Magnetotelluric imaging of the southeastern Borborema province, NE Brazil

Andrea C. L. Santos*(INPE), Antonio L. Padilha (INPE), Ícaro Vitorello (INPE), Reinhardt A. Fuck (UnB), Marcelo B. Pádua (INPE), Augusto C. B. Pires (UnB).

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Abstract

In the present work we propose a geoelectric model of the crust and upper mantle in the SE portion of Borborema province, northeast Brazil. Magnetotelluric data were collected at 25 stations obtained from a linear profile deployed perpendicularly to the main structures in the SE portion of the study region. The data were collected and processed with modern instrumentation and modeled with the most advanced techniques currently available for studies of electromagnetic induction within the Earth. For the quantitative analysis an inversion of two-dimensional (2D) resistivity curves and phase in two orthogonal directions (TE and TM) was performed. The analysis suggests that the lithosphere under the Sergipana belt and Pernambuco-Alagoas complex, the SE portion of the profile, and the Alto Moxotó terrain, the NW portion, are geoelectrically different within the middle and lower crust with a well marked discontinuity in the region of the Jatobá basin and the Pernambuco lineament. The data support the conclusion that the crust of the Sergipana Belt and the Pernambuco-Alagoas complex was significantly stretched in the Cretaceous during the opening of the South Atlantic Ocean. Apparently, the Alto Moxotó terrain worked as a region of higher resistance to stretching, causing the crustal thinning to be larger in the SE portion of the profile subdomains. The behavior was favored by the deep lithospheric structure, a shear zone (Pernambuco lineament).

Introduction

The Borborema structural province, located in the northeast of Brazil, consists of a complex set of crustal blocks of different ages, origin and evolution, amalgamated during the Brasiliano/Panafrican Orogeny (700 to 450 Ma). The orogeny encompasses a series of tectonic-orogenic events unlocked at the end of the Late Neoproterozoic, resulting in the formation of lithostructural units of magmatic, metamorphic and sedimentary rocks consolidated in the crust (Almeida *et al.,* 1981). Studies from diverse authors were relevant for the knowledge of the geologic and structural framework of the Borborema province, above all based on geochemical and geochronological data (see e.g. Brito Neves et al., 1984; Silva Filho et al., 2002; Neves, 2003; Nascimento, 2005; Van Schmus et al., 2008; Silva Filho et al., 2010). However, these efforts have been insufficient to establish and understand the tectonic complexity of northeast Brazil, superimposed by the continental rupture that separated South America and Africa and led to the formation of the southern Atlantic Ocean. There are a considerable number of segments with their own geologic characteristics, reunited in the various domains and sub-domains proposed for the province. Although they are reasonably well known and delimited on the surface, the true nature of their limits has still not been established, especially when represented by important and extensive shear zones, nor have possible differences in their geophysical signatures been individualized. In this last case, the additional benefits provided by gravimetric and aerogeophysical studies have been insufficient to establish and understand the crustal structure of the northeast of Brazil (see e.g. Ussami *et al.,* 1986; Oliveira, 2008). The magnetotelluric method (MT) is an electromagnetic geophysical exploration technique for determining the electrical conductivity distribution within the Earth. It is based on the simultaneous measurement of the total electromagnetic field time variations at the Earth's surface. The magnetic field and the electric field components are recorded at the Earth's surface. Apparent resistivity and phase lags can be calculated at any measured frequency from these mutually perpendicular fields. The penetration depth of these signals increases with period and resistivity in the surface. In this paper we propose a geoelectric model obtained by bidimensional (2d) inversion of MT soundings conducted in regions of different conductivities in the SE portion of the Borborema province in northeast Brazil. The utilized data were collected with modern instrumentation and processed and modeled with technology currently available to the community of studies of electromagnetic induction in the interior of the Earth. The 2D geoelectric section derived from this procedure is robust in relation to the different sensitivity tests and adequately represents the distribution of electric conductivity above the profile used here. The use of the MT geophysical method was an important tool for the understanding of the dynamic processes in the lithosphere under the Borborema Province. Obtaining these geophysical data allowed us to analyze the problems that characterize the structure of the Borborema province in the study area, leading, for example, to the individualization of geoelectric responses of different domains and their sub-domains, and allowing to characterizing the different geological settings, and defining their boundaries.

