invariants. 2D modeling of the MT dataset for this profile is not acceptable because it is not possible to determine a common geoelectric strike angle for the entire period range and for all sites along the profile. Thus, 3D inversion is necessary to avoid misinterpretation of the geoelectrical structure beneath this part of the Borborema Province and NW border of onshore Potiguar Basin.

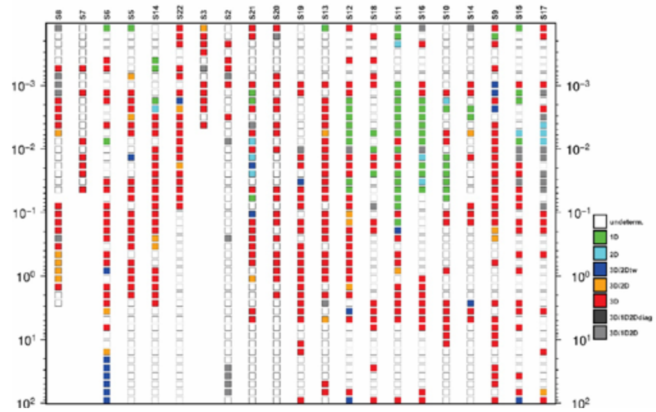

Figure 2: Map of dimensionality analysis using the WALDIM code at each site for the entire period band.

Figure 3 displays the strike angle obtained from tensor decomposition at each station for the whole period interval. At sites 6 and 22 close to SPSZ and OSZ in long periods there is a consistent change in strike, rotated to N-S direction. The same pattern occurs at site 9 near FBSZ. At the other stations, the azimuth of the geoelectric strike is oriented NE-SW (or NW-SE due to the 90◦ ambiguity in magnetotelluric strike analyses) it is consistent with the dominant geological trend in this sector of BP. This spatial variations in the azimuth are taken as evidence of dominant 3D structure.

Besides, a dimensionality analyses was done to 2D model also. So, dimensionality of the measured impedances was studied by using the Smith decomposition method (Smith, 1995). The behaviour of the E1rot and E2rot parameters of the Smith's decomposition is usually stable till 1 to10s, showing that the distortions (ocean effect is this case) start at longer periods. Figure 3 shows the strike direction at each site. As in the induction arrows, a different behaviour can be observed from north-west to south-east. In the north-western part of the profile (sites 8 to 19), the strike directions varied between 30º and 80º, whereas in the south-eastern part (sites 13 to 17) they are more stable, with the main strike values around 15º. Taking into account the strike of the main superficial tectonic structures and the results of the dimensionality analyses, a geoelectric strike of 40º, for all the profile, was assumed. Accordingly, the N130ºW and the N40ºE directions were associated with the TM and TE mode, respectively.

Results

<u>1D TDEM</u>

The TDEM data were inverted using 1D layered models. The resistivity pseudo-section constructed from the models is displayed in Figure 4. In general the uppermost layers connected to wet sands have resistivity between 20 and 100 Ωm. The layers between 0 and 20 m corresponding to freatic aquifers, and clayey materials show resistivities from 4 to 10 Ωm. The deep part of the model shows relatively high resistivity values (> 500Ωm) in the northwestern part of the profile and low resistivity values to southeastwards. The investigation depth of the TDEM was limited to 100-150 m due to the limited time-range of the data and due to the low resistivity of the upper part of the earth, in the survey area.

