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Mapping the basement architecture using magnetotelluric data across a coastal part of the Borborema structural province, Ceará – Brazil

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ABSTRACT

The Borborema Province (BP) constitutes part of the west Gondwana supercontinent formed by several tectonic collisions during Neoproterozoic, widely known as Brasiliano - Pan-African orogeny. It consists of a complex tectonic mosaic composed mainly by Archean to Paleoproterozoic migmatite-gneiss basement complexes, Proterozoic metasedimentary belts, a large volume of Neoproterozoic granitic intrusions, and Phanerozoic covers that represent ca. 25 % of the total area of BP. This work presents the results from 21 Magnetotelluric (MT), and electromagnetic time-domain (TDEM) soundings interpretations carried out along a 120 km profile in a coastal area of the northeast Borborema Province covered by Phanerozoic sedimentary rocks and sediments. The final geoelectric model allows delineating the architectural geometry of the subsurface and variations in physical properties of different crustal blocks bounded by major electrical discontinuities. The interpretation was based on a 2D and 3D model from the inversion of the MT data. The 2D model has a visually satisfactory agreement with the region's geological framework and a reasonable resolution of the upper crust compared to the 3D model. The geoelectric section allows delineating the variation in physical properties of different upper crust blocks bounded by major electrical discontinuities. The result enables the characterization of 1) the uppermost structures correlated to the Mesozoic to mid-Cenozoic sedimentary formations; 2) covered lithotectonic framework represented by lithotypes and main shear zones related to Ceará Central and Rio Grande do Norte crustal tectonic domains; 3) distinctive anomalies corresponding to the Senador Pompeu, Orós, and Jaguaribe Neoproterozoic main shear zones. Our interpretations agree with the results and interpretation presented by previous MT works in the Borborema Province, which reveals the existence of an important conductive zone, interpreted as a suture zone, spatially related to the Senador Pompeu shear zone and in smaller proportion to the Orós shear zone. The results presented here are a starting point to further MT long-period investigation to understand this complex part of the Borborema Province.

1. Introduction

The major tectonic framework under analysis in the Borborema Province (BP) is linked to the structures developed and consolidated during the Brasiliano-Pan African orogeny in the Neoproterozoic II and III (750–550 Ma). The BP covers a large region in the central part of the Neoproterozoic orogenic system resulted from the convergence and collision of the São Luis-West-Africa, Amazonian, and São Francisco-

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Congo Kasai cratons (Fig. 1, Almeida et al., 1981; Brito Neves et al., 2000; Brito Neves et al., 2001; Dada, 2008; Van Schmus et al. 2008). As well as its counterpart located nowadays on the African continent (Fig. 1), BP is an important member of the west portion of the Gondwana Supercontinent (Arthaud et al., 2008; Dada, 2008; Van Schmus et al., 2008). Since Almeida et al. (1981), the BP has been considered as a large crustal segment where Neoproterozoic tectonic thermal events reworked Archean-Paleoproterozoic basement and generated new tracts of meso and Neoproterozoic supracrustal and granitic rocks (Brito Neves et al., 2000; Van Schmus et al., 2008). BP can be subdivided into five major tectonic domains based on geological, geochronological, and stratigraphic characteristics (Caby et al., 1991; Brito Neves et al., 2000), occurring from north to south: Médio Coreaú (MCD), Ceará Central (CCD), Rio Grande do Norte (RGND), Transversal Zone (TZD) and Meridional (MD). Major transcurrent shear zones (Vauchez et al., 1995), recognized as the so-called Transbrasiliano, Senador Pompeu, Patos, and Pernambuco lineaments, are the limits between those domains (Fig. 2). In addition, not rare coeval to main shear zones, subsidiary smaller shear zones occur cutting the main tectonic domains and splitting those into minor tectonic blocks.

BP is mainly composed of rocks ages ranging from Archean to Neoproterozoic (Almeida et al., 1981; Brito Neves et al., 2000; Van Schmus et al., 2008), and a large volume of Phanerozoic sedimentary rocks and sediments that cover the Precambrian lithostructural patterns. In this context, it is complex to define the spatial location of the main structures in-depth precisely. The geology at the southeastern coast of the Ceará State, where the sedimentary record covers more than 5,000 km^2, depicts very well that scenario. The sedimentary cover extends up to 60 km onshore from the coast, increasing the lack of regional Precambrian lithostructural patterns between BP and its West-African counterpart. The major structures observed in the BP have their continuity in the African side (Castaing et al., 1993; Brito Neves et al., 2001; Arthaud et al., 2008; Van Schmus et al., 2008). Thus appropriate modeling of major structures in the subsurface with a proper geophysical survey represents a goal in applied geophysics for constraints the interpretations to the more viable scenarios.

To fill part of that gap and to provide new information related to understanding of the actual articulation of the crustal blocks and the role of the primary shear zones in bringing these blocks together, the Magnetotelluric (MT) and Time-Domain Electromagnetics (TDEM) surveys have been conducted in NE of Ceará (BP northeast region). The importance of this study relies on two main factors: i) the major tectonic domains and their marginal shear zone are well known and delimited on the surface but is yet poor described at subsurface; ii) traditionally, the most MT geophysical studies in the BP are concentrated in the interior of the continent, distant more than 100 km away from the coast (Santos et al., 2014; Padilha et al., 2016, 2017).

MT data have been used in various tectonic settings around the world to investigate crustal structures and models of crustal resistivity structure (Selway (2014), Gokarn et al., 2002; Gürer et al., 2004; Gokarn et al., 2006; Turkoglu et al., 2008; Bertrand et al., 2009; Selway (2014), Comeau et al., 2020; Thiel et al., 2020). As a geophysical tool, MT data have proved efficient in imaging shallow and more deeper situations. In the first case, imaging sedimentary fluids-rich rocks, shear zones

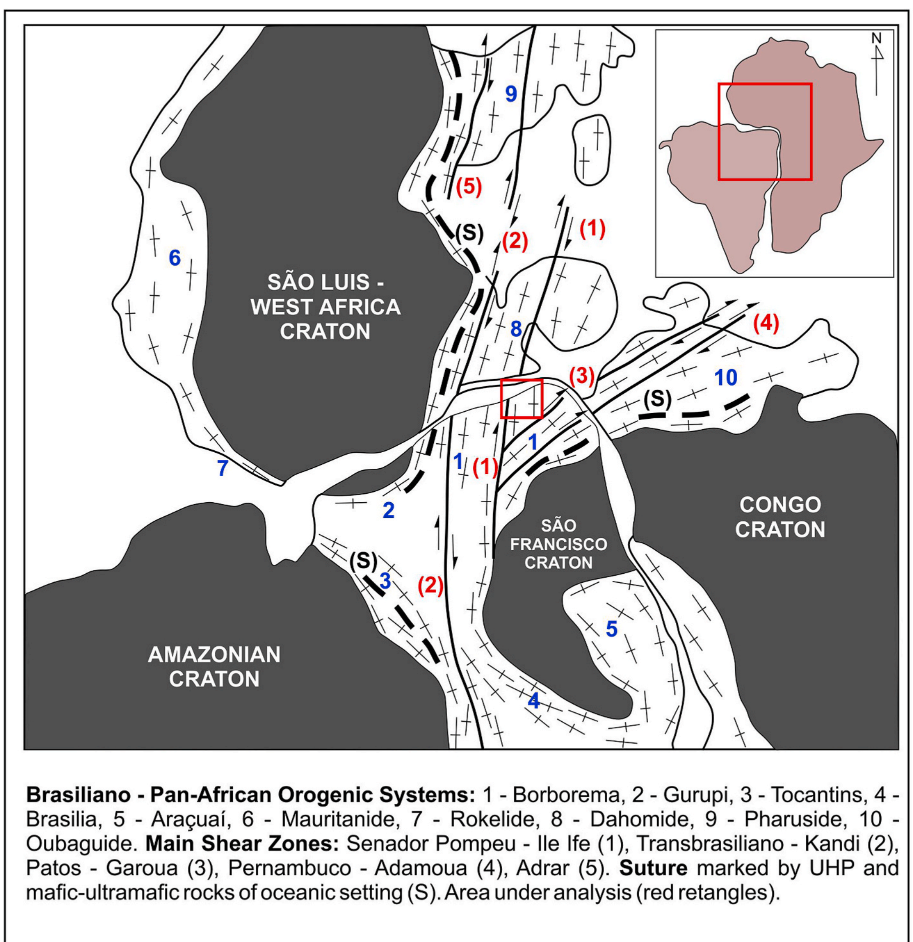

Fig. 1. Pre-drift reconstruction of Western Gondwana portion circa 500 Ma. Main geological provinces and the correlation between northeastern Brazil and West Africa (modified from CABY, 1989; Trompette, 1997; Santos et al., 2008; Van Schmus et al., 2008). The study area (red rectangle).