Geological setting

Based on U-Pb and Sm-Nd isotopic data, the Borborema province comprises three large sub-provinces delimited by extensive E-W trending lineaments (Patos and Pernambuco lineaments), known informally as northern, transversal and southern (see Van Schmus et al., 2011). The study area is located in the transversal and southern sub-provinces of the Borborema province, between the Alto Moxotó terrain and Sergipano belt. The transversal zone, where the Alto Moxotó terrain is located, is limited by the Patos and Pernambuco lineaments and encompasses several other internal segments of the NE-SW (Brito Neves *et al.,* 2000). The southern sub-province, situated between the Pernambuco lineament and the northern margin of the São Francisco Craton, consists of the Pernambuco-Alagoas complex, and the Sergipana and Riacho do Pontal belts (Brito Neves et al., 1984). The MT survey crosses the Alto Moxotó terrain and the Pernambuco-Alagoas complex is separated by the PL, the Sergipano belt (Poço Redondo, Canindé, Marancó and Macururé domains) and, the Jatobá sedimentary basin at right angles (Fig. 1).

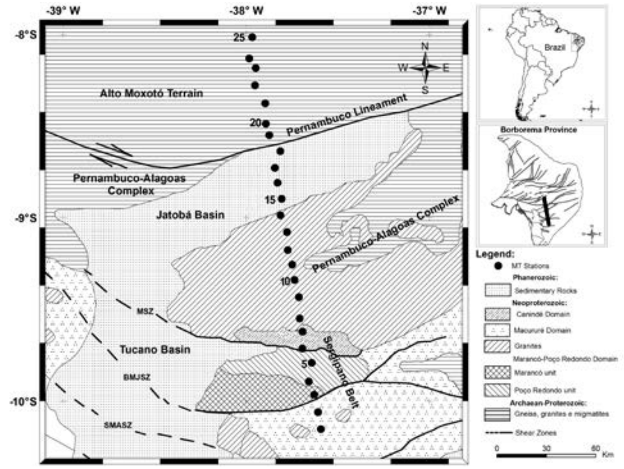

Figure 1. Simplified geology of the southeastern Borborema province, NE Brazil, with the location of the MT stations (numbered blacks dots). The Marancó-Poço Redondo domain is separated into two sub-domains. MSZ, BMJSZ, and SMASZ stand for Macururé, Belo Monte-Jeremoabo and São Miguel do Aleixo shear zones, respectively (modified from Oliveira et al., 2010). Inset maps show the location of the study area in Brazil and the MT profile in the Borborema province.

The gneissic basement of Alto Moxotó terrain (AMT) is dominated by banded, diorite to granodiorite orthogneiss. U–Pb and Pb–Pb evaporation zircon ages indicate crystallization of their protoliths mainly around 2.1 Ga (Neves et al., 2006). Overlying metasedimentary rocks are traditionally grouped in two main sequences, Sertânia and Caroalina complexes. Sertânia is dated at around 2.0 Ga. Both are intruded by deformed mafic and felsic rocks. Neoproterozoic sequences are found locally. The Pernambuco lineament (PL) is described as a transverse and continuous shear zone, starting in the coastal plain of Recife and extending to the Parnaíba Basin. It developed in the Neoproterozoic, during the collision of the Brasiliano Orogeny (Davison et al., 1995). The shear zone is interpreted as a deep feature that would have reached the base of the continental crust, and separating crustal blocks or terrains of distinct ages (Van Schmus et al., 1995). This interpretation was corroborated by recent geophysical investigations that suggest that the PL is effectively an important divisor of different lithospheres (Oliveira, 2008; Santos, 2012). A different view has been forwarded by Neves and Mariano (1999), according to which the PL is not a continuous structure, comprising two distinct segments: the East Pernambuco shear zone and the West Pernambuco shear zone. In this way, it could not be considered as a limit separating different terrains. This alternative hypothesis is thought to be supported by geochronological data (Melo, 2002).

The Jatobá basin (JB) represents the northernmost portion of the Recôncavo–Tucano–Jatobá rift system. It is located on the PE-AL) and has its origin related to a series of thermomechanical events that took place in Early Cretaceous. It is structurally characterized by hemigraben with the substrate composed predominantly of rotated blocks and progressively lower toward NW (Peraro, 1995). Ussami et al. (1986) suggest that this basin has been formed by extension and lithospheric rifting that led to the South Atlantic opening.

