Geoelectrical structure of the Archean Serrinha Block and surroundings, Northeastern Brazil, obtained from 3D modeling of magnetotelluric measurements

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Abstract

Results from a three-dimensional inversion of broadband magnetotelluric (MT) data collected at 68 stations, deployed along six intersecting profiles, are evaluated for accuracy and potentiality for yielding tectonic information. The MT profiles have different orientations from one another, making the data distribution over the area unusual for 3-D modeling. The study area is located in the northeastern part of the São Francisco Craton and encompasses an Archean nucleus, the Serrinha Block, ruptured by a rifted basin developed mostly in early Cretaceous times during the opening of the South Atlantic Ocean. The inversion were performed using the Modular System for EM inversion (ModEM) with 13 periods from 0.01 to 3200 seconds on a 3 x 3 km grid. The inversion results indicate the presence of several conductive deep bodies beneath the central part of the Archean Serrinha block, probably associated with the closure of the ancient Itapicuru ocean. At uppermost mantle depths we observed a lateral transition of resitivity nearly coincident with the surface position of the strong crustal conductors. Therefore, It seems that our model has imaged a important limit within the lithosphere of the Archean Serrinha Block.

Introduction

The National Institute of Science and Technology of Tectonic Studies (INCTET) encompasses several Brazilian research institutions, joining geoscientists specialized in different techniques and methodologies. The scope of the program is to study the deep lithospheric structures of Northeastern Brazil, particularly the Borborema Province and the adjoining São Francisco Craton, in order to understand the tectonic structure and present dynamics of the region. The INCTET includes data acquisition of two deep seismic refraction experiments, broad band seismographic stations in selected areas and hundreds of magnetotelluric (MT) soundings. The first MT sites were acquired in 2005 along a ca. 500 km-long profile in the northern sector of the Borborema Province. Since then, several other MT profiles with different orientations from one another have been performed, making the data distribution over the area highly uneven.

Traditionally, interpretation of MT data has been performed with basis on 2-D inversions at individual profiles. A major reason for this is that 3-D inversions of MT data still have high computational costs, and hence demand plenty of time. In addition, data acquisition using array configuration, which is ideal for 3-D inversions, is usually far more expensive and logistically more complicated than data acquisition along profiles. Despite the data distribution of the INCTET program is suitable to 2-D interpretations, preliminary analysis suggested the presence of 3-D electromagnetic effects in the MT data. One of the sources of distortion is the coast effect (e.g., Ranganayaki and Madden, 1980). Pádua et al. (2007), for example, observe that this effect is significant in the Borborema Province even for those sites located 100 km from the coastline. Furthermore, in some cases we have observed phases out of quadrant at sites thought to be free from the influence of the coast effect, suggesting that other distortion sources, probably related to the geologic complexity of the region, may be present.

Here we performed 3-D inverse modeling of a subset of MT data from the INCTET program to evaluate for accuracy and potentiality for yielding tectonic information. The dataset comprised 68 broadband MT sites deployed along six intersecting profiles near the border of the Northern São Francisco Craton and the Borborema Province (Figure 1). The study area encompasses an Archean nucleus, the Serrinha Block, ruptured by a rifted basin developed mostly in early Cretaceous times during the opening of the South Atlantic Ocean. To the east, the block is obscured by the Early Cretaceous Tucano-Jatobá rift basin and the Neoproterozoic Sergipano fold belt to the east, and bounded by the Salvador-Curaçá belt to the west. The Serrinha block is composed of Archean gneiss-migmatite terrains and Paleoproterozoic supracrustal sequences of the Rio Itapicuru and Rio Capim greenstone belts, both intruded by several syn- and late-tectonic granitoids associated to the Transamazonian orogeny. Despite the important contributions given mainly by geochronogical and isotopical studies in the past years (e.g., Figueiredo, 1989; Barbosa and Sabaté, 2004; Rios et al., 2009; Oliveira et al., 2010), the tectonic evolution of the area is still a matter of debate, in part due to the lack of geophysical data capable of providing information about its lithospheric structure. The most striking result from our study were the presence of strong crustal conductors in the central part of the Archean Serrinha

Block spatially coincident with an lateral variation at lower crust and uppermost mantle depths.

