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Magnetotelluric transect across the São Luís cratonic fragment, the Gurupi belt and the Parnaíba basin, N-NE Brazil

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ABSTRACT

The study area is located in the N-NE region of Brazil where Precambrian rocks of the São Luís Cratonic Fragment and the Gurupi belt are overlain by Phanerozoic sediments of the Parnaíba and São Luís basins, making the assessment of the extents of these geotectonic domains difficult. One of the main objectives of the present study was to elaborate a NNW-SSE-trending, 180-km long magnetotelluric transect, aiming to identify the geotectonic domains of the study area by means of their geoelectric characteristics. The magnetotelluric (MT) technique is a geophysical method that detects the natural variations of the terrestrial electric and magnetic fields so as to investigate the geoelectric characteristics of the subsurface. By means of a MT survey for field data acquisition, calculation of impedance tensors and 2D inversion modeling, the geophysical transect and additionally an interpretive geological model were elaborated for the study area. The combined transverse electric (TE) and transverse magnetic (TM) geophysical model revealed superficial conductive (Parnaíba and São Luís basins and sedimentary coverings), resistive (São Luís Cratonic Fragment) and very resistive (Gurupi mobile belt) portions up to depths of the order of 15 km. These results attested for correlations between the São Luís Craton (South American Plate) and the West African Craton (African Plate), especially regarding the Gurupi Belt (in Brazil) and the Rokelide Belt (in Liberia), which are considered to be the boundaries of a triple junction related to the supercontinent Rodinia taphrogenesis. Besides presenting an unprecedented geophysical investigation along the São Luís Cratonic Fragment and the Gurupi Belt, this study promotes the discussion on the correlations between the Brazilian Gurupi and the African Rokelide belts for metallogenetic purposes.

1. Introduction

The São Luís Cratonic Fragment is located in the N-NE region of Brazil, in the State of Maranhão. The geological limits of this cratonic fragment, which is composed of Archean and Paleoproterozoic units, are poorly known due to the scarcity of outcrops, because Phanerozoic sedimentary deposits (the Parnaíba and São Luís basins and Cenozoic deposits) cover the Precambrian rocks and structures. The Neoproterozoic Gurupi Belt marks the limit between the cratonic fragment and the Parnaíba Basin. It developed after the break-up of the Rodinia supercontinent (1.0 Ga) and underwent reactivations in the Phanerozoic via preexisting shear zones (Almeida et al., 2000; Klein et al., 2005a; b; Vasques and Rosa Costa, 2008; CPRM, 2012).

In order to better define the extent of the São Luís Cratonic Fragment and the Gurupi Belt in the subsurface, the contacts between the Phanerozoic basins and the Precambrian rocks, and the thickness of the overlying Phanerozoic sedimentary deposits, a 180 km long magnetotelluric transect trending NNW-SSE was performed, results of which are presented in this paper.

The magnetotelluric (MT) technique is a passive geophysical investigation method that detects the natural variations of the terrestrial electric and magnetic fields to identify the geoelectric characteristics of

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the Earth's interior (Simpson and Bahr, 2005; Chave and Jones, 2012). Magnetotelluric surveys have been commonly used in several geological contexts such as sedimentary basins, suture zones and cratonic regions (Porsani and Fontes, 2001; Naganjaneyulu and Santosh, 2011; Naganjaneyulu et al., 2013; Solon et al., 2018). For example, Daly et al. (2018) carried out an integrated basin analysis of the Parnaíba Basin, using a deep-crustal geophysical dataset, including an E-W-trending MT transect, to determine the deep structure of the basin and the underlying crust and mantle.

Porsani and Fontes (2001) also emphasize that the MT technique is quite effective in regional geological studies, and in the identification of the geoelectric basement, operating at lower costs than seismic methods. Furthermore, geophysical investigations as a whole have greatly contributed to correlation studies, such as those regarding the São Luís Cratonic Fragment and the West African Craton (Lesquer et al., 1984; Brito Neves et al., 2001).

In addition to the main objectives of this survey, it also was an opportunity to train and qualify teams in the field data collection as well as in the tasks of modeling numerical data for geological studies of the Earth's subsurface.

2. Geological and tectonic settings

The pre-drift reconstruction of northeastern Brazil and northwestern Africa is extremely important for the understanding of Gondwanaland's evolution (Fig. 1). Such attempt encourages the publication of new studies, as a follow-up to the International Geological Correlation Programs (IGCPs) (Brito Neves et al., 2001).

The study area is located in the Parnaíba Province, northeastern part of the South American Platform (Fig. 2), and includes geological units that are chronologically distributed in the Precambrian-Cenozoic interval: i) the São Luís Cratonic Fragment; ii) the Gurupi Belt; iii) Phanerozoic sedimentary basins, and iv) Cenozoic deposits (Almeida et al., 1976; Hasui et al., 1984; Almeida et al., 2000; CPRM, 2012*et a*).

2.1. The São Luís Cratonic Fragment

The São Luís Cratonic Fragment comprises the oldest rocks of the study area. This Precambrian terrain makes up only 2% of the State of Maranhão, cropping out in its north-westernmost part. Most of the cratonic fragment is covered by Phanerozoic sedimentary rocks and sediments (CPRM, 2012).

The term São Luís Cratonic Fragment is adopted here as proposed by Vasques and Rosa Costa (2008), who pointed out that this fragment is only a small portion of a larger cratonic area, the West African Craton, which separated from South America in the Mesozoic.

The ages of the rocks from the cratonic fragment range from Archean to Paleoproterozoic (Klein et al., 2005). The main lithotypes are metavolcanosedimentary and metavolcanic rocks, and pre-, syn- and post-collisional granitoids (Fig. 3A and B) (CPRM, 2012).

The units in chronological order are: the Aurizona Group, the Piaba Granophyre, the Tromaí Intrusive Suite, the Rosário Intrusive Suite, the Serra do Jacaré Volcanic Unit, the Rio Diamante Formation, the Negra Velha Granite, the Rosilha Volcanic Unit, the Garimpo Caxias Microtonalite, and the Igarapé de Areia Formation.