The Pernambuco-Alagoas complex (PE-AL) is located immediately to the south of the PL and is mainly formed of orthogneisses and migmatites with quartzite intercallations (Santos, 1995). It houses peraluminous granite bodies and banded migmatites with mesosome of diorite to tonalite compostion and syenogranite leucosome. Neoproterozoic plutonism is represented by peraluminous intrusions, and a smaller volume of calc-alkaline intrusions (Silva Filho *et al.,* 2002). East and north portions of the basement include remains of the Paleoproterozoic crust and Archean relics, while the southeast portion presents Mesoproterozoic ages (Van Schmus *et al.*, 2008). The Sergipano belt (SB) encompasses several structural and lithological sub-domains that allow it to be compared with Phanerozoic orogens. According to Brito Neves et al. (1977) much of the SB was formed by compression between the São Francisco Craton and the Borborema Province during the Brasiliano orogeny. During this convergence, the PE-AL acted as a major crustal block, compressing units of the SB against the São Francisco Craton. The SB consists of six lithostratigraphic domains: Estância, Vaza Barris, Macururé, Marancó, Poço Redondo and Canindé, each separated from the other by major shear zones (Davison & Santos 1989). The Estância and Vaza Barris domains are not part of the study area, therefore they will not be discussed further in this paper. The Macururé domain lies to the north of the Vaza Barris domain from which it is separated by the São Miguel do Aleixo shear zone, a major crustal boundary. The Macururé domain comprises amphibolite facies, garnet-bearing metaturbidites, feldspathic aluminous micaschists with minor intercalations of quartzite, marble and meta-volcanic rocks, and lenses up to 200 m across of amphibolite, garnet amphibolite and chlorite schist, intruded by granite plutons. Depositional age is estimated between 900 Ma and 625 Ma (Van Schmus et al., 2008). The Poço Redondo-Marancó domain is separated from the Macururé domain by the Belo Monte-Jeremoabo shear zone. The Poço Redondo sub-domain is composed of migmatite, biotite gneiss and several granite intrusions, such as the Serra Negra augen gneiss (952 ± 2 Ma; U–Pb SHRIMP, Carvalho et al. 2005). The Marancó sub-domain comprises greenschist to amphibolite facies, pelitic to psammitic metasedimentary rocks, rhythmites interleaved with calc-alkaline andesite to dacite, intercalations of basalt, andesite, gabbro and serpentinites. The Canindé gabbroic complex comprises massive and layered olivine gabbronorite, leucogabbro, anorthosite, troctolite, and minor pegmatitic gabbro, norite and peridotite. These units are crosscut by granites, granodiorites, and rapakivi granites (Oliveira et al., 2010). The tectonic setting of the Canindé domain is controversial. On the basis of major and trace elements, and Nd-isotope geochemistry, Nascimento (2005) suggested that the Canindé domain is the root of an inverted continental rift sequence. However Jardim de Sá et al. (1986) suggested that the Canindé domain is associated an island arc.

Method

Magnetotellurics (MT) is a method that provides information on the electrical conductivity of the subsurface of the Earth by measuring the natural time-varying electric and magnetic fields at its surface. Under the plane wave assumption, the natural electromagnetic wave propagates vertically into the Earth. It is used to investigate the electrical resistivity structure of the subsurface, from depths of tens of meters to hundreds of kilometers. The depth of penetration of fields is dependent on period (lower periods penetrate deeper) and the conductivity of the material (the lower the conductivity, the greater the depth). The estimates of depth can be made for the calculated apparent resistivities and phases. Further details on the MT method can be found in Simpson and Bahr (2005). For this study, five-component MT data were recorded at 25 sites with a spacing of 10 km, along a profile of 260 km in the NNW-SSE direction. Two campaigns were conducted, one during the year 2007 and another one in 2008. Broadband data were obtained using Metronix ADU-06 equipment, which uses horizontal telluric fields acquired with lead–lead chloride electrodes in a cross configuration with 150 m lengths and the three components of the magnetic field acquired with high-sensitivity induction coils. The electric dipoles and the magnetic sensor coils were aligned with geomagnetic coordinates. Typical acquisition time for each station was about 24 hours and the period ranged from 0.0008 to 1024 s. The MT impedance tensor and the vertical to horizontal magnetic field transfer functions were estimated in the measurement coordinate system using the robust code of Egbert (1997). The magnetotelluric profile interpreted in this study and the location of the performed profile are shown in Fig. 1.

