# Preliminary results on the crustal geo-electrical distribution of the Parnaíba Basin from broadband magnetotelluric data

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## Abstract

The magnetotelluric (MT) method is a passive electromagnetic technique to characterise the geoelectric behaviour of the Earth's interior from shallow depth to the upper mantle. The use of this method in tectonic contexts and sedimentary basin studies makes it possible to identify suture zones (generally associated with conductive anomalies) and to define the sedimentary sequence that overlies the basement. The Parnaíba Basin is a fundamental tectonic unit to understand the formation of Western Gondwana, as well as being an important onshore oil and gas exploitation area for Brazil. Therefore, in this study, new magnetotelluric data (not considered in a previous MT study) are analysed to evaluate the regional electrical resistivity structure of the basin. We present a 2D resistivity model from broadband MT data acquired along an E-W transect profile of ~1400 km long. The model revealed graben-like structures that deepen towards the central part of the basin (Parnaíba Block) from the two extreme blocks, the Amazonian Craton and the Borborema Province. In the central part of the basin, the model identifies a subvertical conductor extending into the upper mantle, interpreted as the suture zone between the Grajaú and Teresina domains (both belonging to the Parnaíba Block). Adjacent to the conductor, a graben-like structure up to 10 km depth is identified, which can be interpreted as a graben buried beneath the Parnaíba basin, formed during a Neoproterozoic-Eopaleozoic extensional phase. These results and interpretations are still at a preliminary stage, but this is one of the first images of the internal resistivity of the entire basin in which graben-like structures are evident (not visible in previous seismic surveys). Furthermore, these results will contribute significantly to the construction of a 3D resistivity model (currently under development) and integration with other geophysical data (potential field and seismic) to help explaining the formation of the basin and its role in the amalgamation of Western Gondwana.


## Introduction

The Parnaíba basin located in the northeastern part of Brazil is one of the largest intracratonic sedimentary basins developed on the South American platform, together with the Amazon and Paraná basins. It has an approximately circular shape and its depocenter reaches 3,500 meters in the central part of the basin (Vaz et al., 2007). Daly et al., (2014) through a deep seismic reflection profile showed the presence of three distinctive blocks of continental crust accreted during the Brasilian Orogeny that compose the Parnaíba Basin: Amazonian craton, Parnaíba block and Borborema Province. These blocks are separated by steep crustal-scale boundaries across which seismic facies change abruptly. Hence, these authors confirm the existence of the Parnaíba block beneath the Parnaíba basin, initially suggested by Brito Neves et al., (1984). In addition, Daly et al., (2014) identified a mid-crustal reflector (MCR), interpreted as a dense magmatic body located in the central part of the basin. Tozer et al., (2017) suggest that it represent an intrusive body in the lower crust that would have loaded and flexed the crustal surface.

The mechanism of the formation of the Parnaíba basin has been the subject of extensive debate in the literature, which is generally the case with intracratonic basin. It is discussed whether extensional or thermal processes predominate as the first pulse leading to the formation of the basin. Daly et al., (2018) discusses the latest geophysical results obtained within the basin to outline some of the significant features of cratonic basins. The authors indicate that basin initiation and development is purely vertical subsidence of the lithosphere, either thermally or mechanically driven. Thermal subsidence may be related to orogenic thickening, radiogenic heating and erosion associated with supercontinent assembly, whereas mechanical subsidence may be a result of the emplacement in the lower crust or upper mantle of a dense igneous body. In contrast, De Castro et al., (2014) based on magnetic and gravity data revealed coincidences between residual gravity, residual magnetic, and pseudo-gravity lows, indicating two complex systems of Eopaleozoic rifts related to the initial phase of the basin. Recently, Porto et al., (2022) present another comparative analysis of geophysical and geological datasets in the Parnaíba Basin and propose a new tectonic configuration for its pre-Silurian basement, composed of different terranes amalgamated during the Brasiliano orogeny. These authors, propose a transitional domain called Barra do Corda, interpreted as Neoproterozoic Belt that separate the Parnaíba block in two domains, Grajaú and Teresina. In this last domain, the presence of MCR is interpreted as crustal-scale thrust faults related to the boundary between the two domains. Porto et al., (2022) contradicts the idea of a stable cratonic block beneath it, inciting new formation models.