2.2. The Gurupi Belt

The NW-SE-trending, 160 km long Gurupi Belt is a Neoproterozoic orogen and extends to the State of Pará. Its contact with the São Luís Cratonic Fragment is via the Tentugal Shear Zone, which is treated as a geochronological boundary by several authors (Almeida et al., 1976;

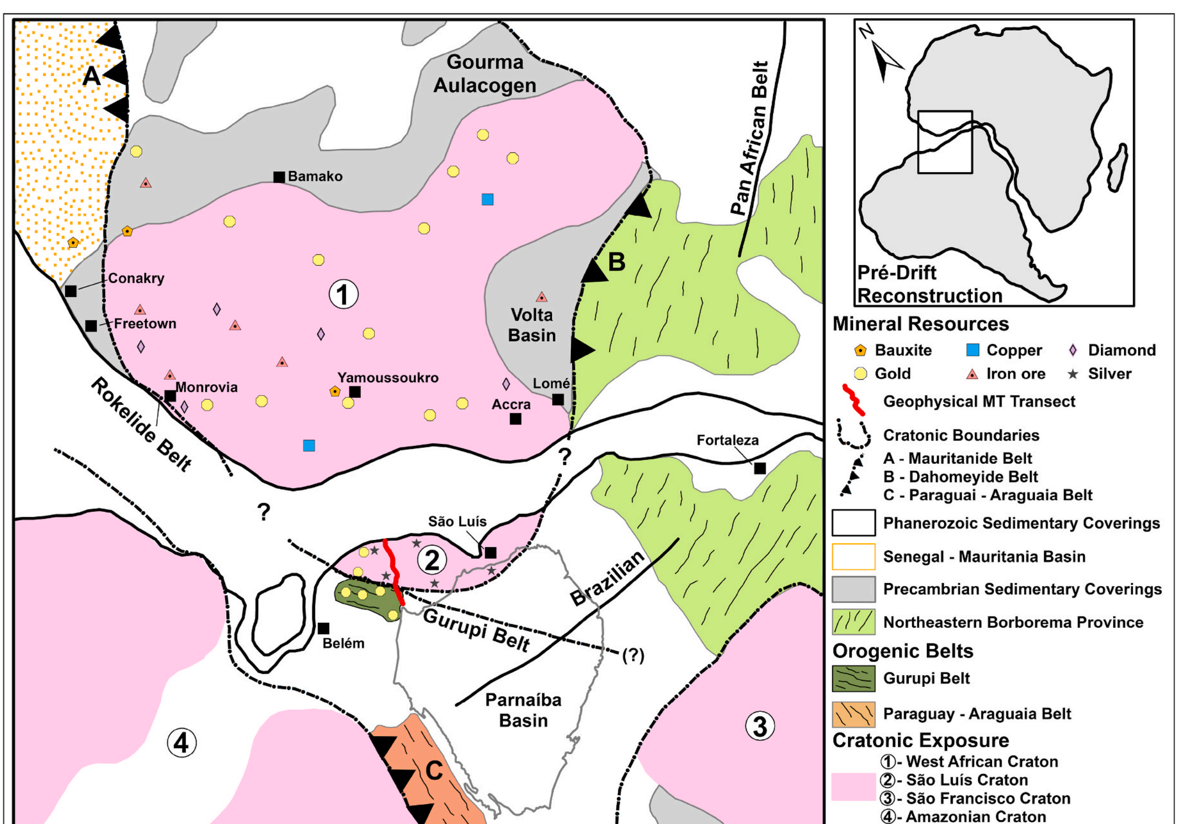

Fig. 1. Pre-drift reconstruction of the northeastern Brazil and northwestern Africa, highlighting the São Luís and West Africa cratons and the surrounding structures (sources: Lesquer et al., 1984; Villeneuve and Cornée, 1994; Brito Neves et al., 2001; CPRM, 2012; Markwitz et al., 2016).

Fig. 2. Location and geological map of the study area with the indication of the MT transect.

Hasui et al., 1984; Costa, 2000; Klein et al., 2005a).

The lithological associations that compose the belt include metasedimentary and metavolcanic rocks (Fig. 3E) and granitoids, with ages from the Archean to the Neoproterozoic (Klein et al., 2005a; Klein and Lopes, 2009).

The units in chronological order are: the Itapeva Complex, the Chega Tudo Formation, the Maria Suprema Granite, the Moça Granite, the Igarapé de Areia Formation, the Gurupi Group, the Marajupema Formation, the Cocal Amphibolite, and the Piriá Formation.

Fig. 3. Outcrops observed along the MT transect. A) and B) Granitoids from São Luís Cratonic Fragment. C) and D) NW-SE-trending (310° Az) quartz vein associated with the Gurupi units. E) Metavolcanic rocks from the Gurupi Belt. F) Sandstones from the Parnaíba Basin.

2.3. The Phanerozoic basins

The Phanerozoic basins of the State of Maranhão formed during the evolutionary stages of the South American Platform, which started with the Brasiliano/Pan-African event in the Neoproterozoic-Cambrian (Almeida, 1969; Almeida et al., 2000).

The study area encompasses the intracratonic Paleozoic Parnaíba Basin (Fig. 3F), the Cretaceous São Luís Basin, which represents an estuarine, graben-type valley incised in the São Luís Cratonic Fragment, and superficial Cenozoic coverings (Rossetti and Truckenbrodt, 1997; Rossetti, 2000; CPRM, 2012).

3. The magnetotelluric technique

The magnetotelluric (MT) technique is an electromagnetic geophysical method and was initially proposed by Tikhonov (1950) and Cagniard (1953). Natural variations of the Earth's electric and magnetic fields are detected in order to acquire the resistivities/conductivities of the geological environment in subsurface from the calculated EM wave impedances. By means of these parameters, it is possible to distinguish the main differences between the physical and chemical characteristics of the geoelectrical structures present in the subsurface (Santos, 2012).

The main steps of the MT technique are: field data acquisition, noise removal, calculations by means of transfer functions, dimensionality analysis, inversion and MT modeling (Fig. 4).