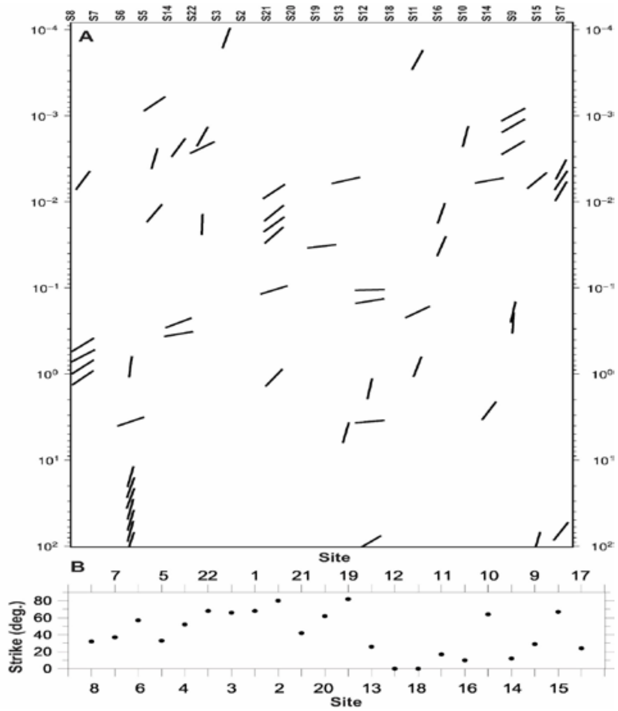

Figure 3: Geoelectric strike directions derived from the MT data along profile obtained from tensor decomposition at each station for the whole period interval (A). Strike angle for each site. Northwards of the site 13 the strike are ranging from 30º to 80º. Southwards, the strike values are mainly around 15º (B).

2D MT

2D inversion was undertaken using the Mackie's program (Mackie et al. 1997), which solves for the minimum resistivity distribution that fits the data at each site. The inversion was carried out on both TE and TM modes jointly (including tipper data at the sites where such data are available) using a regularization parameter of 10, a damping factor of 0.001 and error floors of 10% for apparent resistivity and of 5% for phase. Figure 5 shows the model obtained after 30 iterations. The global data fit (rms) is 3.2%. The resistivity distribution model displays four main resistive (1000-5000 Ωm) domains, that correspond to the main (regional) geological units: at NNE (between sites 8 and 6, between sites 2 and 4 and 1 at ESE (between sites 20 and 17) of the survey. These domains are separated, in depth, by low resistivity zones (10-100 Ωm) that correlates very well with known shear zones (Fig. 5).

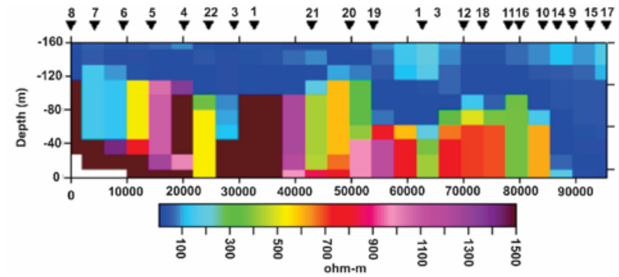

Figure 4: Stitched resistivity pseudo-section constructed from 1D TDEM inverted models.

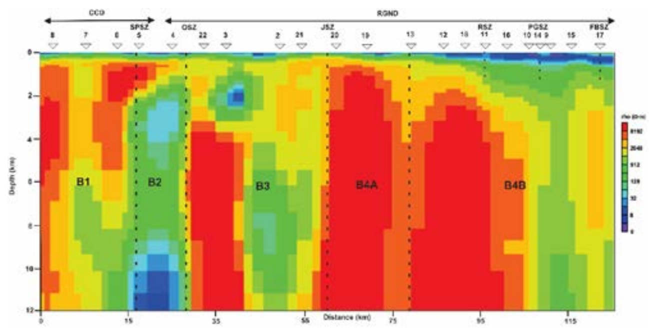

*Figure 5: 2D inversion model. Location of MT sites (closed triangles) and shear zones: Senador Pompeu (SPSZ), Orós (OSZ), Jaguaribe (JSZ), RSZ: Retir**o**, PGSZ: Ponta Grossa; FBSZ: Fazenda Belém**.** Block divisions (B1-B4) are discussed in the text.*

3D MT

A 3D resistivity model was generated through 3D inversion of the MT data (Fig. 6). The 3D MT inversion algorithm ModEM (Egbert & Kelbert 2012; Kelbert et al. 2014) was used to estimate the resistivity distribution of the MT profile in northeast of Ceará and northwest of Potiguar Basin. The algorithm seeks the smoothest resistivity model using the non-linear conjugate gradients (NLCG) method in order to minimize the misfit between modelled and observed data.

In the inversion all the impedances belonging to components Zxy, Zyx, Zxx, Zyy were used. In addition, tipper data has been included on the sites where it is available. We also use "Error Setting" (data error observed in the calculated model), "Error Flow" of 5% and "Error Computation" being % of $\sqrt{|Z_{xy}Z_{yx}|}$ (percentage of the square root module of the impedances Zxy and Zyx), total time inversion was 9 days, 128 interations and with RMS equal to 4.8%. The inversion model was constructed with a cell size of 1000 x 800 x 20 m, a factor of 1.2 multiplier of the first z-layer, and a multiplication factor of 1.3 increment of the 20th cell in x-axis and increment of the 40th cell for to y-axis.