Recently, Solon et al., (2018) proposed a lithospheric-scale resistive model of the area based on 3D inversion of long-period magnetotelluric data. The results revealed three distinct resistivity patterns bounded by major electrical discontinuities. Resistive blocks are associated to the Amazonian Craton and Province Borborema, while the Parnaíba block showed a conductivity domain, unexpected in a crystalline crustal basement. However, this long period surveys (> 1s) focus on characterizing deep structures only. In this paper, we model a much dense array of broadband MT data from 2D-inversion process, to image structures at shallow depths with great lateral resolution, with can allow to better characterise near-surface structure compared to a 3D inversion (Padilha et al., 2019). The results show a detailed image of the internal structure beneath the Parnaíba Basin.

## Methodology

The magnetotelluric method is an electromagnetic technique developed in the late 1940s (Rikitake, 1948) and early 1950s (Tikhonov, 1950; Cagniard, 1950) which consists in measuring the temporal variations of the electric and magnetic fields at the surface. From these measurements is defined a 2x2 complex transfer function called the impedance tensor, *Z*. The impedance tensor is used to calculate the apparent resistivity and phase curves, which are usually employed to derive the resistivity of the earth's interior. In this study, the electric field was measured by four non-polarizable electrodes in N-S (Ex) and E-W (Ey) directions. Simultaneously, the magnetic field was measured along its three components, N-S (Hx), E-W (Hy) and vertical (Hz), using three induction coils. The magnetotelluric data used in this study have been acquired as part of the Parnaíba Analysis Project-PBAP, in which Brazilian and British academic institutions signed one of the most important geophysical cooperation agreements implemented in Brazilian territory. In total, 219 broadband magnetotelluric soundings deployed along one transects profile in an E-W direction (Figure 1), with approximately 5 km between neighboring stations. For each station, the data was recorded continuously for approximately 1 to 2 days.

### *Processing and analysis*

The processing of the MT data comprises the estimation of the impedance tensor, *Z*. In this work, it has been used the robust processing of Egbert and Booker, (1986), which consists of an automatic robust analysis scheme which accounts for the systematic increase of errors with increasing power and which automatically downweights source contaminated outliers. As an example, the Figure 2 shows the apparent resistivity and phase values varying with the frequency of the stations MT267 and MT113, for the *XY* and *YX* polarizations. In general, the data is of good quality, covering a frequency range from 1000 to 0.001 Hz, especially the stations located to the east and west of the profile (red and green dots in Figure 1). However, some stations located in the central part of the basin (blue stations in Figure 1) are affected by noise for periods > 10s and had to be discarded.

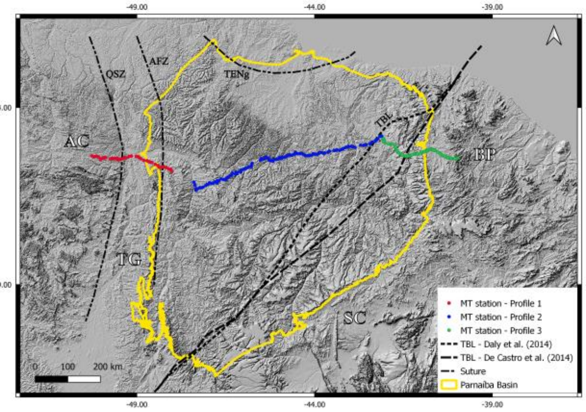


*Figure 1. Map of the location of the MT stations subdivided into three sub-profiles. Tectonic units: AC - Amazonian Craton, SC - San Francisco Craton, BP - Borborema Province. Suture Zones: QSZ-Quatipuru Suture Zone; AFZ-Araguaia Fault Zone; TBL-Transbrazilian Lineament; TENg- Tentugal.*