The MT survey started in May 2018 with the installation of 15 MT stations (labeled MT01 to MT15) in the study area (Fig. 2). The distance between the stations was approximately 12 km. The MT array adopted in this study was the one proposed by Simpsom and Bahr (2005) and the equipment used was the MetroniX analog/digital signal conditioning unit ADU-07e, PbCl electrometers and induction coils. At the end of the data acquisition, a time-series was obtained. Further information about field data acquisition can be found in Uchoa et al. (in press).

Noise removal from the time-series was performed using the Fast Fourier Transform (FFT). The transformation of a time-series into a frequency domain makes the calculation of MT transfer functions or impedance tensors (Z) possible.

Geoelectric dimensionality is understood as the distribution of resistivities/conductivities in subsurface and can assume 1D, 2D and/or 3D characteristics. This procedure is essential in selecting the inversion modeling to be applied, conferring reliability to the geophysical model and interpretation (Martí et al., 2009).

The product of the inversion is the MT model, which allows differencing the characteristics of the subsurface by means of electrical resistivity contrasts (Simpsom and Bahr, 2005).

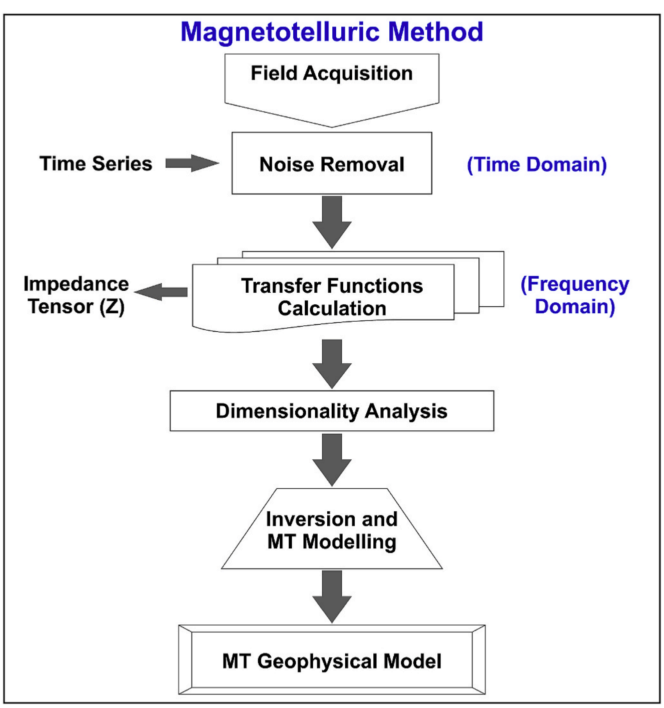

Fig. 4. Flowchart showing the steps of the MT technique.

4. Results

4.1. Magnetotellurics transfer functions

The impedance tensor (Z) is equivalent to the ratio between the orthogonal components of electric (TE) and magnetic (TM) fields and is expressed by the parameters apparent resistivity (r_a) and phase (F) (Simpsom and Bahr, 2005; Chave and Jones, 2012). Fig. 5 lists the apparent resistivities and phases calculated for each of the fifteen MT soundings.

4.2. Dimensionality analysis

The WALDIM code (Martí et al., 2009) was applied to determine the geoelectric dimensionality of the MT data acquired for this study (Fig. 6). For other methods of dimensionality analysis see Bahr (1988), Groom and Bailey (1989), McNeice and Jones (2001), and Cadwel et al. (2004).

The WALDIM code indicated that the dimensionality of the data generally tended towards 3D, with a slight 2D influence. This result is compatible with the geotectonic characteristics of the area, which includes sedimentary basins (2D), cratonic regions (3D), intrusions (3D) and orogens (3D).

The WALDIM code is quite reliable because it makes use of eight invariants, differently from the four used by Bahr (1988, 1991). Galvanic distortion (effects of surface bodies) was not taken into account in this study, because our objective was the characterization of the subsurface. The dimensionality analysis pointed to the use of the 2D inversion of MT data to generate the final geophysical model.

It is important to note that the 2D inversion can be used even in situations influenced by 3D environments (Simpson and Bahr, 2005; Santos, 2012).

4.3. Inversion and modelling

The definition of the parameters used in the inversion program took into account the results of the dimensionality analysis; the influence of the Atlantic ocean; the resistivity of the homogeneous half-space subjacent to the inversion grid, for which values ranging from 100 Ω-m to 1000 Ω-m were tried; and the data fit between the observed and calculated data.

The background with lowest RMS and consequently best data fit between calculated and observed data was 300 Ω m. All the values ascribed in the initial inversion block were controlled by means of a careful analysis of the resistivities presented in each MT sounding, with the objective of generating a reliable model for the study area. Subsequently, an inversion with 70 interactions was processed and a combined transverse electric (TE) and transverse magnetic (TM) geophysical model was generated.

The inversion of TE and TM modes was performed using the minimum and maximum resistivity values (0.2–20,000 Ω-m). Station data were used instead of interpolation data. As inversion smoothing parameters, a standard Laplacian grid operator was used and the smoothest variations away from the apriori model were applied. The standard deviation errors used were 10% for resistivity and 5% for phase and an error floor of 2.5% was assigned.

It is important to note that a joint 2D inversion of the TE and TM modes was carried out and the same weight was attributed to the data