Interpretation and Discussion of MT result

The following discussion will focus only on the 3D model of the geoelectric structure beneath northeast of the BP shown in Figs. 6 and 7. A visual inspection of the geoelectric slices in Fig. 7 shows that there is no obvious relationship between the resistivity distribution in the 3D model and the terrane subdivision proposed for this part of the province. The correlation would be expected at least at the deepest depths in the model. The horizontal section at 1 km depth shows conductors between the main shear zones (Orós and Jaguaribe) and at in the east of profile within Potiguar basin sediments. The first conductor has a preferred NE-SW orientation, while the second has any preferred orientation that allows correlating them with free fluids along Mesozoic sediments. At 3.5 km depth this slice only shows one conductor in neighborhood of Senador Pompeu shear zone and continues with this signature until approximately 7 km (Fig. 7). Even, the bodies are characterized by a high resistivity and a NE-SW orientation with exception of the structure below the Potiguar Basin. Leopoldino Oliveira *et al.* (2018) presented a gravity model in this region showing that Supracrustal rocks of the Santarém Formation is less pronounced below in westward of Potiguar Basin and Paleoproterozoic rocks has more expression of gravity values.

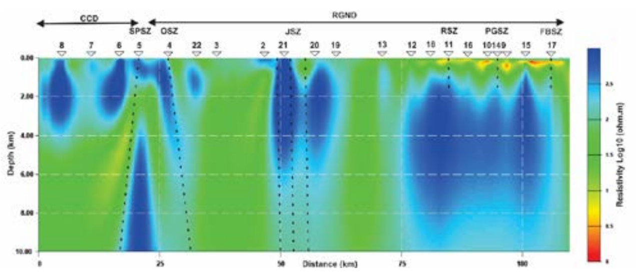

Figure 6: Vertical cross-sections of the final 3D inversion model. Location of MT sites is represented by closed triangles. Shear zones: Senador Pompeu s (SPSZ), Orós (OSZ), Jaguaribe (JSZ), RSZ: Retiro, PGSZ: Ponta Grossa; FBSZ: Fazenda Belém.

It is possible notice that Orós-Jaguaribe belt has not significant expression in this model, with exception for one conductive and one resistive body at 1.125 depth, any other signature of this geological unit is presented (Fig. 7). Senador Pompeu shear zone, which is the most expressive lineament in this part of BP has poor resolution in shallower depths and appears less characterized that Jaguaribe shear zone. On the other hand, with the increased footprint sampled by the MT data at larger depths (7 and ~15 km), a trend of geoelectric alignment in the NE-SE direction becomes more apparent and their signature has increased from shallow to deep upper crust.

The vertical section of the 3D resistivity model shows pronounced variations in resistivity within the crust (Fig. 6). Resistivity of several thousands (up to 20,000) Ω·m is observed in different coherent blocks (Ceará Central and Rio Grande do Norte domains) of the BP. This model also shows a thin sedimentary basin depicting different litho units, overlying a resistive basement. Beneath the part of the profile that falls in the sedimentary region, the average thickness of the basin is about 0.5–1 km, correlating with gravity modeling by authors above mentioned. The 3D model can be subdivided into blocks that are marked out by main shear zones (Fig. 6).

Ceará Central domain has two high resistive bodies reaching 4 km depth that can be related with rocks from Paleoproterozoic structural high. The geophysical signature of Senador Pompeu shear zone is very pronounced in subsurface, even more that other shear zones. Orós shear zone present a better signature in shallower depths and seems to dip for E-W, while Jaguaribe shear zone has the same depth and vertical behavior. With exception to bodies with higher resistivity in Ceará Central Domain and to that bodies related to shear zones, almost all basement in this region has moderate resistivity. Below the Potiguar Basin, the basement has high resistivity values and is characterized by highs and lows that seem to be conditioned by other shear zones less expressive. Furthermore, note that at station 13 it is possible to observe the presence of a resistive body and of small depth. This feature is similar to those mapped by Leopoldino Oliveira *et al.* (2018) using potential field methods, which have short-wavelength maxima within the Aracati High, possibly unraveling a quite rugged paleo relief of the Paleoproterozoic Jaguaretama complex or shallow-seated magmatic bodies emplaced in the Precambrian basement.