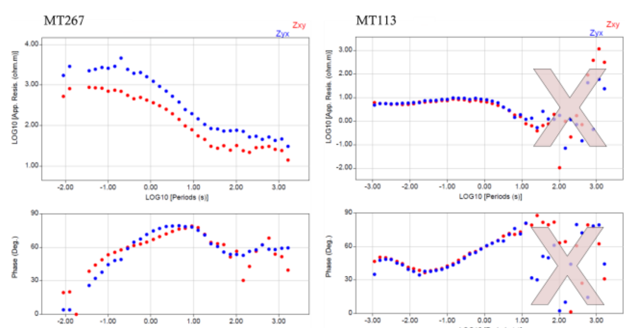


*Figure 2. Apparent resistivity and phase curves of stations MT267 and MT113, for XY and YX polarizations. The symbol "x" represents the frequencies discarded of our dataset as very noisy.*

For this work, it was decided to apply 2D inversion routines. Prior to this process, we perform a strike analysis to assess the regional dimensionality. 2D inversion of 3D data can lead to erroneous models and thus to misinterpretations if not performed with caution. We performed this analysis using the Phase Tensor (Caldwell et al., 2004) and WALDIM (Martí et al., 2009) approaches. The results are shown in Figure 3 for each sub-profile considering the frequency range 1000-0.001 Hz. The rosette diagrams show that there is no preferred strike direction for any of the sub-profiles. This may lead us to estimate that a 2D inversion process is not justified for our data set. However, Ledo (2006), states that in general, a wise 2D interpretation of the 3D magnetotelluric data can be a guide for a reasonable geological interpretation, and it also provides a first approximation of the internal electrical structure (Garcia et al., 1999). Thus, despite the clear presence of 3D effects in our data, we perform a 2D inversion as a first approximation to model this dataset. Furthermore, the 2D model can be used as a starting model for the 3D interpretation (García et al., 1999). In this context, for the 2D inversion process the data were not rotated then the N-S direction to magnetic north was retained, having the TE mode (XY polarization) oriented N-S, and the TM mode (YX polarization) oriented E-W, perpendicular to the assumed strike of the geological structures.

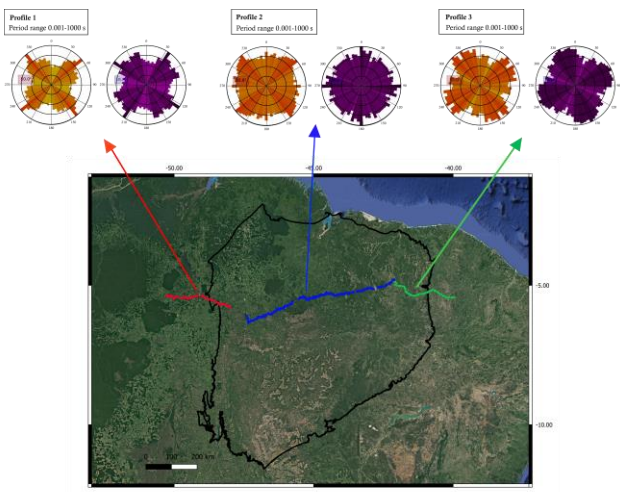


*Figure 3. Strike analysis for each of the three sub-profiles using two methodologies, WALDIM (Martí et al., 2009) – Orange Rosette and Phase Tensor (Caldwell et al., 2004) – Purple Rosette.*