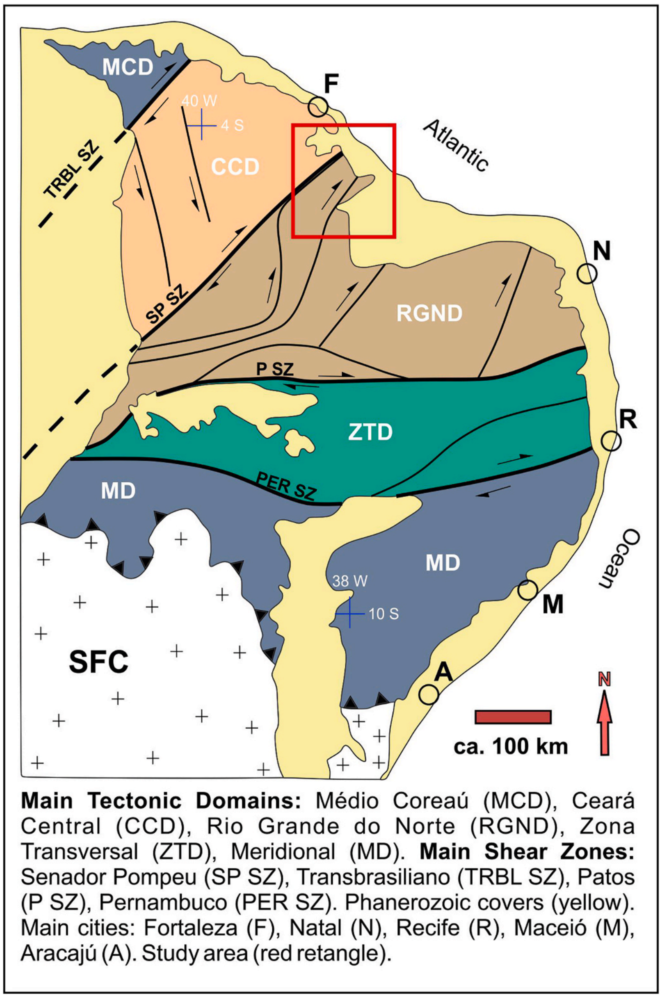

Fig. 2. Borborema Province. Main crustal blocks and shear zones adapted from Van Schmus et al. (1995), Vauchez et al. (1995), Santos et al. (1999); Brito Neves et al. (2000), Van Schmus et al. (2008), Van Schmus et al. (2011).

containing interconnected conducting structures, fault zones, and rock bodies with low resistivity behavior (sulfide-rich rocks). In deeper situations, conductivity bodies in the medium and lower crust and the mantle-crust limit.

In this paper, aiming imaging the shallow (upper 15 km) spatial behavior of the main crustal blocks and shear zones close to the coast, we present and interpret a new dataset consisting of twenty-one MT stations located along a cross-section through the Ceará Central and Rio Grande do Norte tectonic domains (Fig. 3). The section and its interpretation provided a gain in imaging deep structures and allowed better correlations among crustal blocks, tectonic domains, and main shear zones occurring in NE Brazil and on the African counterpart.

2. Methodological procedures

The procedures used to attain the main goals of this research are shown on the flowchart in Fig. 4. The method consists of seven main stages that are summarized below.

2.1. Literature review

The geological information is necessary to understand the major litho-tectonic framework regarding the study area's main crustal blocks and shear zones. Considering the complexity of the geological structures and aiming an entire comprehension of the geoelectrical features, several works were compiled, it can be highlighted the results from Caby et al. (1991), Van Schmus et al. (1995), Vauchez et al. (1995), Cavalcante (1999), Fetter (1999), Brito Neves et al. (2000), Fetter et al. (2000), Arthaud et al. (2008), Van Schmus et al. (2008), and Pinéo et al. (2020). These works and others are addressed in chapter three related to the study area's geological context.

Theoretical concepts about how to plan, processing, and interpret the MT patterns were mainly obtained in the works from Jones (1992), Jones et al. (2003), Nover (2005), Jones (2006), Chave and Jones (2012), Unsworth and Rondenay (2012).

The MT method determines the impedance tensor **Z**, *i.e.,* the frequency-dependent transfer functions between the horizontal electric field and the magnetic field at the Earth's surface. In this study, estimates of the complex elements of **Z** were obtained using robust processing techniques (Egbert and Booker, 1986). The apparent resistivities (ρa) and phases (Φij) can be calculated for a large range of frequencies using the Fourier transform components of the time series of the electric and magnetic fields measured in the impedance tensor field. The variations of the fields **E** and **H** we expressed in S.I. ([mV/km]/nT) are determined, respectively, by the following expressions:

$$\rho_{xy} = 1 \Big/ (\omega\mu_o)|Z_{xy}|^2$$

$$\rho_{yx} = 1 \Big/ (\omega\mu_o)|Z_{yx}|^2$$

$$\varphi_{xy} = \text{arctang}\left(\frac{Im\{Z_{xy}(\omega)\}}{Re\{Z_{xy}(\omega)\}}\right)$$

$$\varphi_{yx} = \text{arctang}\left(\frac{Im\{Z_{yx}(\omega)\}}{Re\{Z_{yx}(\omega)\}}\right)$$

where ω represents the angular frequency, and μ_o is the magnetic permeability of the vacuum.

2.2. Planning and data acquisition

Due to geological context and logistic reasons, the stations were carried out between 4 and 12 km away from the coastline, spaced to ca. 5–10 km, along a section that runs from NW to SE (Fig. 3). Twenty-one stations of TDEM and MT data were surveyed. Time-domain electromagnetic soundings (TDEM) were carried out using a TEM-FAST 48 device at each MT site to correct possible static-shift effects over the MT data and provide a preliminary and rough image of the uppermost layers in depth. TDEM soundings were acquired with a coincident loop scheme using a 100m-sided loop. In general, the recorded data were of good quality and highly repeatable over the bandwidth of 7.0–500μs (up to 10^4 μs at a few sites).

MT soundings were surveyed using the ADU06 Metronix device with a period range of 0,004–1000 s. The horizontal fields were measured on the N–S and E-W directions, with the vertical magnetic component recorded only at twelve sites. Measuring times lasted sixteen to 24 h per station.

2.3. Processing

2.3.1. Induction arrows

The magnetic transfer function can be represented as inductions arrows (or vectors), allowing a qualitative study of lateral conductivity contrasts. The real induction arrows point away from the high-conductivity zones (Wiese convention) and have the highest magnitudes where the gradient of conductivity distribution is highest. According to Parkinson convention, the real part of the induction vectors points in the direction of conductive regions, and their magnitude are related to the conductivity gradient (Parkinson, 1962). For this reason, for a 2D structure, the induction vectors are expected to be