The high-quality of data is shown in Fig. 2. Comparison between the curves obtained for the two directions TM (transverse magnetic) and TE (transverse electric) shows greater concordance between them in the region of JB (site 18), indicative of 1D effects probably due to the sedimentary rocks of the basin. On the other hand, in the sites of crystalline rocks (sites 6, 10 and 21), there are differences in both directions, which result of the occurrence of two-dimensional and three-dimensional conditions (2D/3D). Phase curves showed more information pointing to resistive structures (phase below 45º), which become conductive (phase above 45°) in periods longer than 1 s. The dimensionality of the dataset and the geoelectric strike direction were determined using invariant techniques (Bahr, 1988) and tensor decomposition (Groom & Bailey, 1989).

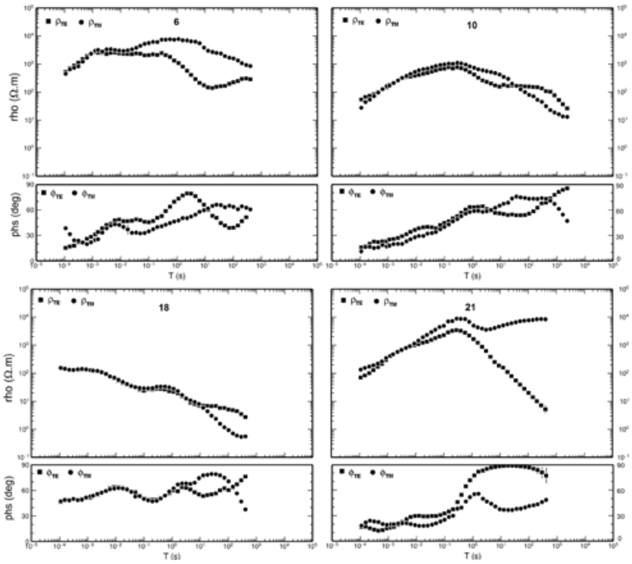

Figure 2. MT responses at sites representative of each geological unit along the profile. The data are rotated to the N70°E geoelectric strike direction. TM - transverse magnetic mode; TE - transverse electric mode.

Decomposition analysis was used to evaluate galvanic distortion in the data and recover the undistorted regional impedance tensor. A single common strike value, which could be used for all stations of the profile, was estimated by fitting all of the measured impedance tensors. The strike value that gave the best fit was N70°E, and is consistent with the dominant ENE geological trend in this specific region. We neglected two stations (sites 21 and 22) where the azimuth departed significantly from the average NE-SW trend and the diagonal elements of the impedance tensor are somewhat significant. The final 2D resistivity model is shown in Fig. 3 and has an overall RMS misfit of 3.6 related to the assumed error floor. The robustness of the model in the region of the upper mantle was tested for different inversions, by adding and removing of structures of different conductuvity through forward modeling. Sensitivity tests confirmed the existence of the two geoelectric regions in the upper mantle, observed in the model (Fig. 3). In addition to the decomposition, an empirical technique proposed by Santos (2012) to estimate the maximum depth of reliability of geoelectric models derived from two-dimensional (2D) magnetotelluric was used for the data set. The results show that the maximum depth of reliability of the 2D geoelectric model is usually given by the phase of the TE mode, whereas the maximum depth of propagation of the EM signal is usually given by the phase of TM mode. The results show that the 2D conductivities model in the SE region of the Borborema province can be interpreted up to the maximum depth shown (150 km) for the southern and northern portion of the profile, comprising the SB, PE-AL and AMT. Under the JB the signal penetrates only in the crust, up to about 30 km (See Fig. 3).