*2D Inversion*

The 2D inversion was carried out using the code of Rodi and Mackie (2001). This code minimises the penalty function using the non-linear conjugate gradient algorithm. In the literature, there are mainly two strategies for bidimensional inversions: i) considering only the TE (Transverse Electric) or TM (Transverse Magnetic) modes and ii) joint inversion of both modes. Several publications (e.g., Berdichevsky et al., 1998; Kalscheuer et al., 2017) recommend the joint inversion of both modes, as the sensitivity of both modes is considered (TE-mode responses are sensitive to conductive structures, whereas TM-mode responses are predominantly sensitive to conductivity contrasts). In this paper, we use the strategy in which both modes are considered as well as the induction vector information in a sequence of successive inversions. First, the TE mode is inverted, reducing in each inversion process the regularised smoothness parameters, horizontal and vertical. Subsequently, the TM mode is inverted jointly with the TE mode and the smoothness parameters are also reduced. Finally, the Tz (induction vector) is added and a last joint inversion process is performed. Given the volume of data, the entire transect profile has been subdivided into three smaller segments (Figure 1) to reduce the computational cost of the inversion process. Each sub-profile has been inverted independently following the strategy described above. Figure 4 shows the resistivity distribution for each segment. Conductive anomalies are associated with intense colours (red) and resistive anomalies with cold colours (blue). As mentioned above, there are many stations where the same frequency range was not reached, thus varying the sensitivity in the depth resolution of the model. In this sense, the Niblett-Bostick transform (Niblett and Sayn-Wittgenstein, 1960; Bostick, 1977) was used to determine the resistivity-depth distribution beneath the recording location. On the top of the model of each profile, the depth-resolution of selected soundings has been calculated by means of the Niblett

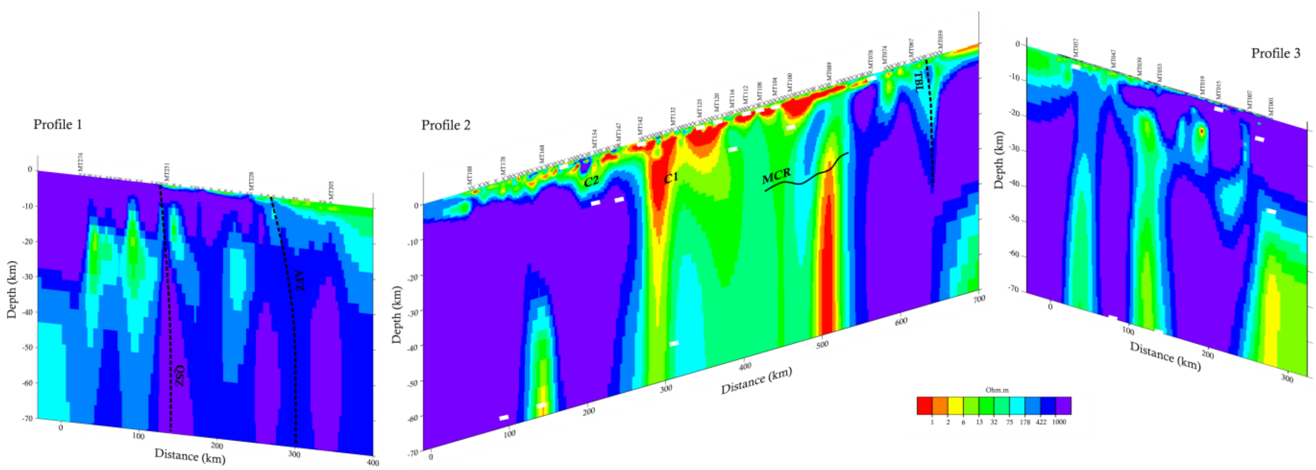


*Figure 4. Resistivity models obtained from two-dimensional magnetotelluric inversion for each profile. The dashed line represents the suture zones: QSZ- Quatipuru Shear zone; AFZ-Araguaia Fault Zone; TBL-Transbrazilian Lineament. The conductivity structures are labeled as C1 and C2. The MCR is the mid-crust reflector signed by Daly et al., (2014). The white traces represent the depth resolution calculated from the Niblett-Bostick transform for the selected stations. See text for explanation.*

transform (white traces). At stations where no result is shown, it is because they show values > 70 km depth.