Method and Data Analysis

The MT method utilizes a large range of transient variation of the geomagnetic field as the signal source for determining the structure of electrical resistivity of the Earth's interior. The MT signals are generated primarily by global thunderstorms in the lower atmosphere and interactions between the solar wind and Earth's magnetosphere. According to the principle of electromagnetic induction, such fluctuations induce electric currents inside the Earth and its distribution and magnitude depend on the electric structure of the subsurface. The electrical conductivity is determined from the relationship between the orthogonal components of electric and magnetic fields observed on the surface. The depth of investigation of the method depends on the period of oscillations and the conductivity of the medium. In general, signals ranging from milliseconds to 1000 s probe depths from tens of meters to tens of kilometers. But in regions with low resistivity, the signal is attenuated more quickly, reducing the depth of the research method..

The five-channel MT data employed in this work were collected using broadband instruments (GMS06, METRONIX Gmbh) at 68 locations from six intersecting profiles with an average site spacing of 12 km. Typical occupation time was of at least 1-2 days per site. The time series were processed using a robust processing code (Egbert, 1997), resulting in most cases in response curves over the period range from 0.001 s to 410 s. Longer periods (up to ~3,200 s) with good quality were obtained in some stations along the northernmost E-W profile and at a few stations in other profiles (excluding the sedimentary basin, where the electric fields are strongly attenuated). A single site processing gave usually good responses possibly as a consequence of the low levels of cultural noise.

Figure 2 exemplifies the MT results for three representative sites, displayed as sounding curves (apparent resistivity and phase) for all four components of the impedance tensor. Site ser003a is within the Salvador-Curaçá belt. Apart from some scattering at specific periods, associated with 60-Hz transmission lines and around 10 seconds, curves are smooth, and the data appear to be of good quality. However phase values for the xy-component go out of quadrant, exceeding 90 degrees for periods higher 1 second. The diagonal components are very well resolved, and are of the same order of magnitude as the off-diagonal components. All of these characteristics suggest that the data maybe 3-D, particularly for periods higher than 1 second. Site ser010a, located in the Serrinha Block, has smooth responses along the entire period range for all components. The yx-component phases leave quadrant from periods between 1 and 10 seconds. Similarly to the site from the Salvador-Curaçá belt, responses at the site ser010a also suggest strongly 3-D complications, displaying large amplified diagonal components. For site ser017a, located over the sedimentary basin, the curves are almost 1-D for periods shorter than 10 seconds, i.e., curves for xy- and yx-components have similar shapes and the diagonal responses are weak, and poorly estimated compared with the previous two sites.

We performed decomposition of the impedance tensor based on Groom-Bailey method (McNeice and Jones, 2001). The procedure failed in recovering an adequate regional 2-D response for most of the sites. In general the parameter are period-dependent, changing their values abruptly at periods around 1-10 seconds. In addition, the vertical transfer functions, which are generally useful for assessing lateral contrasts in electrical resistivity within a certain region, display a complex pattern of tipper directions, and there is no clear strike, even on individual profiles. All of this characteristics provides further evidences for 3-D complications.

3-D inversion

We used ModEM, a 3-D regularized inversion code (Egbert and Kelbert, 2012), to fit the full impedance (all four complex components), plus the vertical magnetic fields Tz components, at 13 selected periods logarithmically spaced between 0.01-3200 s. The forward mesh consisted of 102 x 112 x 53 nodes with a nominal grid spacing in the central core of 3 km horizontally, resulting in at least three element columns per MT station increasing geometrically downward from 50 m thickness at the surface. Poor-quality data were removed from the dataset, and error floors were set at 5 per cent of $|Z_{xy}Z_{yx}|^{1/2}$ for impedances, and at 0.03 for Tz. Several models were generated using half space prior models with different resistivities. The preferred solution (Figures 4 and 5) used a 100 ohm-m as the prior, which converged to a normalized root mean square (rms) misfit of 2.94 in 282 iterations. Even for this relatively small dataset from the INCTET program the parallel code required about 3 hours per iteration on 16 processors (2.40 Hz) and 24 Gb of available RAM.