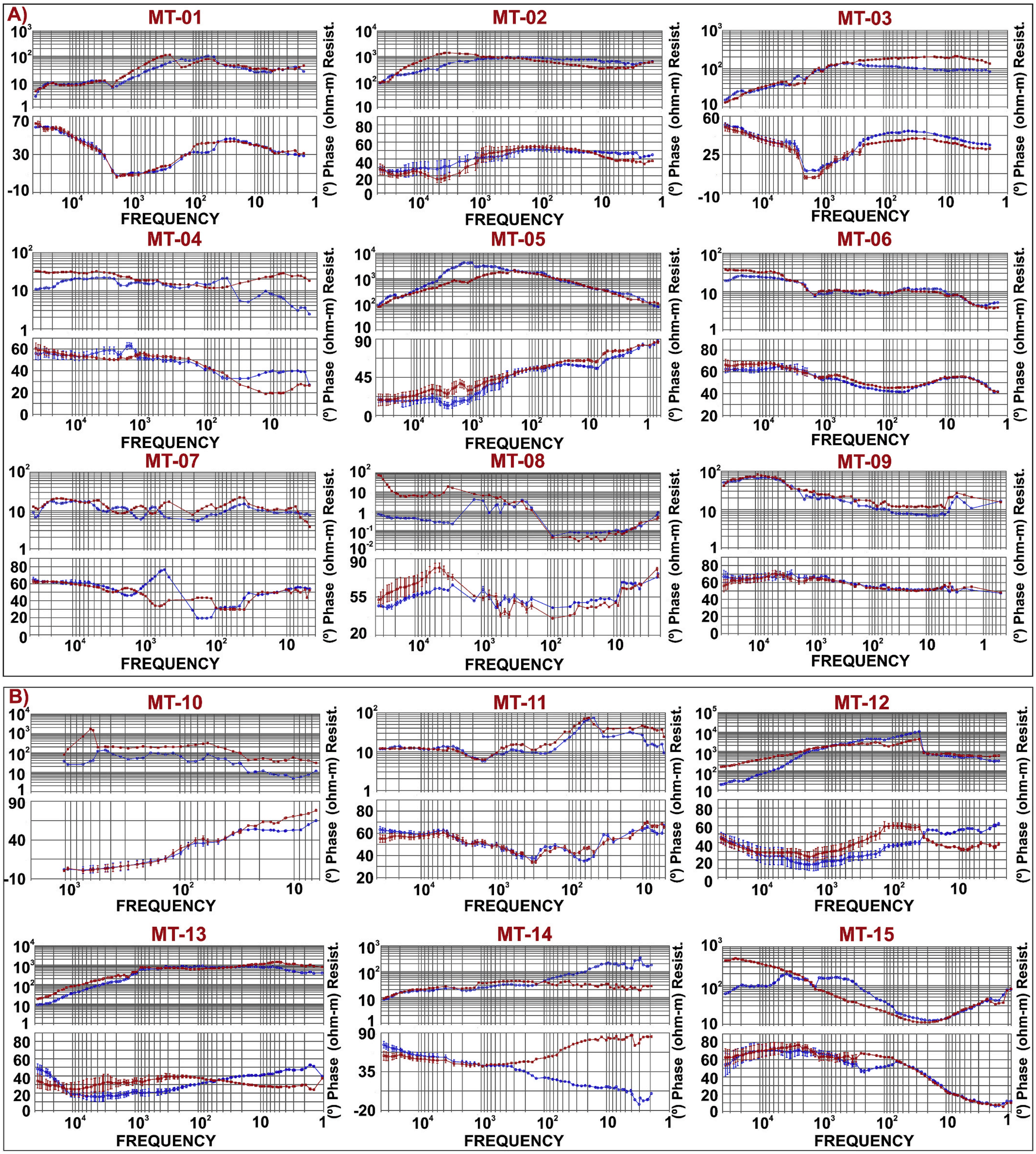

Fig. 5. A and B) Apparent resistivities and phases calculated for MT01 to MT15 soundings. The top and bottom curves represent the apparent resistivity (ohm-m) and phase (degrees), respectively. Blue and red curves represent, respectively, Transversal Electric (TE) and Tranversal Magnetic (TM) components of the impedance tensor. (Source: Uchoa et al., in press). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

set of both modes during the inversion. The data inversion was performed considering the real coordinates of each MT soundings and the profile assigned in the processing was point to point (see Fig. 2 profile AB).

The final results were generated with a 2D inversion using a homogeneous half-space of 300 Ω-m. The sea water was modeled with a resistivity of 0.2 Ω-m. The influence of the ocean was strongest in the first MT soundings (MT01 to MT03). Convergence was achieved after 70 iterations, with an RMS misfit of 3.08%.

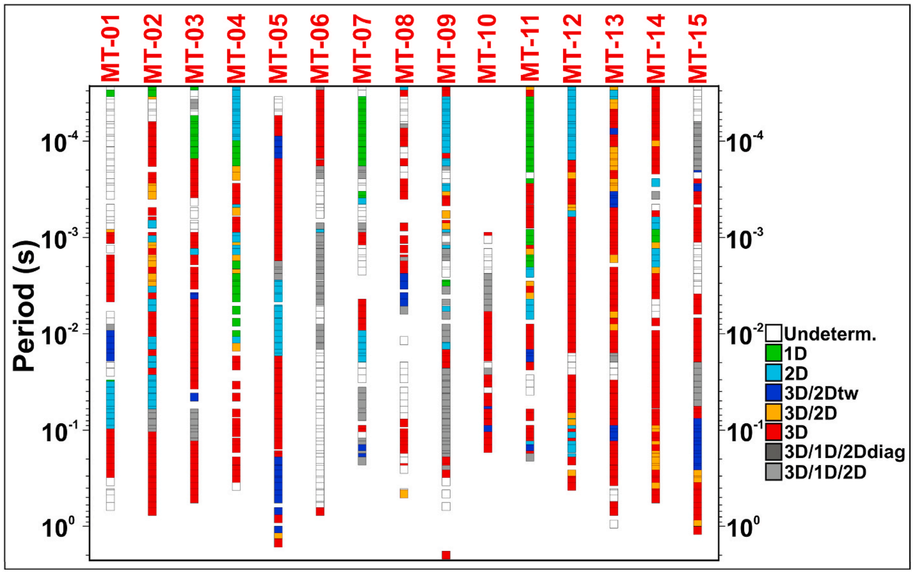

Fig. 6. Determination of the dimensionality of the MT survey applying the WALDIM code. (Source: Martí et al., 2009).

4.4. MT modeling and interpretation

After careful analysis of the various models generated and integration with surface geological data, the MT model with the best data fit between observed and calculated data was selected (Fig. 7).

Prior to the MT modeling the impedance tensors (Z) were rotated, a grid compatible with the observed data was generated, and finally the data were interpolated.