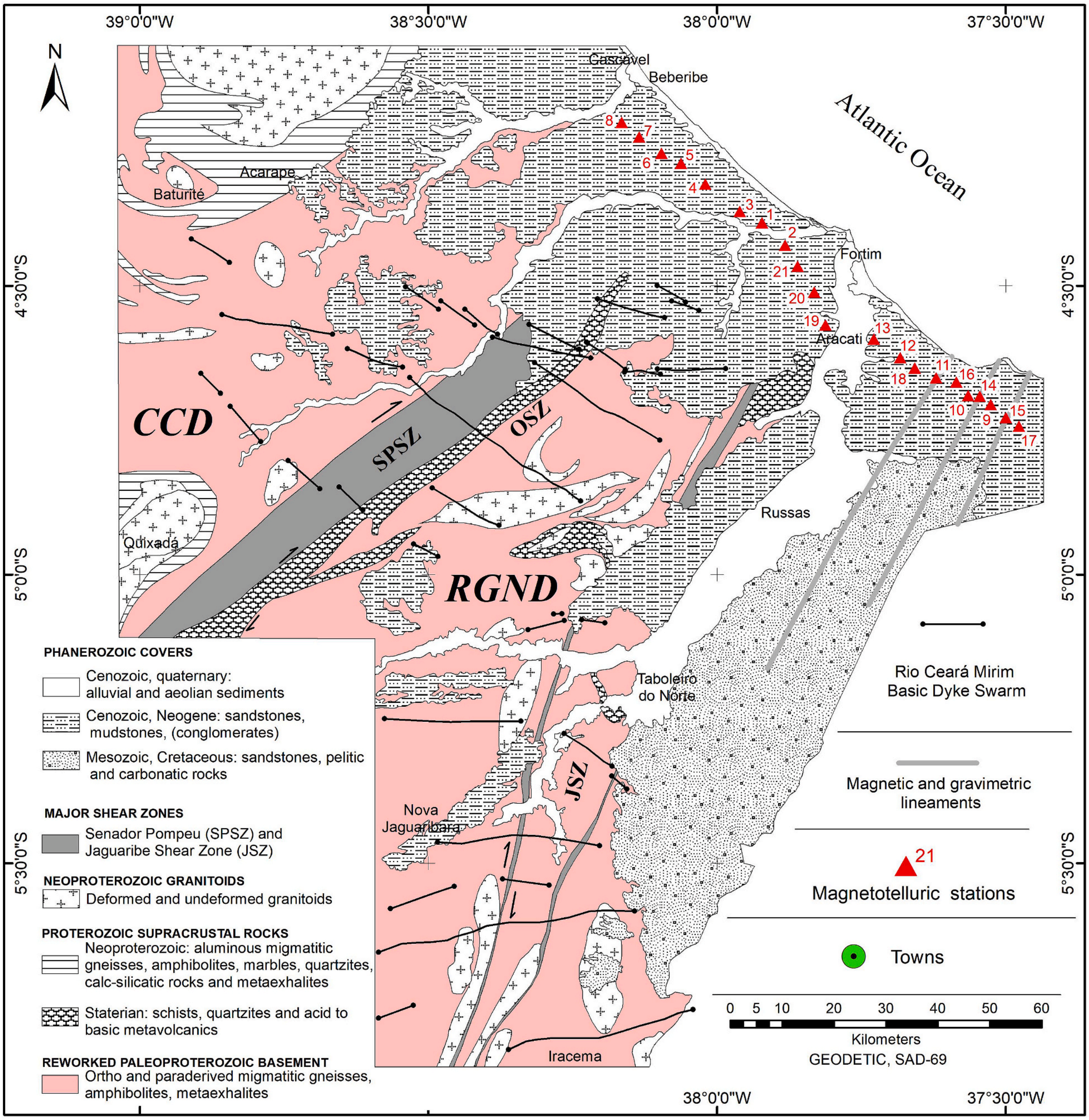

Fig. 3. Geological map of east Ceará State, close to the southeast coast and adjacent continental lands, and the positions of MT stations. Geology: modified from Cavalcante et al. (2003) and Pinéo et al. (2020). Major tectonic domains and shear zones adapted from Van Schmus et al. (1995), Cavalcante (1999), Santos et al. (1999), Brito Neves et al. (2000), Van Schmus et al. (2008). Neoproterozoic shear zones: Senador Pompeu (SPSZ), Orós (OSZ), Jaguaribe (JSZ). Magnetic and gravimetric lineaments from Leopoldino Oliveira et al. (2018): Retiro (RL): Ponta Grossa (PGL); Fazenda Belém (FBL).

perpendicular to the strike direction.

2.3.2. Dimensionality

Dimensionality analyses were done looking for a common strike to calculate a 2D model. So, the dimensionality of the measured impedances was studied using the Smith decomposition method (Smith, 1995). The behavior of the E1rot and E2rot parameters of the Smith's decomposition is usually stable from one to 10s, showing that the distortions (ocean effect in this case) start at longer periods.

For the 3D model, the 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 Marti et al. (2009). From I3 to I7 and Q, they represent the variables that determine the type of dimensionality and galvanic distortion in the data Martí et al. (2009, 2014). The WALDIM (Martí et al., 2010) results were used to access the dimensionality and evaluate possible anisotropy effects on our dataset.

2.3.3. Static-shift analysis

Before the inversion procedure, the static-shift effects caused by small-scale surface bodies were considered. The static-shift distortion is characterized to shift the apparent resistivity curves by a frequency-independent factor. The phase curves are not affected by that distortion. Generally, to correct the static-shift distortions, a commom averaged level for the apparent resistivity curves is estimated after the rotation of the impedance tensor, and the apparent resistivity curves are then shifted accordingly. In this work, the TDEM data were used to

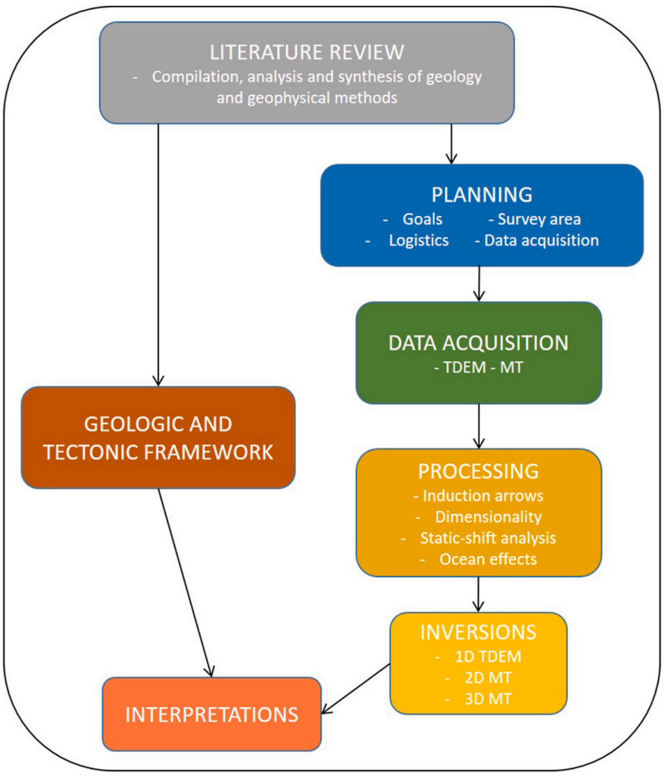

Fig. 4. Research procedures flowchart.

correct the MT apparent resistivity curves. Firstly, the TDEM apparent resistivity-time (t) curves were converted into apparent resistivity-frequency (f) curves, using Meju's approach (Meju, 1996): $f = 1/(3.09\ t)$. After this, the MT apparent resistivity curves were shifted till the high-frequency band matched TDEM curves.

2.3.4. Ocean effects

Pádua et al., 2007 demonstrated through the numerical model that the coast effect is significant on MT data acquired in this region of Brazil. Due to the large contrast in conductivities between the sea and the highly resistive rocks of the crust, the effects extend landwards over considerable distances from the coast. MT data acquired in the proximity of the ocean should be analyzed for possible distortions (Rikitake and Honkura, 1985; Monteiro Santos et al., 2001). The ocean distortion of the MT parameters is frequency-dependendant and is mainly conditioned by i) the distance from the coast, ii) ocean bathymetry and, iii) land and bottom oceanic sediments resistivity distribution. For soundings onshore, the coast effect will lead to a splitting in the apparent resistivity curves at long periods, with higher values in component Z_{xy} and lower values in the component Z_{yx}, whereas the induction arrows will acquire a strong alignment towards the sea-land boundary at the most prolonged periods.

2.3.5. Inversions

2.3.5.1. 1D TDEM. The TDEM data were inverted using 1D layered models.

2.3.5.2. 2D MT. 2D inversion was undertaken using Mackie's program (Mackie et al., 1997), which solves 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 5% for phase.

2.3.5.3. 3D MT. A 3D resistivity model was generated through 3D inversion of the MT data. The inversion and 3D modeling were performed in function of the dimensionality analysis that suggests a 3D type distortion of the obtained field data (Fig. 4). The 3D MT inversion algorithm ModEM (Egbert and Kelbert, 2012; Kelbert et al., 2014) was used to estimate the resistivity distribution of the MT profile northeast of Ceará and northwest of Potiguar Basin. The algorithm seeks the smoothest resistivity model using the non-linear conjugate gradients (NLCG) method to minimize the misfit between modeled and observed data.

All the impedances belonging to components Zxy, Zyx, Zxx, and Zyy were used in the inversion. In addition, tipper data was included on the sites where it was available. We use "Error Setting" (data error observed in the calculated model) and "Error Flow" of 5 %. Also, the "Error Computation" was a percentage of the square root module of the impedances Zxy and Zyx. The total inversion time was nine days, 128 iterations, and an RMS of 4.8%. The inversion model was constructed with a cell size of 1000 x 800 × 20 m, a factor of 1.2 multipliers the first z-layer, a multiplication factor of 1.3 increments of the 20th cell in the x-axis, and an increment of the 40th cell for the y-axis.

In general, 25 impedance values were inserted into the initial model for each station with periods ranging from 8x10^{-3} to 8x10^{2} s. The initial model consisted of a cube with 240 x 240 × 100 km dimensions and an initial resistivity of 100 Ω m. The following equation defined the calculation:

$$\mathrm{Pi} = \sqrt{\frac{2}{\omega\mu\sigma}} \approx 500\sqrt{\rho T}(\mathrm{meter})$$

Where:

Σ is conductivity of the medium.
ω = 2 π f (angular frequency).
μ is the magnetic permeability.
ρ is the resistivity of the medium (ohm.m).
T is the period in seconds.

Since data acquisition was near the Atlantic Ocean, a prominent conductor of 0.3 Ω m was considered in the 3D inversion model. Bathymetric data estimated the 3D interpolation of the ocean floor. We assume that the model area would be at least three times the investigation depth of the input model resistivity to eliminate possible boundary effects during inversion. The thickness of the first layer (z) was stipulated to be about 1/3 of the depth of investigation corresponding to the lowest resistivity of the highest frequency. After the inversion, it was generated a 2D profile.

2.4. Interpretations

About 160 m depth was interpreted based on the TDEM response and enlightened the study area's more superficial sedimentary cover. MT data were analyzed based on the geoelectrical properties of the subsurface, its correspondence in the geological knowledge of the surface (Fig. 3), and geophysical signatures provided by the literature review of the Borborema Province. A 2D model was considered and interpreted due to a visually good agreement between the model and the region's geological framework. Further, considering that the geoelectrical strike of the main superficial tectonic structure was 40° in common sense. Aiming to avoid misinterpretation of the geoelectrical features in the subsurface, a 3D interpretation was performed using the WALDIM dimensionality analysis, which pointed out that 3D structures are predominant.