Results

The geoelectric model obtained by the 2D inversion of the MT data provides important information about the variation of the electric conductivity in the crust and upper mantle below the SE portion of the Borborema province. Based on the conductivity distribution in the analyzed profile, it was possible to discriminate two geoelectrically distinct regions in the crust and lithospheric mantle. The first is confined between stations 1 and 19, with a moderately resistive crust (~100 Ω.m to ~800 Ω.m). The second is located in the NW portion, between stations 19 and 25. The sedimentary rocks are separated in the upper-intermediate crust by the anomaly with oval geometry and low resistivity, on the order of 3 Ω.m, located particularly in the region of the PE-AL, below the JB and coincident with the PL (see Fig. 3). The 2D model shows a shallower resistive basement in the SE region. In the NW portion the model suggests a deeper resistive root. These results agree with the seismic refraction data (Soares *et al*., 2011), which suggest a relatively thinner crust for the SE region of the profile than for the NW portion. Only in the most NW part of the profile, between soundings 15 and 19, occurs, in the upper crust, a thin layer of lower resistivity values in the upper crust, coincident with the JB. In the region of the upper mantle in the SE portion of the profile, a sub-horizontal layer of lower resistance occurs along the SB and PE-AL.

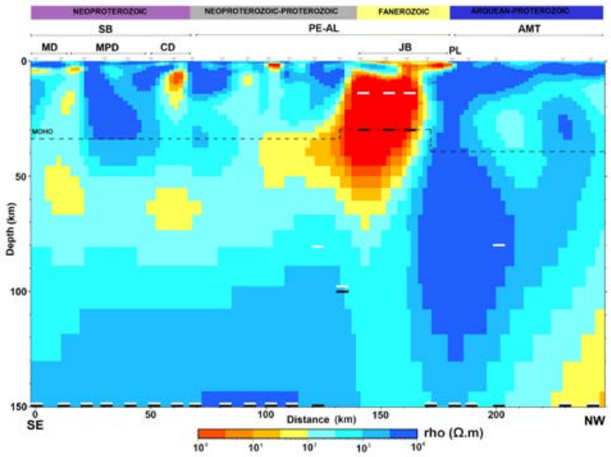

Figure 3: Two-dimensional conductivity model of the southeastern Borborema province from inversion of MT data. SB is the Sergipano belt (with the MD - Macururé, MPRD – Marancó-Poço Redondo, and CD - Canindé sub-domains), PE-AL is the Pernambuco-Alagoas complex (with JB - Jatobá basin), and AMT is the Alto Moxotó terrain. Dashed lines are seismic refraction interpretation of crustal thickness (Soares et al., 2011) and short horizontal bars represent the estimated maximum depth of investigation beneath each site (black bars for the TM mode, white bars for the TE mode). Bars plotted at the 150 km level have deeper penetration.

In the SB and in the PE-AL the large scale geoelectric structures are distinct when compared with those observed in the AMT. The distribution of resistivity in the crust is heterogeneous, both vertically and laterally. There are various side by side structures with a differentiated crustal geoelectric response, reflecting blocks of diverse nature, with distinct tectonic evolution. Also, the upper mantle is distinct, and is anomalously conductive below the SB and the PE-AL, and is resistive in greater depths below the AMT. There is an indication of anisotropy in the anomalous mantle of high conductivity, indicated by the presence of conductor blocks (in yellow) at depths greater than the Moho. The Fig. 4 shows the geologic map simplified from Oliveira et al. (2010) correlated with the presented geoelectric model. It can be seen that the limits of the SE portion, projected within the Tucano Basin, coincide with the shear zones observed at the surface. The obtained model suggests a different organization for the entire SE portion of the profile (SB and PE-AL). The conductive anomaly, between stations 15 and 19, is repeated in other regions of the profile (2, 7 and 11), with less expressivity. This suggests that the SE portion of the profile responds in a similar form to the forces of the South Atlantic Ocean opening, in the Cretaceous, different from the NW region of the profile. These limits (we call them deep lithospheric shear zones) of the Neoproterozoic, reactivated in the Cretaceous, could have influenced the organization and the geometry of the Tucano Basin.