The interpretive geological model was obtained by integrating MT data, surface geological data and previous geological works (Pastana, 1995; Veiga and Sã o Lu í s NE/, 2000; CPRM, 2012).

Figs. 8 and 9 show, respectively, the combined transverse electric (TE) and transverse magnetic (TM) geophysical model and the geological interpretation.

5. Discussions

By means of the acquisition of the time-series, processing and calculation of impedance tensors, dimensionality analysis, inversion and integration of existing geophysical and geological data, it was possible to obtain a regional geological and geophysical transect for the study area, representing a line of 180 km of length and an investigation depth of 15 km.

Fifteen impedance tensors were calculated from the MT soundings. A good linearity and coherence >0.7 were obtained, conferring reliability to the MT model. However, the higher noise in the MT07, MT08 and MT10 soundings made it difficult to obtain a smooth and linear curve. The apparent resistivity values (r_a) varied from 0.027 to 10.530 Ω m at stations MT08 and MT12 respectively. Phase (F) varied between −15 and 90° at stations MT15 and MT05 respectively. These ample ranges of data result from the different geoelectric characteristics of the subsurface, expressing lithological, structural and geotectonic variations.

The errors presented by the data fit curves show that the 2D geophysical model is extremely reliable. Except for the MT08 and MT10 soundings, all other soundings yielded RMS values below 3.48%. High RMS values at these soundings are due to man-induced noises (such as proximity to powerlines, as in Maracaçumé city). Despite the errors at these stations, the final RMS was 3.08%, which we consider very good, allowing analogies with important MT surveys developed in northeastern Brazil in the last decade (Santos, 2012; Silva, 2018). The adjustment of the curves and the low RMS produced a reliable geophysical model compatible with the acquired data.

The generated geophysical model can be divided into conductive, resistive and highly resistive portions. The conductive portion is subdivided into three areas around the MT01, MT08 and MT15 stations. The highly resistive portion extends in area from station MT11 to MT14, and in depth up to 7 km. Finally, the resistive portion starts at 7.4 km to a maximum of 15 km in depth.

The considerations resulting from the analysis of the 2D inversion model, previous geological and geochronological data (CPRM, 2012), and field observations are listed below and illustrated in Fig. 9:

i. The São Luís Cratonic Fragment can be subdivided into two major units: the lower cratonic unit, unaffected by the Gurupi Orogeny, and the upper cratonic unit, affected by the Gurupi Orogeny and Phanerozoic events (rifting that generated the São Luís graben).
ii. The boundary of the São Luís Craton Fragment marked by the Tentugal Shear Zone is recognized around the MT13 station.
iii. The Tromaí Intrusive Suite represents a cratonic portion that was reworked in the Meso- and Neoproterozoic during the Gurupi (Grenvillian?) Orogeny. Its tectonic contact with the Chega Tudo Formation is via the Tentugal Shear Zone.
iv. The thicknesses of the Phanerozoic and Cenozoic sedimentary deposits are compatible with those presented in the literature (CPRM, 2012).
v. Between the MT14 and MT15 stations a 400 m thick sedimentary package is depicted and is treated here as the Serra Grande Group of the Parnaíba Basin, differing from the CPRM geological map (Fig. 2), which considers it as belonging to the Itapecuru Group of the São Luís Basin. This change is proposed on the basis of the sandstone outcrops near the MT14 station (Fig. 3F). Moreover, this outcrop is located after the Ferrer-Urbano Santos Arc, which marks the southern limit of the São Luís Basin.
vi. The maximum thickness found for the Itapecuru Group in the São Luís Basin is around 500 m. Its depocenter is located east of the transect and has a thickness of 3000 m (CPRM, 2012).
vii. Two Cenozoic coverings are recognized in the transect: the Barreiras Group (MT01, MT06 to MT11), with a maximum thickness of 30 m, and alluvial deposits (MT09 and MT10) with a thickness of around 20 m.
viii. Correlations between the São Luís and West African cratons have been made, considering the similarities between the Gurupi (Brazil) and the Rokelide (Liberia) mobile belts, e.g., mineral resources, such as gold deposits, occurring on both sides.