3. Geological setting

The study area under geophysical analysis is located at the transition between the Ceará Central (CCD) and Rio Grande do Norte (RGND) tectonic domains, close to the coast of the Ceará state (Fig. 3). The geophysical transect cuts a portion of the CCD and the Senador Pompeu shear zone from northwest to southeast. It then cuts the RGND, which is characterized by the Staterian Orós unit (meta-volcano sedimentary association) intensively deformed by the transcurrent shear zone. That tectonic framework, adding the setentrional lithostructural configuration of RGND occurs covered by up to ca. 100 m of Phanerozoic sedimentary rocks and sediments. The main geologic units sectioned by the geophysical transect are the reworked Archean to Paleoproterozoic basement, Proterozoic supracrustal, Neoproterozoic granitoids, major shear zones, and Phanerozoic covers (Fig. 3).

The reworked Archean to Paleoproterozoic basement rocks are more important in volume, occurring toNW (CCD) and SE of the SPSZ (RGND). The oldest Archean rocks occurs to W-SW from the study area (Mombaça - Pedra Branca region in the CCD ,and S-SE in Granjeiro and São José do Campestre regions, RGND). This unit consists mainly of ortho and paraderived migmatitic gneisses with tonalitic to granitic compositions with a minor volume of amphibolitic rocks. Amphibolites, quartzites, paragneisses, and meta-exhalites (banded iron formations) are present in minor volume. The Paleoprotherozoic nature and the large volume of these rocks were depicted very well by Van Schmus et al. (1995) and Fetter (1999). The different isotopic signatures of the CCD and RGND rocks led Fetter et al. (2000) to conclude with Nd isotopic signatures that CCD and RGND had different growth before their amalgamation during Neoproterozoic.

Under the term, Proterozoic supracrustal were included rocks of Statherian and Neoproterozoic ages. The Statherian record, represented by the Orós-Jaguaribe Complex, comprises Al-rich schists and a minor volume of quartzites, calc-silicate rocks, carbonaceous schists, Ca or Mg-rich marbles, and metavolcanic rocks (Parente and Arthaud, 1995). Supracrustal of Neoproterozoic ages identified in the study area are only in the northwest of the SPSZ, included under the Ceará Complex, mainly comprises Al-rich paragneisses and minor portions of the quartzites, amphibolites, calc-silicate rocks, and marbles (Arthaud et al., 2008).

The Neoproterozoic (640–600 Ma) intense deformation and metamorphism are recorded in the basement and supracrustal rocks, with the metamorphic conditions having been transitory between eclogites to high-pressure granulites, and amphibolite facies (Caby et al., 1991; Monié et al., 1997; Castro, 2004; Garcia and Arthaud, 2004; Amaral et al., 2012; Santos et al., 2015).

The expressive volume of Neoproterozoic (ca. 640 to 600 Ma) granitoid rocks occurs in both CCD and RGND. At the CCD, the granite volume is mainly represented by the arc-related granitoids of Santa Quitéria (Fetter, 1999; Fetter et al., 2003; Castro, 2004; Ganade de Araujo et al., 2012) and Pacatuba-Maranguape (Pitombeira, 2019) arcs, and coeval granitoid bodies in the RGND. Close to the study area, younger granitoids (ca. 590 to 570 Ma), interpreted by Fetter (1999) as transcurrent-related, are mainly represented in the CCD by the Quixadá-Quixeramobim and Pedra Aguda Complexes (Fig. 3).

The main Neoproterozoic shear zones in the study area are represented by Senador Pompeu (SPSZ) and Jaguaribe Shear Zones (JSZ), with both belonging to the Borborema Shear Zone System defined by Vauchez et al. (1995). In the BP, SPSZ cuts a narrow mylonitic belt with ca. 400 km long and 5–10 km wide, with an impressive N45-50°E straight trend, marked on terrain and easily visible in SRTM and LANDSAT images. High-temperature mylonites, migmatites, and granulitic rocks constitute the primary lithologies on the deformed zone with dextral transcurrent shear (Vauchez et al. (1995). In almost all cases, the mylonitic foliation has high angles (>60°) and shows associated low angle (<20°) stretching lineation. At the NE portion of SPSZ, close to the study area, the plastic behavior of the metapelite lithologies of Orós Complex shows strong transcurrent dextral shear. In this context, mylonitic schists represent an extension of the SPSZ. To the south (southwestward from the area in Fig. 3), the strike of sheared zone gradually diverges from the SPSZ, configuring the Orós Shear zone described by Cavalcante (1999). Locally, rocks such as cataclasites, breccias, and pseudotachylite attest that latter evolutive stages and reactivations have developed with low temperatures.

The JSZ consists of a main sinuous, narrow belt (<4 km wide) of mylonites and mylonitic gneisses that crops over ca. 400 km from north of Campos Sales city to the southwest of the Aracati city, close to the coast. Close to the study area (Fig. 3), the JSZ is represented by two main narrow and slightly curved mylonitic belts with a strike of N10E in the south and N30E in the north region. JSZ shows some similarities with SPSZ, such as the high angle mylonitic foliation, low angles lineation stretching, and dextral sense shear. Also, locally latter evolutive stages and reactivations under low temperatures (Cavalcante, 1999).

The taphrogenic process accountable by the Atlantic Ocean opening was a huge tectonic thermal event that reached the South American Platform during the Cretaceous. The effects of this event are recorded in the entire Brazilian territory through local sedimentary basins, magmatism, and brittle zones. Two main geological products were generated in the study area: i) basic dykes (Rio Ceará-Mirim Dyke Swarm) and ii) the Potiguar Basin. The Rio Ceará-Mirim Dyke Swarm (Gomes et al., 1981; Oliveira 1993; Mizusaki et al., 2002; Souza et al. (2003), mainly composed of basaltic rocks, outcrop in the study area through several dykes with strike between N60W to E-W (Fig. 3), many of which are detectable by airborne magnetic images.

Over 15,000 km^2 of the study area is covered by Phanerozoic sedimentary rocks and sediments of Mesozoic and Cenozoic ages (Fig. 3). The Mesozoic rocks belong to the Potiguar basin, an oil-producing basin included by Matos (1992) on the sedimentary basins belonging to Cretaceous Northeast Brazilian Rift System. In the southeastward of the study area, the Potiguar basin comprises a sedimentary record compound by three primary sedimentary sequences (Pessoa Neto et al., 2007): i) continental basal, with sandstones, pelitic rocks, and conglomerates; ii) transgressive marine, with sandstones, pelitic, and carbonatic rocks); iii) marine regressive, top sequence, with a significant predominance of pelitic and carbonatic rocks. During 93, 49, 31 to 24, and 14 to 8 Ma, four magmatic events developed with the Potiguar basin evolution. They are locally present and contribute to approximately 10 % of the total sedimentary record, reaching 6 km of thickness in its depocenter. The Potiguar basin is covered by Cenozoic sedimentary rocks belonging to Barreiras Group (Mabesoone et al., 1972; Bigarella, 1975) and (Suguio and Nogueira, 1999), a predominant continental sedimentary record composed of weakly lithified clay-rich sandstones, sand-silty-rich argillites, and local conglomeratic lenses. Despite the large areal distribution, the thickness of the Barreiras Group in the study area, estimated with a basis in unpublished drill and geophysical data, reaches a few meters up to 80 m in some locations. The previous stratigraphic records described are covered by quaternary sediments, represented by fluvial and coastal deposits. Regarding the alluvial sediments, a remarkable volume is associated with the Jaguaribe river, including the extension between Fortim, Russas, and Tabuleiro do Norte cities (Fig. 3). In this region, a mainly N40°E oriented graben structure yields a sedimentary record of up to 15 km in width and 95 km long.

4. Results and interpretations

4.1. Induction arrows

Fig. 5 shows the real induction arrows at 0.1, 1, 10, and 100s. In general, they are small, except for periods greater than 10s. There are two reversals in the vectors orientation that might be correlated with low resistivity zones, between sites 1 and 4 and between sites 9 and 14 at 1s. The induction vector behavior in the southeastern part of the profile (eastwards of site 13) suggests that the geological structures are of great complexity (probably 3D). The vectors do not show a preferential orientation for short periods. At the shortest period (0.1 s), the vectors have a complex pattern, controlled mainly by local structures at shallow depths close to the sites. Results at 1 s are like those at 0.1 s, characterized by intricate patterns and null of most vectors.