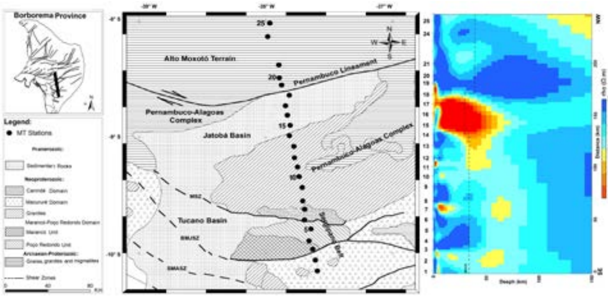

Figure 4: Two-dimensional conductivity model with simplified geology (modified from Oliveira et al., 2010) of the southeastern Borborema province, NE Brazil, with the location of the MT stations.

The MT responses show sub-horizontal geoelectric structure of lower resistivity, on the order of 300 Ω.m between depths of 40 km and 90 km, below the region of the SB and the PE-AL. In depths of the upper mantle, Jones *et al*., (2008) suggest that the presence of connected graphite films could provide lower values of resistivity. Other alternative sources of higher conductivity in the upper mantle include the presence of free aqueous fluid, conductor minerals (sulphides) and melt (Jones, 1999). In this work we suggest that the most probable cause for the high conductivity in the mantle below the SB and the PE-AL is the presence of carbon in the form of interconnected graphite films. The graphite films tend to facilitate the current flux along the direction of maximum interconnection, favoring the observed anisotropy.

The sedimentary package of the JB (between sites 7 and 11) is imaged as a shallow conductive layer (1-10 Ω.m) that extends from the surface to a maximum depth of 4 km. Causes for significantly high conductivity may include changes in the salinity of the fluids or may result from a significant increase in the relative porosity of the sediments. Immediately below the JB another strong conductor appears in the upper crust, which extends from a little past the southern border of the basin to a little more than its center. This conductor coincides with the region of thinnest crust, indicated by seismic data (See Soares *et al*., 2011).

The limit between the PE-AL and AMT is clearly shown in the proposed geoelectric model. This explicit limit, marked by site 19, coincides with the LP, to the north of which occurs the crustal thickening of the Borborema province The data suggest that the LP represents an important lithospheric discontinuity, separating blocks with distinct geophysical and geological characteristics. In this way, the NW portion of the profile characterizes a region of aggregated crustal blocks, with the LP as an important divisor, with lithospheric depth. The crust of the AMT does not present the same characteristics of lateral variation of conductivity of the SB or of the PE-AL, with the SE portion totally distinct from the NW portion of the profile. Geochronological data demonstrate contrast between the supracrustal rocks and Paleoproterozoic basement of the AMT and the other terrains of the Transversal Zone, of Meso- to Neoproterozoic age, which prevents their correlation and implies individualization of this terrain as an independent tectonic unit. The high resistivity observed in the NW portion suggests an older crust. The resistivity of around 10,000 Ω.m is typical of Paleoproterozoic rocks that correspond to the basement of the AMT (Santos *et al.,* 2004). The set of evidence allows the suggestion of the AMT as an ancient continental plate that collided in the Neoproterozoic with the PE-AL, during collision of the Brasiliano Orogeny. The limit underlined by the proposed model, separating blocks with distinct geoelectric characteristics (station 19), is characterized, in this work, as an indication of the collision of crustal blocks with possible dipping of the AMT below the PE-AL.

Conclusions

Analysis of magnetotelluric data collected in the SE region of Borborema province has yielded one- and two-dimensional models for the dataset. A conductivity contrast is revealed in the lithosphere under the region between the SE (SB and PE-AL) and NW (AMT) portions of the profile. The model suggests a different organization for the entire SE portion of the profile, indicating that this region of the profile responded in a similar way to the forces that culminated in the fracturing and rupturing of the Gondwana continent, separating South America and Africa in the Cretaceous, different from the NW region. The conductive anomalies observed in the geoelectric model, associated in this work to shear zones from the Neoproterozoic reactivated in the Cretaceous, which could have influenced the organization and geometry of the Tucano basin. We suggest that the PL is a shear zone on the lithospheric scale and marks the position of the origin of the JB in the Cretaceous, when the stretching occurred, resulting in the rupture of the South American and African continents. In summary, the coherence between our 2D conductivity model and the seismic refraction data suggest that the crust from the SB and the PE-AL were significantly stretched in the Cretaceous. The AMT terrain behaved as the region of highest resistance to the stretching, so that crustal thinning was most significant in the sub-domains of the SE portion of the profile.

Acknowledgments

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