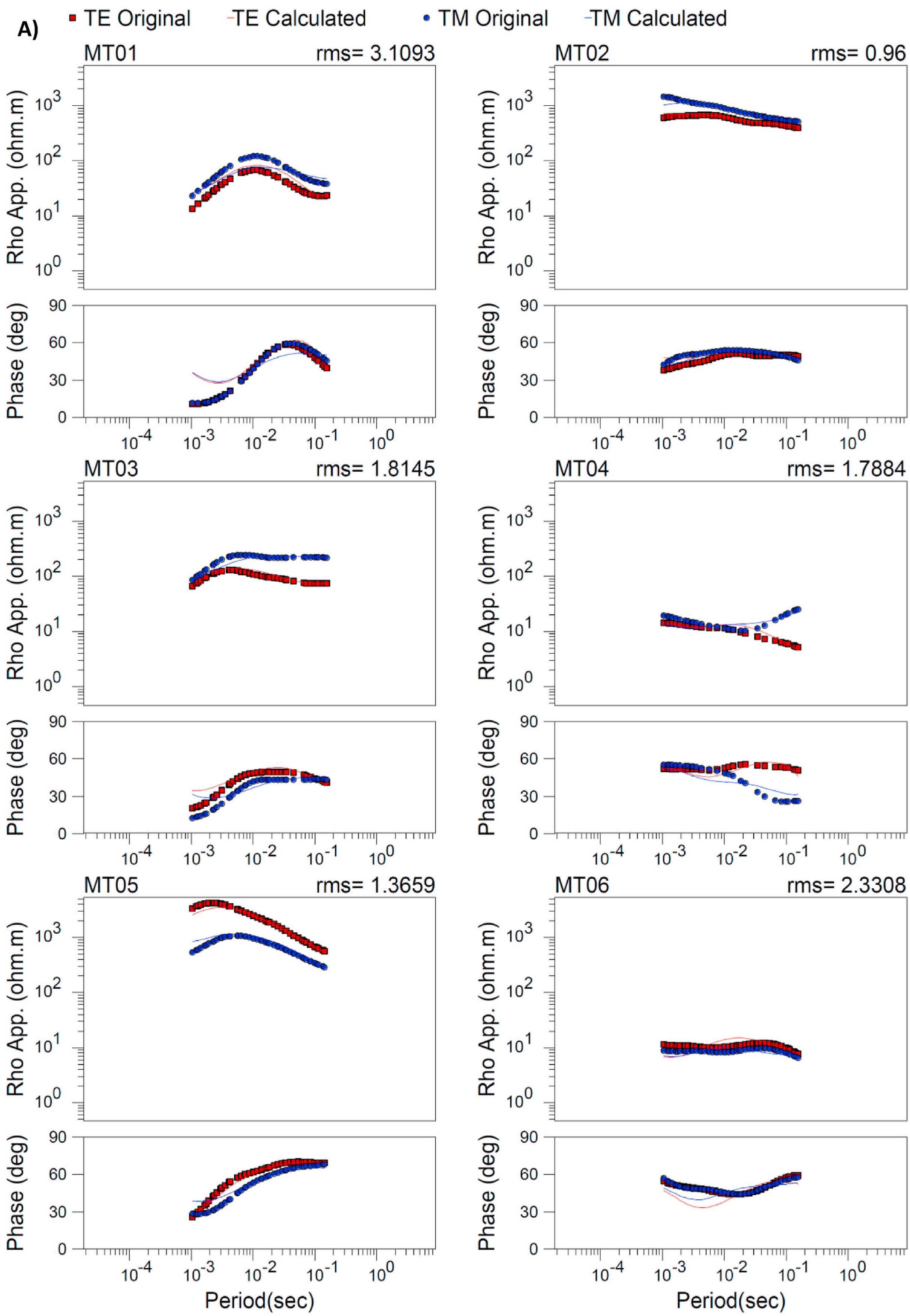

Fig. 7. Adjustment of the calculated curves with the observed data (data fit). A) Stations MT1 to MT06. B) Stations MT07 to MT12. C) Stations MT13 to MT15. Total RMS of 3.08%.

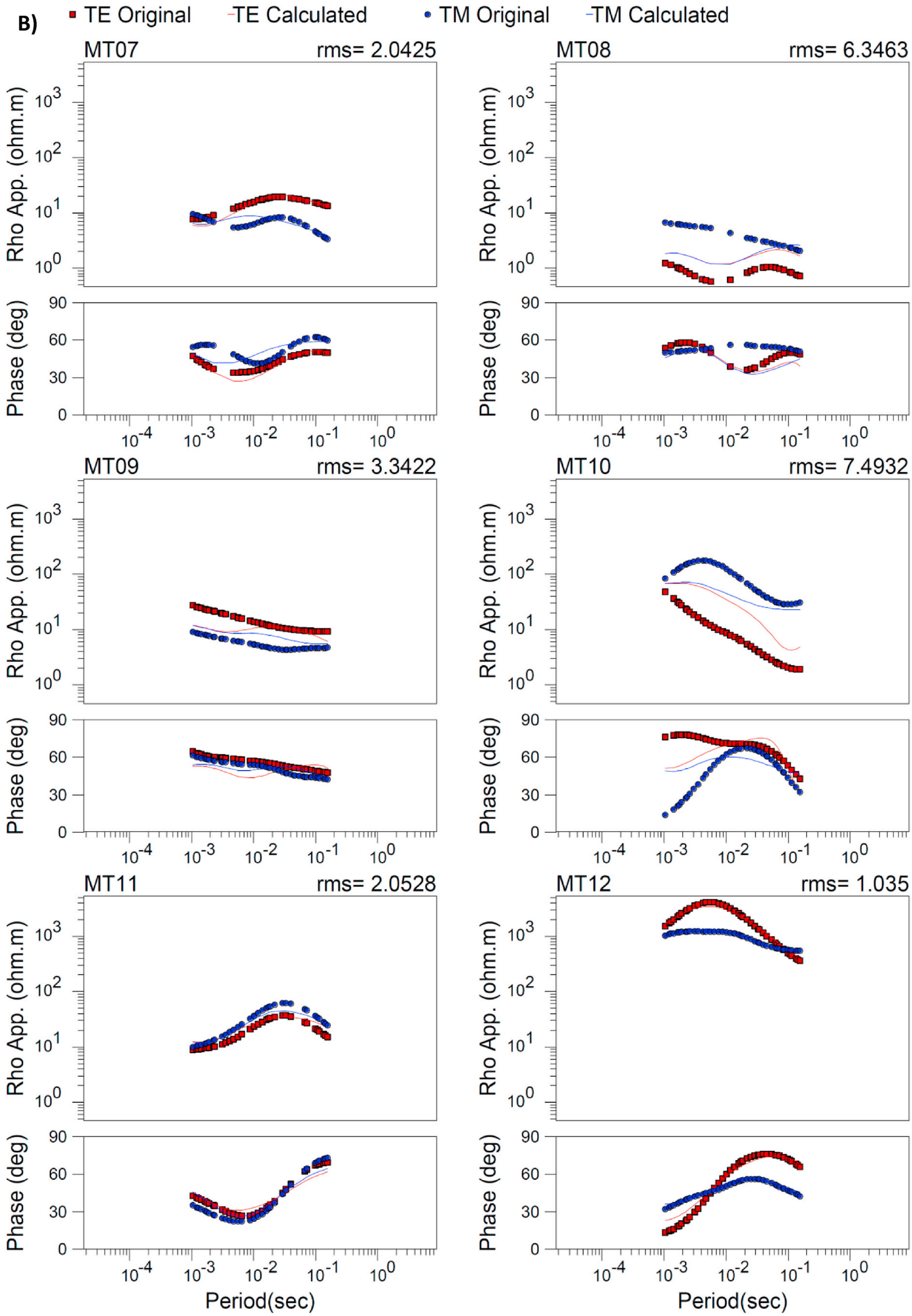

Fig. 7. (*continued*).