The Ceará Central domain shows a vector pointing to conductors in

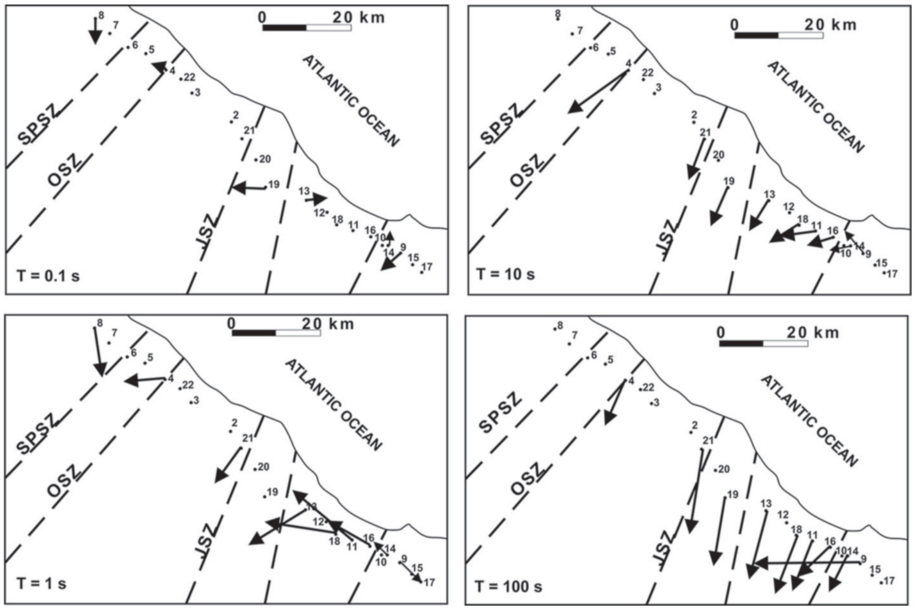

Fig. 5. Real induction vectors for 0.1, 1, 10, and 100s. SPSZ: Senador Pompeu; OSZ: Orós, JSZ: Jaguaribe.

the S-SW direction in these two periods. This behavior is like that presented by Padilha et al. (2017) near Senador Pompeu shear zone in the south of Ceará state. In the eastern profile, vectors are to point towards structures perpendicular to the geological lineaments. At 10 s, vectors present a coherent pattern pointing to off-profile conductors in the S-SW direction (between Orós-Jaguaribe belt). At the eastern end of the section, vectors are affected by structures located in the N-NE direction. These are probably related to conductive anomalies associated with the NW border of the onshore Potiguar Basin. The vectors' direction presents a reversal at the eastern side of the section followed by null vectors. Yet null vectors characterize the western side of the area, which corresponds to the Ceará Central domain. At 100 s, most of the vectors point toward the S-SW direction. Again, the exception is the eastern side of the profile and the Ceará Central domain, which are observed null vectors. At long periods, the Ceará Central domain is characterized by null induction vectors. Padilha et al. (2017) also observed that the Senador Pompeu shear zone marks a transition between the Ceará Central domain vectors and the behavior observed in the Rio Grande do Norte domain.

4.2. Dimensionality

Fig. 6 shows the result obtained at each site for the entire period band using the WALDIM code. The dimensional complexity of the geoelectric structures beneath this section predominates undetermined structures and 3D dimensionality. From the center to the east of the profile, there is an increase of 1D cases concentrated at short periods, being associated with the Potiguar basin. Long periods at sites over Rio Grande do Norte

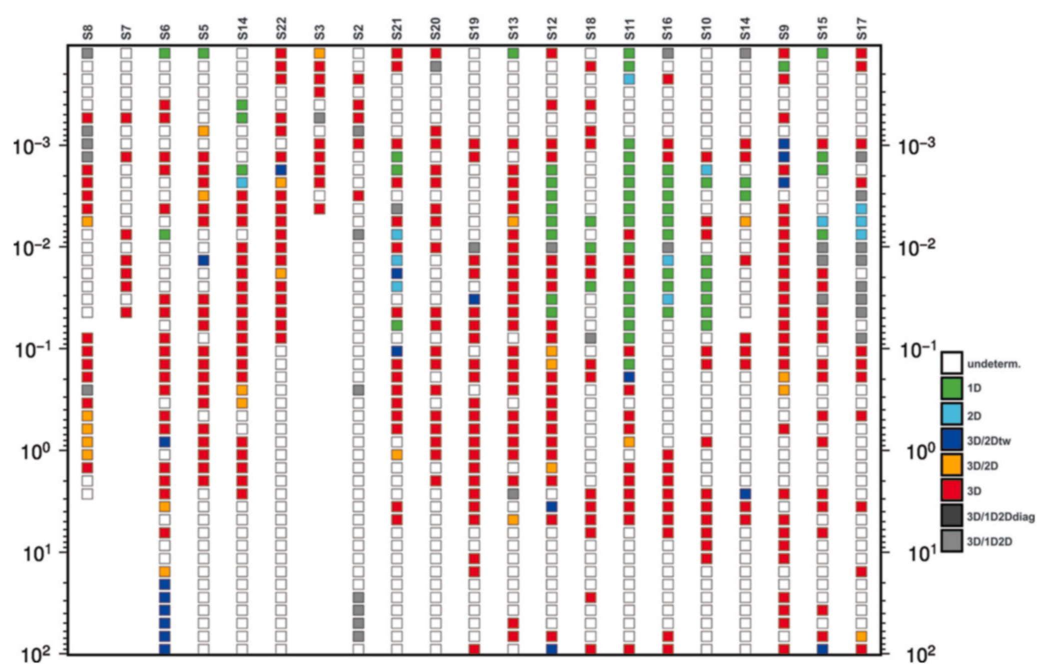

Fig. 6. Map of dimensionality analysis using the WALDIM code for each period band at each site.

domain are dominated by undetermined structures. 2D modeling of the MT dataset for this profile can generate interpretative errors because it is not possible to define a common geoelectric strike angle for the section. For this reason, a 3D inversion is ideal for comparing with the 2D inversion model and for avoiding interpretation mistakes of the geoelectrical framework in the subsurface of this part of the Borborema Province and NW border of onshore the Potiguar basin.

Fig. 7 displays the result of the dimensionality analysis for the 2D model. The striking angle obtained from tensor decomposition at each station for the whole period interval is shown in Fig. 7. There is a consistent change in a strike at sites 6 and 22 close to SPSZ and OSZ in long periods, rotated to N–S direction. The same pattern occurs at site nine near FBSZ (Fig. 3). 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 Borborema Province. This spatial variation in the azimuth is taken as evidence of a dominant 3D structure. Fig. 7 also shows the strike direction at each site. As in the induction arrows, different behavior can be observed from northwest to southeast. In the northwestern part of the section (sites 8 to 19), the strike directions varied between 30° and 80°, whereas in the southeastern region (sites 13 to 17), they are more stable, with the main strike values around 15°. Considering the strike of the main superficial tectonic structures and the results of the dimensionality analyses, a geoelectric strike of 40°, for all the sections, was assumed. Accordingly, the N130°W and the N40°E directions were associated with the TM and TE modes, respectively.

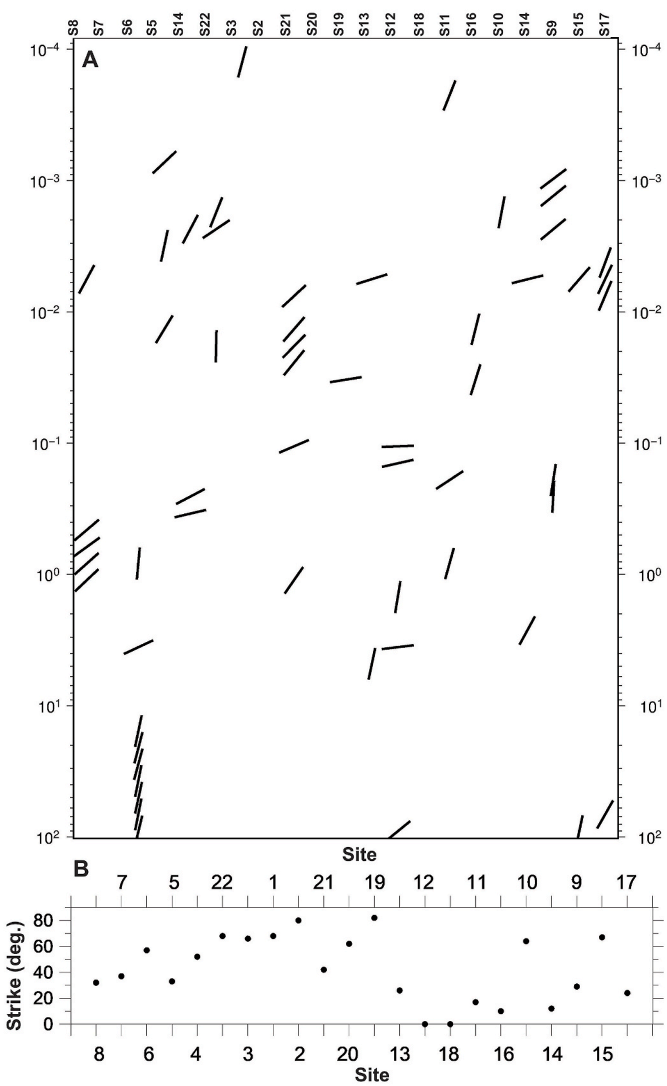

Fig. 7. Geoelectric strike directions derived from MT data along profile obtained from tensor decomposition at each station for the whole period interval (A). Strike angle for each site. Northwards of site 13, the strike is ranging from 30° to 80°. Southwards, the strike values are mainly around 15° (B).