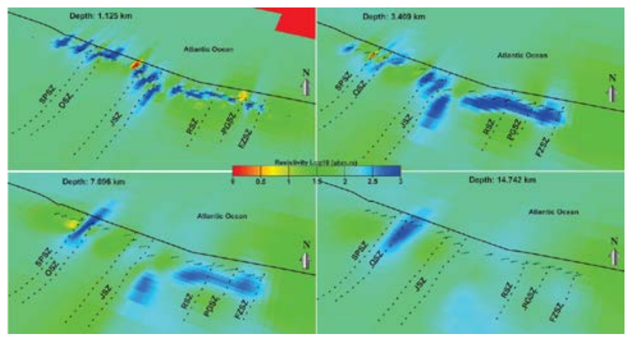

Figure 7: Horizontal sections of the 3D geoelectrical model at depths of 1.125, 3.4, 7 and 14.7 km, with projection of the locations of the continental margin and the major shear zones.

Model Validation – 2D Inversion

The geoelectric model in Fig. 5 shows a thin conductive sedimentary formation with an average thickness of about 0.5 – 1 km, overlying a resistive basement. The tectonic terrains traversed by the MT profile present significant lateral and vertical variation in the electrical resistivity throughout the crust, reflecting differences in its geological and tectonic history of development. This section shows consistencies with the geotectonic picture shown in Fig. 1, so four distinct blocks are identified, based on crustal section of 12 km and the distribution of resistivities presented, and described in the next paragraphs. These blocks have similar geoelectric signatures with intercalated highly resistive and more conductive zones at varying depths. This intricate pattern in resistivity structure probably reflects a long and complex tectonic history that includes emplacement of granites from post-Brasiliano to anorogenic settings into the Paleoproterozoic high-grade basement rocks of the whole Northern Province.

Block- 1 (B1) - Absolute predominance of more resistive continental crust (200 to 1000 Ωm) in the upper and moderate resistive (20 to 100 ohm-m) in the lower part. This is the expression of the Paleoproterozoic structural high (partly juvenile, partly reworked Archaean rocks), in its subsurface projection for the coastline. The Supracrustals of this structural basement are vestigial and the presence of granites and other intrusive Brasiliano bodies is rare. This block corresponds with Ceará Central Domain and is limited to east with SPSZ.

Block 2 (B2) - It registers a sudden crustal elevation, with uplift from the most resistive layer to near the surface (below 1000 Ωm) and significant rise of less resistive materials, 10 to 50 Ωm (above) and 2 to 10 Ωm (below). There are several possibilities of interpretation of this zone of coalescence of deep lineaments as SPZS and OSZ, among them the presence of deep magma cushions of Neoproterozoic and/or Tertiary. Checking the region south of the section (Fig. 1), there is a profusion of Neoproterozoic stocks. This block is limited to east with OSZ and correspond with Rio Grande do Norte Domain.

Block 3 (B3) - This block match with Jaguaribean range basement, consisting of ortho-derived Paleoproterozoic rocks, TTG and similar, including granite, rocks of the Jaguaretama Complex, with very few and small Braziliano granites intruded on it. In the upper part of this block there is a sub horizontal tract with low resistivity (10 to 20 Ωm) that articulates with that dominant in B2. Among the various possibilities, we suggest underplating magmatic materials, either Braziliano or Tertiary (Macao or Rio Ceará-Mirim) as mapped by Leopoldino Oliveira et al. (2018) using potential methods.

Block 4 (B4) was divided into two, A and B, respectively. The limit B3 and B4 identifies important crustal change, with probable vertical movements, which coincides with a projection to the north of the Jaguaribe shear zone. Block 4 – A (B4A), western part of block 4 repeats the general characteristics of B1, with little difference to be added. From geological and geotectonic point of view, we repeat the situation of B1, since we are on the westernmost edge of the Rio Piranhas Massif (Paleoproterozoic rocks and reworked Archaean rocks).

Block 4 – B (B4B) has a natural continuity with the B4A block, being dominated by high resistivity values, practically returning to those features B3. This is the western border of the Rio Piranhas Massif (for the most part below to the Potiguar Basin), where Paleoproterozoic rocks predominate, with local Archaean nucleus. The region of B2 deserves attention because it is an area of two large shear zones that separate two defined crustal domains in BP. These domains, Ceará Central and Rio Grande do Norte, are separated by a remarkable conductor (Fig. 6) which also presented by Padilha et al. (2017) in MT section further south of this area. The authors also suggest that B3, Orós-Jaguaribe terrain, as a latter cryptic suture and highlights its importance as a key feature in the amalgamation of the BP.