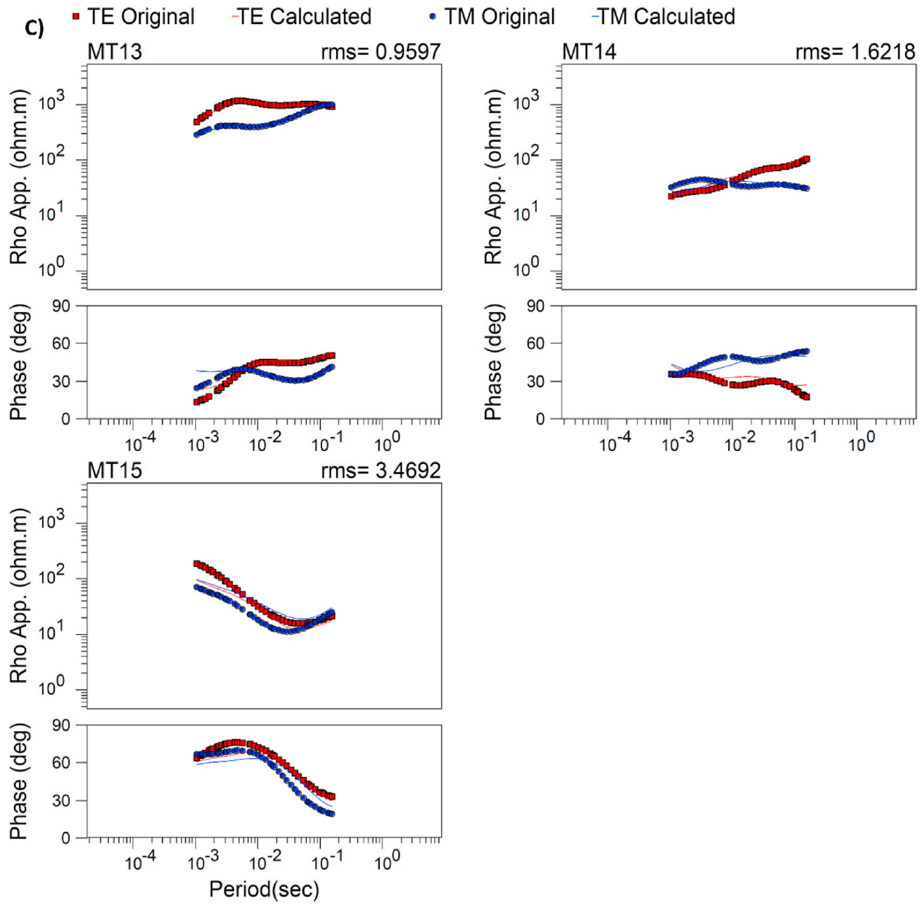

Fig. 7. (*continued*).

However, the fact that the Phanerozoic sedimentation covers much of the Precambrian rocks on the Brazilian side, their mineral potential has been underestimated.

ix. The Neoproterozoic Gurupi-Rokelide, Brasiliano-Pan African and Paraguay-Araguaia mobile belts constitute the boundaries of a triple-point junction of the supercontinent Rodinia (1.0 Ga). The Parnaíba Basin developed along these belts, which represent today the boundaries of cratonic regions. The cratonic borders amalgamated 600 Ma ago were reactivated during the Phanerozoic taphrogenesis via ancient lineaments, promoting the formation of the Phanerozoic sedimentary basins.

x. A regional geophysical investigation is suggested in Liberia in the West African Craton, e.g. a E-W transect across the (N–S-trending) Rokelide belt, as an attempt to reach depths from 2.8 to 7.4 km. This would increase the possibilities of correlation between South American and African plates.

6. Conclusions

A combined transverse electric (TE) and transverse magnetic (TM) geophysical model was for the first time generated for the study area located in the north-western most part of the State of Maranhão. The following geotectonic domains were characterized according to their electrical resistivity contrasts: the São Luís Cratonic Fragment, the Gurupi Belt, Phanerozoic basins and Cenozoic coverings.

The 2D inversion model generated in this study resulted from the best data fit between the observed and calculated data. Despite some man-induced noise near two MT stations, the final RMS was 3.08%, which is considered very good and analogous to that obtained in a previous study in northeastern Brazil (Santos, 2012; Silva, 2018).

Some discussion on the correlations between Gurupi (Brazil) and Rokelide (Liberia) was also made possible by this study encouraging discussions that are generally proposed by international geological correlation programs (IGCPs).

It is recommended that similar geophysical transects be obtained in the African counterpart, so as to enable further correlations between the São Luís cratonic fragment and the West African craton, e.g. a regional E-W geophysical transect in the Rokelide Belt.

As future works Geophysical studies at shallow depths applying high-resolution techniques (e.g., Controlled-Source Audio-frequency Magnetotellurics – CSAMT) are important for the mineral prospecting of the study area.

Credit author statement

Elenilton Bezerra Uchoa; Conceptualization; Data acquisition; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/Writing – original draft; Writing - review & editing. Christiano Magini; Project administration; Resources; Supervision; Writing - review & editing. Reinhardt Adolf Fuck; Resources; Supervision; Visualization. R. Mariano G. Castelo Branco; Project administration; Supervision; Writing - review & editing. Fabiano Mota da Silva; Visualization; Formal analysis; Writing - review & editing. Nilton Cesar Vieira Silva; Data acquisition; Methodology; Validation; Visualization. Jackson Alves Martins; Data acquisition. Charles Régis Maia e Silva; Data acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