4.3. Static-shift analysis

Fig. 8 shows the TDEM curves together with the rotated MT curves for sites 4 and 10. Whereas no static-shift effect is observed at site 4, a minor static-shift distortion can be noted at site 10. The small scatter shown in those examples is typical for all TDEM and collected MT data sites.

4.4. Ocean effects

The survey area at Beberibe is located close to the NE coast of the country. The MT site nearest to the sea is about 5 km away from the coastline and they are located at distances between 5 and 10 km from each other. According to the published data, the ocean's bathymetry near the survey area varies almost uniformly from 10 m, close to de coastline, to 100 m at 50–60 km from the coast. At 50–60 km, the sea bottom goes to a depth of 2 km. There is no information about the geoelectrical parameters of the sedimentary ocean bottom. A 2D model inversion was performed considering the coastal effects of this study (Fig. 9). The sea was modeled as a 0.3 Ωm layer. The inland part and the ocean crust were taken as homogenous media with a resistivity of 100 Ωm. The results show that the coast effect is negligible for periods of 10 s.

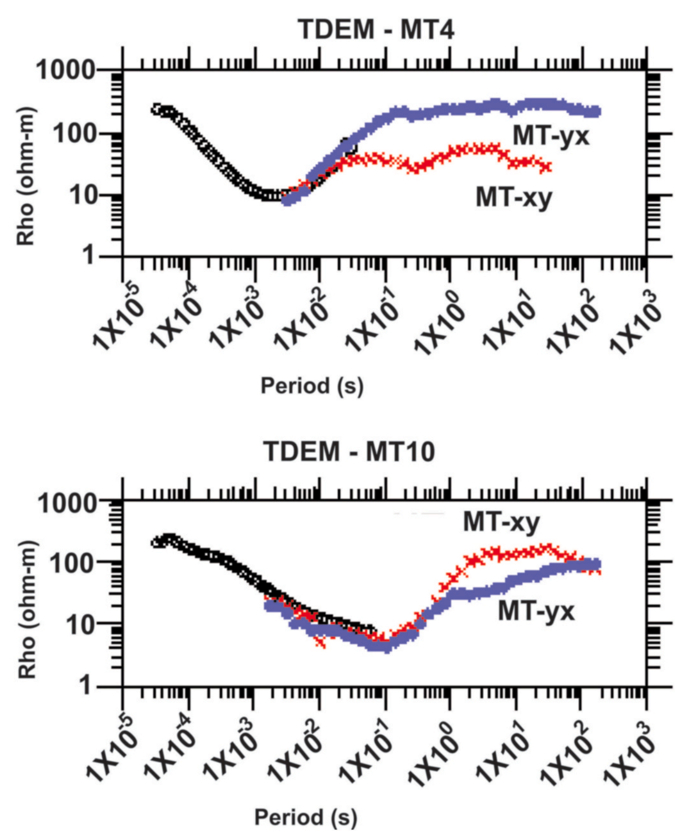

Fig. 8. TDEM and N40°E rotated MT apparent resistivity curves. At site four the curves from both surveys are coincident in the frequency range of 0.003–0.03Hz. The MT apparent resistivity at site 10 must be slightly shifted of an amount that can be determined from data in the frequency range 0.001–0.07Hz.

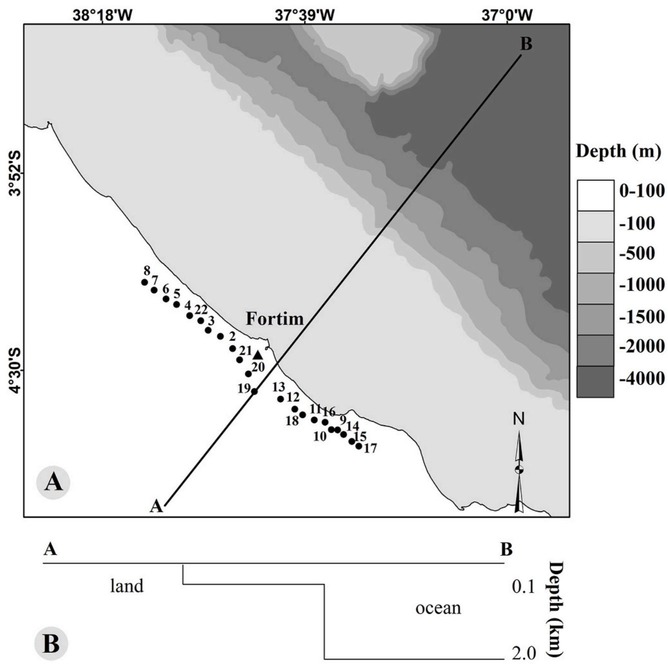

Fig. 9. Simplified bathymetry in the area around the survey profile in Ceará A); vertical cross-sections of the 2D model used to investigate the oceanic effects (B).

4.5. Inversions

4.5.1. 1D TDEM

The resistivity pseudo-section constructed from the models is displayed in Fig. 10. 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 phreatic aquifers and clayey materials showing resistivities from 4 to 10 Ωm. The deep part of the model indicates high resistivity values up to 500 Ωm in the northwestern part of the section and low resistivity values southeastwards. The TDEM investigation depth was limited to 100–160 m due to the limited time range of the data and the low resistivity of the upper part of the Earth in the survey area.

4.5.2. 2D MT

Fig. 11 shows the model obtained after 30 iterations. The global data fit (RMS) is 3.2 %. The resistivity distribution model displays four main resistive domains that correspond to the main regional geological units: NNE (between sites 8 and 6, between sites 5 and 4, 4 and 2) and ESE (between sites 20 and 17) of the survey. These domains are separated in-depth by low resistivity zones that correlate very well with known shear zones.

The geoelectric model (Fig. 11) shows a thin conductive sedimentary formation with an average thickness of about 0.5 – 1 km, overlying a resistive basement (C6 in Fig. 11). The vertical discontinuities are limited and correspond to the Senador Pompeu, Orós and Jaguaribe shear zones. To eastwards, others significant vertical discontinuities exist but probably do not outcrop. It is possible to associate the upper SE low resistivity at the surface with the Mesozoic sedimentary sequence of the Potiguar Basin (C6 in Fig. 11).

This section shows consistencies with the geotectonic picture shown in Fig. 3. Four distinct blocks are identified, based on a crustal area of 120 km and the distribution of resistivities presented and described in the following paragraphs. These blocks have similar geoelectric signatures with intercalated, highly resistive, and more conductive zones at varying depths. This 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 (R1 and R2 in Fig. 11) - Absolute predominance of more resistive continental crust in the upper and moderate resistivity in the lower part. In its subsurface projection for the coastline, this is the expression of the Paleoproterozoic structural high (partly juvenile, partly reworked Archean rocks). The supracrustal 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 the east with SPSZ.

Block 2 (C1 and C2 in Fig. 11) - It registers a sudden crustal elevation, with uplift from the most resistive layer to near the surface and significant rise of less resistive materials, 10 to 50 Ωm. 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 intrusion of the Neoproterozoic age. Looking at the south region of the section (Fig. 3), there is a profusion of Neoproterozoic stocks. This block is limited to the east with OSZ and corresponds with Rio Grande do Norte domain.

Block 3 (R3, R4, C3, and C4 in Fig. 11) - The passage from B2 to B3 is abrupt and well-marked, practically repeating those conditions already discussed for block I as predominance of high resistivity rocks at the beginning of the block. This block match with Jaguaribeana range basement, consisting of ortho-derived Paleoproterozoic rocks, TTG and similar, including granite, rocks of the Jaguaretama Complex, with very few and minor Brasiliano granites intruded on it. The last magmatic events of this NNE-SSW structured range were Statherian (1.70 Ga). The Brasiliano pan-African shear decisively spared this range, allowing even developments of E-W fluvial stretches (e.g., tributaries of the Jaguaribe river). In the upper part of this block, there is a sub-horizontal tract with

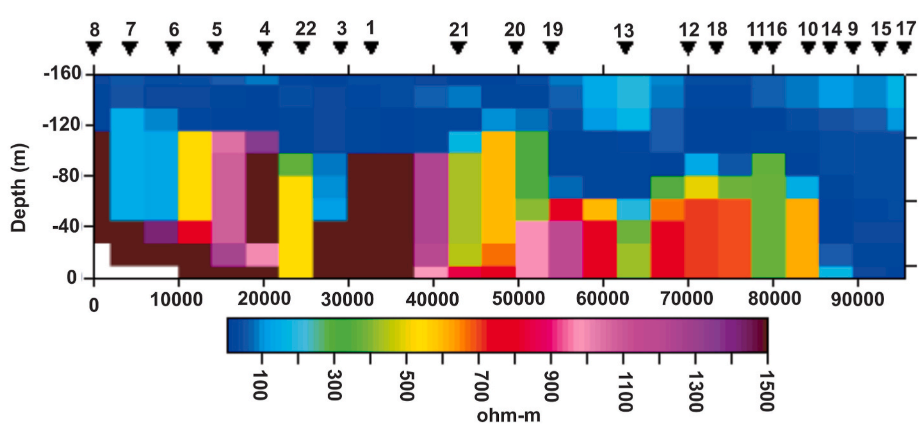

Fig. 10. NW-SE stitched resistivity pseudo-section constructed from 1D TDEM inverted models.