## Results and Discussions

The resistivity distribution (2D inversion) of the study area is shown in Figure 4. The interpretation associated with the models of each profile will be carried out independently. In Profile 1, the Quatipuru and Araguaia suture zones have been displayed, which spatially coincide with elongated resistivity anomalies. An overview of this model suggests a lateral division into three lithospheric compartments with different resistivity signatures. Showing more conductive structures at the western end of the profile and becoming more resistive as we move towards the central compartment and the eastern end of the profile. These results are explained by accretion of terranes, which tends to produce a series of conductive and resistive features throughout the lithosphere (Jones, 1993; Unsworth, 2010).

In the western part of Profile 2, between stations MT188 and MT147, the 2D inversion identifies the unconformity of the sedimentary sequence overlying the basement, which deepens towards the central part of the basin in a stepwise manner, suggesting graben-like structures. In addition, between stations MT168 and MT147, a conductor labelled as C2 is identified, which reaches a depth of ~10 km. Its graben-like structure suggests that it corresponds to grabens buried beneath the Parnaíba Basin, formed during a Neoproterozoic-Eopaleozoic extensional phase, as suggested by De Castro et al., (2014). However, Porto et al., (2022) prefer an interpretation associated with granitic rocks or low-grade metasedimentary sequences within the basement linked to the crustal conductivity anomaly located between stations MT142 and MT132 (C1 in Figure 4). This anomaly previously identified by Solon et al., (2018), was interpreted by these authors as a paleosuture, due to the low resistivity value and its geometrical shape. The low resistivity value is usually associated with the emplacement of metamorphosed and removed graphites and sulphides. Porto et al., (2022), move further and suggest that it corresponds to the suture between the Grajaú and Teresina blocks (domains belonging to the Parnaíba block). Another important result of our model is the validation of the conductive domain in the central part of the basin. Solon et al., (2018) indicate that this may be due to contamination by igneous intrusions during the Triassic and Cretaceous. According to the results of the Niblett-Bostick transform, the resolution in depth within the domain is very shallow, < 2 km. Therefore, no further deep information is available. Additionally, between stations MT067-MT059 an elongated conductor is defined that reaches a depth of 40 km. This structure represents the Transbrazilian lineament (TBL), which corresponds to the boundary between the Parnaíba and Borborema Province blocks. In profile 3, the model appears to be a homogeneous resistive block with elongated conductive structures between stations MT057-MT033. We interpret them as system faults associated to the Transbrazilian lineament. Alternatively, De Castro et al., (2014) suggests that it properly corresponds to the TBL, where Solon et al., (2018) also identify a lithospheric resistivity discontinuity.

The important contribution of these models is the improved resolution of the surface structures, where graben-likes structures associated with extensional mechanisms were identified. The implications of the model in the context of the formation of West Gondwana is still premature, as a more robust 3D resistivity model constraint by available geophysical and geological data is under development.

## Conclusions

A 2D inversion model was obtained from broadband magnetotelluric data acquired along an E-W transect profile of the Parnaíba Basin, to identify its deep electrical structure. In the western part of the profile, the model indicates the presence of accreted terranes, due to the presence of resistive and conductive features, which are corroborated by the Quatipuru and Araguaia known suture zones. In the central part of the basin, a conductive domain is shown at crustal and lithospheric scale, where a remarkable conductive anomaly is imaged and interpreted as the suture zone between the Grajaú and Teresina blocks. The existence of pre-Silurian basins suggested by De Castro et al., (2014) could be associated with the graben structure identified near the suture zone, although it is too premature to affirm that, as there are other interpretations for this structure (Porto et al., 2022). Finally, the eastern part of the profile shows elongated conductive anomalies that could be associated with a fault system linked to the Transbrazilian lineament.

The results shown in this study have been interpreted only in relation to the conductive and resistive anomalies identified in the model, without interpretative implications linked to the formation of the basin itself and its implications for the formation of western Gondwana.

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