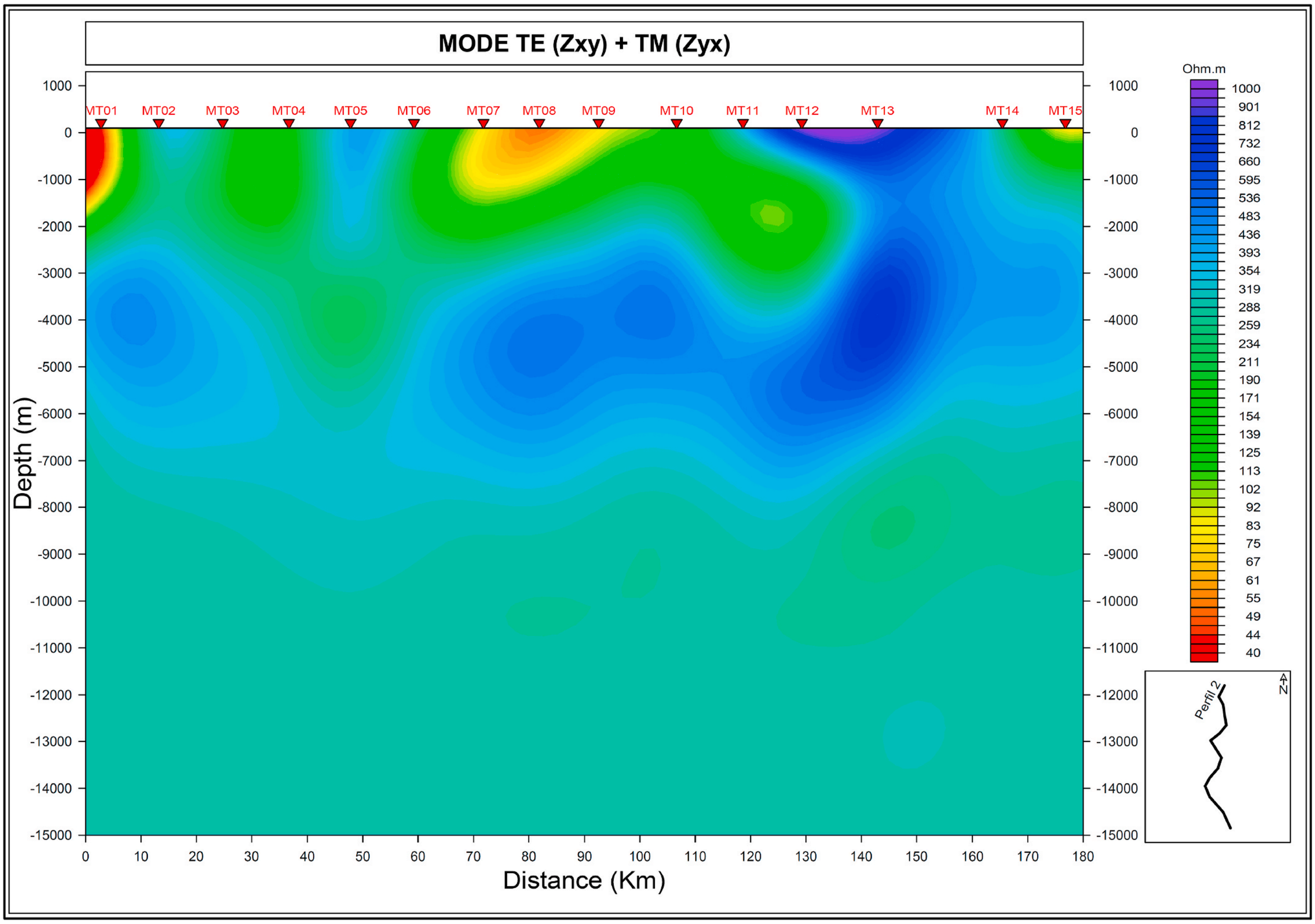

Fig. 8. 2D inversion of the combined transverse electric (TE) and transverse magnetic (TM) modes for the MT transect.

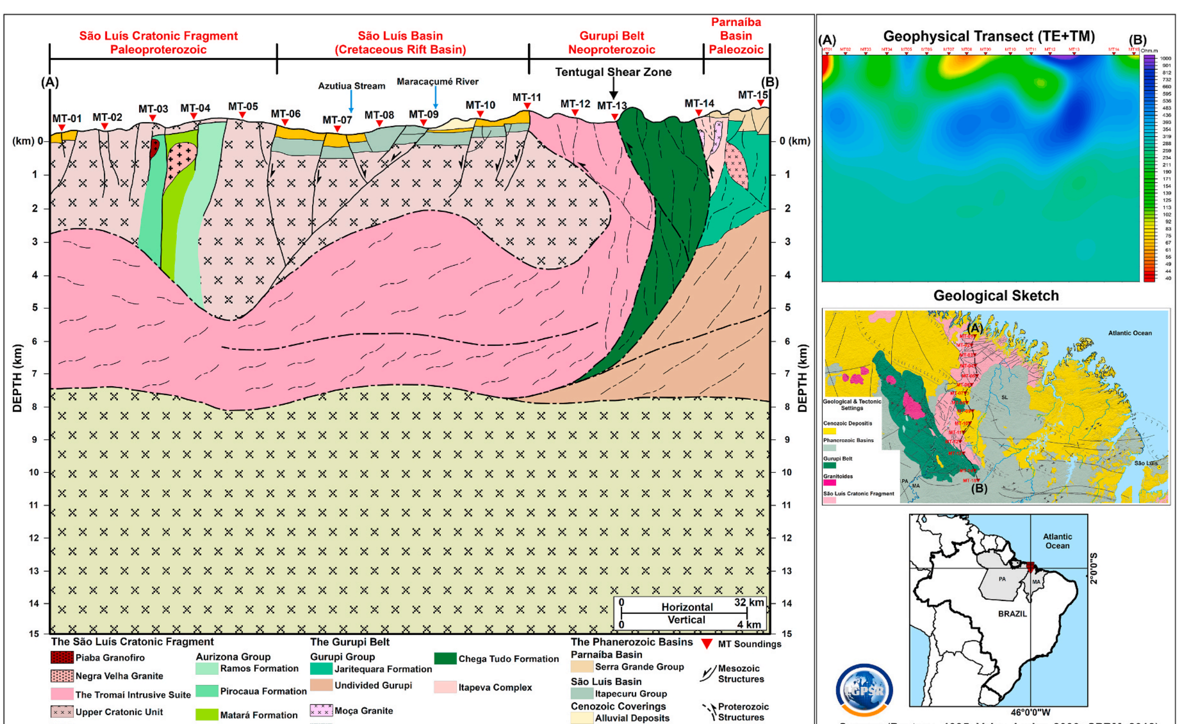

Fig. 9. Interpretative geological model of the study area.

the work reported in this paper.

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