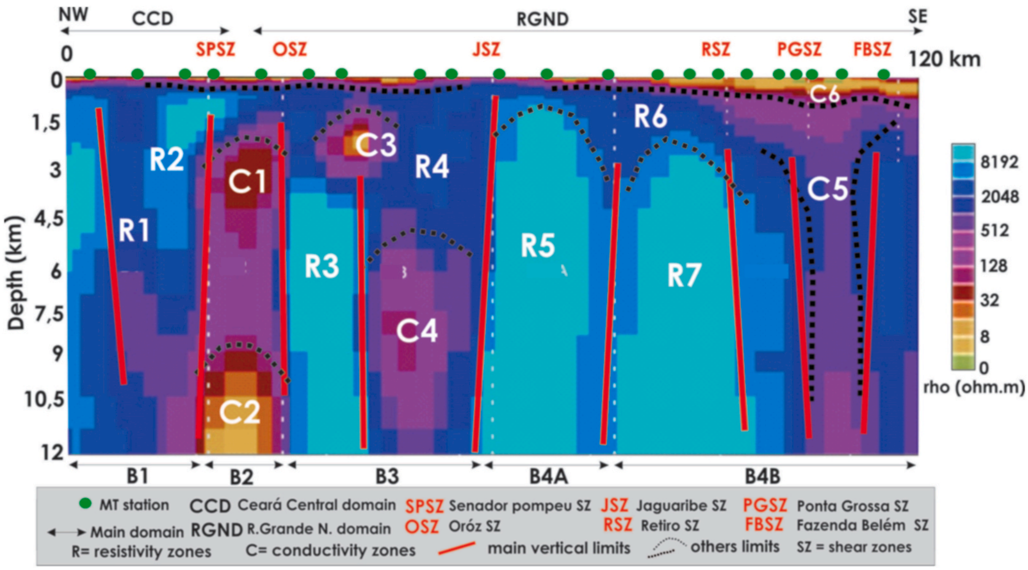

Fig. 11. MT 2D inversion model. MT station's locations (green circles). Main shear zones: Senador Pompeu (SPSZ), Orós (OSZ); Jaguaribe (JSZ). Magnetic and gravimetric lineaments from Leopoldino Oliveira et al. (2018): Retiro (RL), Ponta Grossa (PGL), Fazenda Belém (FBL). Main tectonic domains: Ceará Central (CCD), Rio Grande do Norte (RGND). Block divisions (B1–B4) are discussed in the text.

low resistivity (10–30 Ωm) that articulates with that dominant in B2. Among the various possibilities, we suggest underplating magmatic materials, either Braziliano or Cenozoic (Macao or Rio Ceará-Mirim) as mapped by Leopoldino Oliveira et al. (2018) using potential methods. The possibility of sub-horizon zones cannot be ruled out, but there are no indications in this sense in regional geology.

Block 4 (R5 in Fig. 11) was divided into two A and B, respectively. The limit B3 and B4 identifies significant crustal change, with probable vertical movements, which coincide with a projection to the north of the Jaguaribe shear zone. Block 4 – A (B4A), the western part of block 4, repeats the general characteristics of B1, with some differences to be added. From a 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 Archean rocks). Some Brazilian granites are present more to the south, and this slight difference is recorded in the B4A, with low resistivity in the upper part.

Block 4-B (B4B) (R6, R7, C5, and C6 in Fig. 11) 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 the Potiguar Basin), where Paleoproterozoic rocks predominate, with the local Archean nucleus. The presence of Brasiliano granites is only more profuse to the east of the Porto-Alegre shear zone, which is outside the section. As in B3, it is a domain of ortho-derived rocks whose study and better interpretation demands basement analysis of the superimposed basin.

The region of B2 deserves attention because it is an area of two large shear zones that separate two defined crustal domains in Borborema province. A remarkable conductor separates Ceará Central, and the Rio Grande do Norte (Fig. 11), also presented by Padilha et al. (2017) in the 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 critical feature in the amalgamation of the Borborema province.

In addition to these blocks discriminated along the observed section, there are additional observations to be made in the more superficial part, on top of them. Several structures suggest highs and lows (also attested by preexisting gravimetric data), which may mean posterior vertical displacements related to the evolution of the Equatorial Atlantic margin.

These configurations include horizontal layers of low resistivities in the shallow crust (B2, B3, and B4A) that may indicate water beds in sediments, paleosols, sheets of volcanic rocks (magmatism Messejana or Macau). Moreover, within the limits of blocks described above, there are units of low resistivity that most probably correspond to the sediments of the Potiguar Basin.

4.5.3. 3D MT

The following discussion will focus on the 3D model of the geoelectric structure northeast of the Borborema Province shown in Figs. 12 and 13. The horizontal section at 1 km depth shows conductors between the primary shear zones (Orós and Jaguaribe) and at the east of the area within Potiguar basin sediments. The first conductor has a preferred NE-SW orientation, while the second has any preferred direction that allows correlating them with free fluids along with Mesozoic sediments. At 3.5 km depth, this slice only shows one conductor in the Senador Pompeu shear zone neighborhood and continues with this signature until approximately 7 km (Fig. 12). Even, the bodies are characterized by high resistivity and a NE-SW orientation except for 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 are less pronounced below in westward of Potiguar basin and Paleoproterozoic rocks have more expression of gravity values.

It is possible to notice that the Orós-Jaguaribe belt has no significant expression in this model, except for one conductive and one resistive body at 1 km depth; any other signature of this geological unit is presented (Fig. 12). Senador Pompeu shear zone, which is the most expressive lineament in this part of Borborema Province, has a poor resolution in shallower depths and appears less characterized than the Jaguaribe shear zone. On the other hand, at more considerable depths (7 and ~15 km), a trend of geoelectric alignment in the NE-SW direction becomes more visible, 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. 13). The resistivity of several thousand (up to 20,000 Ωm) is observed in different blocks (Ceará Central and Rio Grande do Norte domains) of the Borborema Province. This model also shows a thin sedimentary basin depicting different rock 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 the authors mentioned above. The 3D model can be subdivided into blocks marked out by main shear zones (Fig. 13).

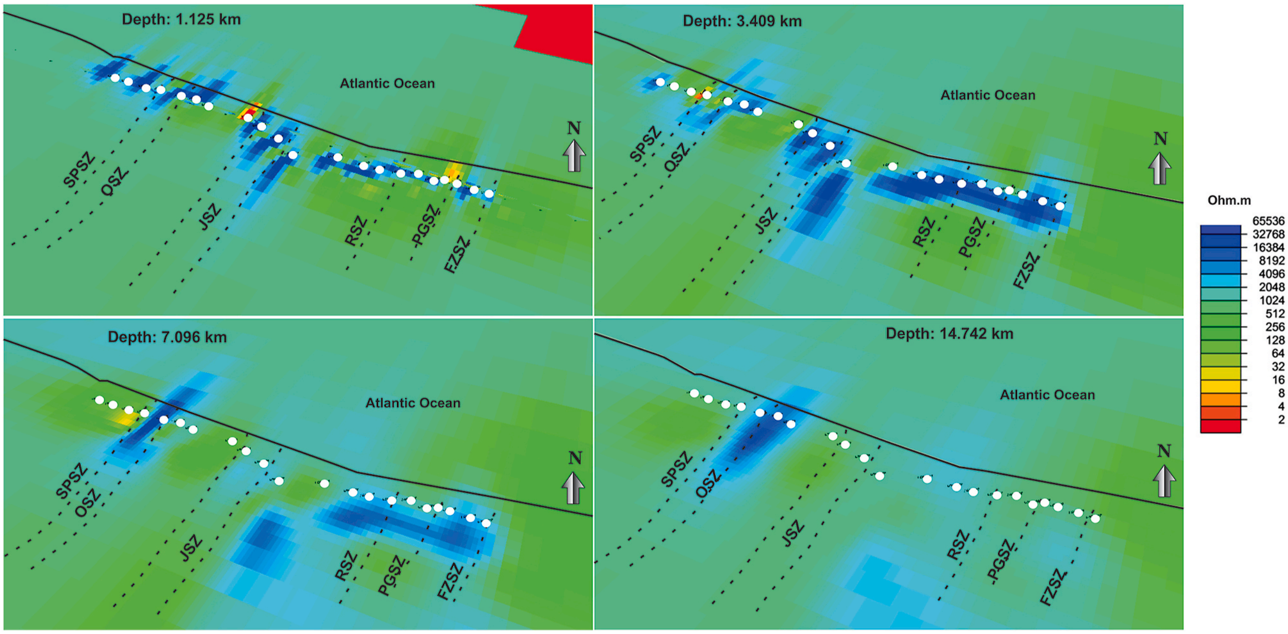

Fig. 12. Horizontal slices of the 3D geoelectrical model at depths of 1.125, 3.4, 7, and 14.7 km, with the projection of the locations of the continental margin and the major shear zones Senador Pompeu (SPSZ), Orós (OSZ), Jaguaribe (JSZ). Magnetic and gravimetric lineaments are from Leopoldino Oliveira et al. (2018): Retiro (RL), Ponta Grossa (PGL) and Fazenda Belém (FBL).