Tectonic Analyses

In general, geoelectrical signature is controlled by the last major tectonothermal event that may overprint or even completely obliterate the signatures of earlier events at some places (Selway, 2014). Despite the significant differences in geological background between both domains, the MT data did not image any significant change in electrical character between them. The extensional effects were intensely felt by the units to the east of the profile but were not able to imprint any clear geoelectrical signature in the deeper parts of the upper crust, which means that those smaller shear zones were formed by reactivation of large shear zones as Senador Pompeu, Orós e Jaguaribe. These results imply that the lithosphere from NE BP was significantly stretched in the Cretaceous as a consequence of stresses generated by the South Atlantic Ocean opening, whereas in the east of profile smaller shear zones-controlled horsts and grabens on the edge of Potiguar Basin. The Senador Pompeu shear zone which defines the limit between Ceará Central and Rio Grande do Norte domain was adequately preserved from later tectonic episodes since the Neoproterozoic. Their resistivity increases gradually as the depth increases.

On the contrary, in this part of upper crust is not observed conspicuous conductivity signatures as presented by Padilha *et al*. (2014) in the Paleoproterozoic Orós fold belt. These authors describe that high conductivity anomalies in this case is usually ascribed to electronic conduction by highly conducting interconnected solid phases precipitated from carbon-rich volatiles during magmatic intrusion (Nover, 2005) that can be enhanced by subsequent compressional events. This pattern observed more a south of BP is not observed near of coast. In addition, the lack of bodies of different resistivity (with exception for the shear zones), corroborate with Arthaud (2008) who studied the evolution of that region using geological and geochronological data and found that the basement of Ceará Central and Rio Grande do Norte domain are similar, at least in upper crust. Yet, different to what is shown by Padilha *et al.* (2017) in this part of upper crust it is not possible the identification of the latter cryptic suture that suggest the Orós-Jaguaribe as a separate domain within the northern sub-province and highlights its importance as a key feature in the amalgamation of the BP. The absence of these proposed sutures in this model does not invalidate the tectonic evolution models for the West Gondwana assembly involving oceanic closure and collision of continental blocks during the Brasiliano Orogeny. For this, an investigation with MT recording long-period data is recommended to investigate in a greater depth.

Conclusions

MT data analysis of this region reveals the dimensionality of the subsurface, indicating 3D structures at deeper depth implying the need for 3D inversion to image complex subsurface structures. This behavior was already expected to be a region of meeting great shear zones. A 3D resistivity model was developed using ModEM inversion code. Observation that the 3D inversion has poor resolution in the upper crust when compared with the 2D inversion of the same profile. The geophysical signature of Senador Pompeu shear zone is very pronounced in subsurface, even more that other shear zones. Orós shear zone present a better signature in shallower depths, while Jaguaribe shear zone has the same depth and vertical behavior. With exception to bodies with higher resistivity in Ceará Central Domain and to that bodies related to shear zones, almost all basement in this region has moderate resistivity. Yet, in this part of upper crust is not observed conspicuous conductivity signatures as presented by Padilha *et al.* (2014) in the Paleoproterozoic Orós fold belt and not even the latter cryptic signature suture shown by Padilha *et al.* (2017). The absence of these proposed sutures in this model does not invalidate the tectonic evolution models for the West Gondwana assembly involving oceanic closure and collision of continental blocks during the Brasiliano Orogeny.

The calculated 2D MT model allowed the characterization of the upper crust, mainly: 1) the uppermost structures correlated to the Mesocenozoic sedimentary formations and groundwater reservoirs, 2) the underlying structures associated with the Ceará Central and Rio Grande do Norte crustal domains and 3) the structures associated with the Senador Pompeu, Orós and Jaguaribe shear fault systems (Neoproterozoic).In addition, the MT results also agree with interpretation of gravity and magnetic data, which suggest magmatic bodies near Aracati city, grabens and horst marked by other smaller shear zones (Leopoldino Oliveira *et al.,* 2018).

3D and 2D model characterize well the basement architecture of NW border of the onshore Potiguar Basin. The sedimentary package has a maximum thickness up to 1.0 km. The model thus establishes that the basement of this region (Potiguar Basin) shares a common signature, indicating that this domain responded in a similar way to the stresses that culminated in the fracturing and rupturing of the Gondwana continent, separating South America and Africa in the Cretaceous. We suggest a new investigation with MT recording long-period data to investigate in a greater depth to clarify the tectonic evolution of this area of large shear zones.

Acknowledgments

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