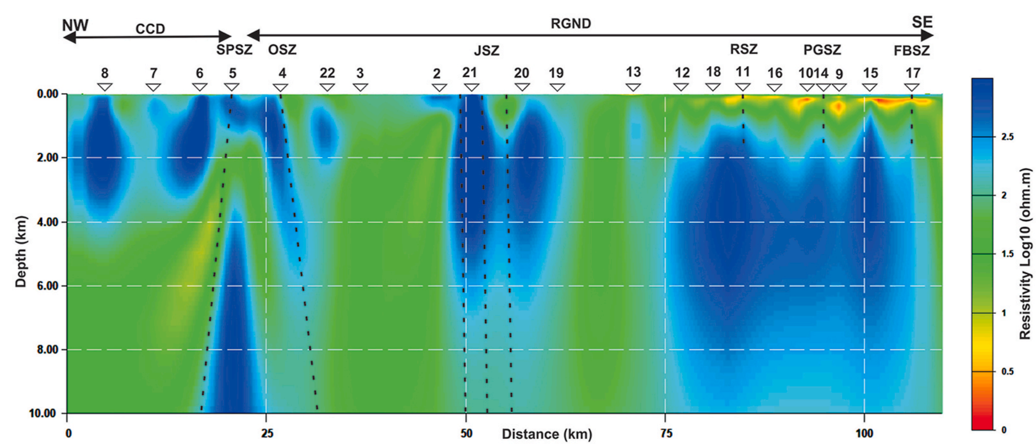

Fig. 13. NW-SE vertical cross-sections of the final 3D inversion model. Location of MT stations: closed triangles. Main tectonic domains: Ceará Central (CCD) and Rio Grande do Norte (RGND). Major shear zones Senador Pompeu (SPSZ), Orós (OSZ), Jaguaribe (JSZ). Magnetic and gravimetric lineaments are from Leopoldino Oliveira et al. (2018): Retiro (RL), Ponta Grossa (PGL) and Fazenda Belém (FBL).

The Ceará Central domain has two high resistive bodies reaching 4 km depth related to rocks from Paleoproterozoic structural high. The geophysical signature of the Senador Pompeu shear zone is very pronounced in the subsurface, even more than in other shear zones. Orós shear zone presents a better signature in shallower depths and seems to dip for E-W, while the Jaguaribe shear zone has the same depth and vertical behavior. Except for bodies with higher resistivity in Ceará Central Domain and that of bodies related to shear zones, almost all basement in this region has moderate resistivity. The basement below the Potiguar Basin 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 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 paleorelief of the Paleoproterozoic Jaguaretama complex or shallow-seated magmatic bodies emplaced in the Precambrian basement.

5. Discussion

The 2D inversion considers only the Zxy, Zyx, and Hz components, discarding the Zxx and Zyy components (geoelectric structures). Although the 3D inversion is only of a single profile (transect), this does not preclude a purely 3D inversion since, in this inversion, all components were included in the calculations for modeling. Therefore, the 3D model helped characterize the geoelectrical architecture of this part of Borborema Province, allowing us to infer the observations discussed in this chapter.

The major geological framework in the study area that contributed by the MT geoelectrical signatures can be addressed considering three main lithotectonic elements: the Paleoproterozoic basement present in both CCD and RGND, the major Neoproterozoic shear zones, and the Cretaceous extensional igneous and sedimentary records. These elements are the product of tectono thermal events developed since Paleoproterozoic times and imprints different responses on MT data.

Expressive, less conductive zones can trace the CCD and RGND gneissic basement. These zones represent portions of a homogeneous Paleoproterozoic basement. The resistivity values for that portions are close to the values reported in the literature for Proterozoic basement rocks not disturbed by subsequent tectono thermal events (Chave and Jones, 2012; Thiel et al., 2020). The CCD and RGND present, in some cases, an interruption of this pattern that is caused by high conductive zones probably related to minor Neoproterozoic shear zones.

Conductivity signatures are often correlated to the main Neoproterozoic shear zones and lineaments interpreted from magnetic and gravimetric data. In the first case, our interpretations agree with the results and interpretation presented by Padilha et al. (2014, 2017), which reveal the existence of an important conductive zone, interpreted as a suture zone, spatially related to the Senador Pompeu shear zone and in smaller proportion to the Orós shear zone. A question that arises from this pattern is whether there is a tectonic suture in this region. As showed by U–Pb and Sm–Nd geochronological results (Fetter et al., 2000), CCD and RGND evolved separately during Paleoproterozoic. In this context, the SPSZ and OSZ must represent crustal structures existing since Statherian times. In this case, probable records a minor suture between crustal blocks, until here without ocean elements identified. In order to improve these interpretations and better comparisons with the MT results of Padilha et al. (2014, 2017), an investigation with long-period MT is recommended for deeper studies.

The taphrogenic process accountable by the Atlantic Ocean opening generates two main geological products in the study area, the basic dykes of Rio Ceará-Mirim Dyke Swarm and the Potiguar Basin. The first case is exemplified by several dykes oriented close to N60W to E-W directions. Through these directions, low resistivity zones on MT results can be expected, contrasting to basement higher resistivity values caused by extensional tectonics and mantellic material apport during Cretaceous. The rifting process responsible for Potiguar Basin genesis with up to 6 km of a sedimentary and volcanic pile can be observed at the SE final segment of the MT section. In this region, the relative conductive zone is related to the Potiguar Basin border and important magnetic and gravimetric lineaments, representing basement structures reactivated during basin generation. Furthermore, the lower resistivity zone can result from the thick sedimentary record and, in some cases, their high hydrocarbons content. The deeper extension (>15 km) of the low resistivity zone indicates mantle apport material and connectivity for that zone, as exemplified by the MT results from Tucano Basin (Bologna et al., 2017).

6. Conclusion

This paper presents the results obtained from the interpretation of a 2D and 3D MT section carried out along part of the northeast Borborema Province in Ceará (Brazil). 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 2D MT results agree with the interpretation of gravity and magnetic data from previous work, which suggest magmatic bodies near Aracati city, grabens, and horst marked by other smaller shear zones.

It was observed that the 3D inversion has a poor resolution in the upper crust compared with the 2D inversion of the same profile. The geophysical signature of the Senador Pompeu shear zone is very pronounced in the subsurface, even more than in other shear zones. Orós shear zone presents a better signature in shallower depths, while the Jaguaribe shear zone has the same depth and vertical behavior. Except for bodies with higher resistivity in Ceará Central Domain and those related to shear zones, almost all basement in this region has moderate resistivity. Yet, our interpretations agree with the results and interpretation presented by Padilha et al. (2014, 2017), which reveal the existence of an important conductive zone, interpreted as a suture zone, spatially related to the Senador Pompeu shear zone and in smaller proportion to the Orós shear zone. As showed by U–Pb and Sm–Nd geochronological results from previous work, the CCD and RGND evolved separately during Paleoproterozoic before amalgamation during Neoproterozoic. In this context, the SPSZ and OSZ must represent crustal structures whose existence goes back since Staterian times, probably representing a minor suture between crustal blocks, until here without ocean elements identified.

3D and 2D models characterize well the basement architecture of the NW border of the onshore Potiguar Basin. The sedimentary package has a maximum thickness of up to 1.0 km in the southeast of the MT profile. The model thus establishes that the basement of this region shares a common signature, indicating that this domain responded similarly to the stresses that culminated in the fracturing and rupturing of the Gondwana continent, separating South America and Africa in the Cretaceous. We suggest that a new investigation with MT recording long-period data investigate in greater depth to clarify the major large shear zones' deeper spatial behavior to increase the tectonic interpretations presented here. In a complementary way, a new CSAMT section could improve the shallow resolution between 0 and 3 km depth.

Credit author statement

R. Mariano G. Castelo Branco: Project administration, Funding acquisition, Conceptualization, Data curation, Resources, Investigation, Formal analysis, Visualization, Writing – original draft. Neivaldo A. de Castro: Formal analysis, Visualization, Writing – original draft, writing - review and editing. Karen M. Leopoldino Oliveira: Supervision, Data curation, Visualization, Validation, Formal analysis, Writing – original draft; Writing – review & editing. Fernando A. Monteiro Santos: Supervision, Data curation, Resources, Visualization, Validation, Writing – review & editing; Eugénio P. Almeida: Supervision, Data curation, Resources, Visualization, Validation, Writing – review & editing. Fabiano M. da Silva: Data curation, Formal analysis, Visualization, Writing – review & editing. Jonathan L. Castelo Branco: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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