Results

A very robust feature in all of the inversion models is a set of strong (~1 ohm-m) crustal conductors extending from the northern part to the southwestern part of the Serrinha Block, roughly following the shape of the western edge of the Block (Figures 3 and 4). The depth to the top of these anomalies is about 7 km at the eastern edge and tend to become deeper (~12 km) to the west.

There are several other anomalies evident in the Figure 3, as for example, a zone of high conductivity beneath the central-eastern part of the Tucano Basin. Despite that the zone seems to extend to higher depths, it is unlikely that the data have enough resolution to map the base of this conductor. In this place, the conductance is relatively high due to the presence of conductive sediments up to 10 km thick (Magnavita et al., 1994). In addition, the soundings lack periods longer than 410 s in this segment of the study area, limiting the MT investigation to only few of tens of depth.

At depths around 25 km the geoelectric model obtained in this work displays elongated resistors alternating with conductive structures aligned in the NE-SW direction. Crustal thickness inferred from a S wave regional tomographic model for the South American continent (Feng et al., 2007) is 35-38 km for the study area. Therefore, the anisotropic pattern of resistivity is probably representative of the lower crust across the entire area.

At deeper depths there is a consistent lateral contrast of resistivity nearly coincident with the position of the crustal conductors inside the Serrinha Block. To the west, across the Gavião Block, Salvador-Curaçá and western margin of the Serrinha Block the subsurface is moderately resistive (200-300 ohm-m), while below the central-eastern part of the model the resistivity decrease about one order of magnitude.

Discussion

The study area is characterized by a complex spatial pattern of conductivity anomalies. The most prominent ones are concentrated along the western margin of the Archean Serrinha Block. The surface position of these features is nearly coincident with several Paleoproterozoic syn- to post-collisional granitoids that occur near the contact between the Archean basement of the Serrinha Block and the Paleoproterozoic Rio Itapicuru Greenstone Belt (RIGB). Based on the presence of ultramafic complexes along this contact led Oliveira et al., (2010) to invoke a suture zone. In this context, the MT anomalies can be associate with the closure of the ancient Itapicuru ocean in which large amount of carbon-rich metasediments were tectonically emplaced into deep crustal levels. Therefore the most plausible mechanism to explain the very high conductivity of these anomalies would be the presence of graphite. Carbon-rich rocks on the surface have been observed in the mafic sequence of the RIGB. Further support for the presence of carbon in th region are diamondiferous rocks from the Braúna kimberlite field.

To the east, beneath the central-eastern Tucano basin we observe a zone of high conductivity, which can represent an thickening of the sedimentary rocks. Alternatively, the anomaly could be a deep feature of the basement. If true, this could constrain the origin of the rift basin, which proposed models generally invoke control by low-angle major crustal detachments (Ussami et al., 1986) or flexural isostatic response associated with magmatic underplating and uplift (Magnavita et al., 1994). Longer periods will be necessary for reliable interpretation of this anomaly.

The central-eastern mantle lithosphere of the Serrinha Block is relatively conductive (<60 ohm-m). Considering the low heat flow values (46-51 mWm$^{-2;}$; Vitorello et al., 1980) for the area, the electrical resistivity of dry silicate minerals (e.g., Constable, 2006) is too high to explain the observed lithospheric mantle values. Then, some interconnected conductive phase must be present, such as carbon, water, melts or volatiles. One plausible mechanism could be related to delamination of the Serrinha Block during late stages of the Transamazonian orogeny. The upper mantle conductivity increase could be associated with the replacement of a delaminated lithosphere by a more fertile, volatile-rich sublithospheric mantle material.

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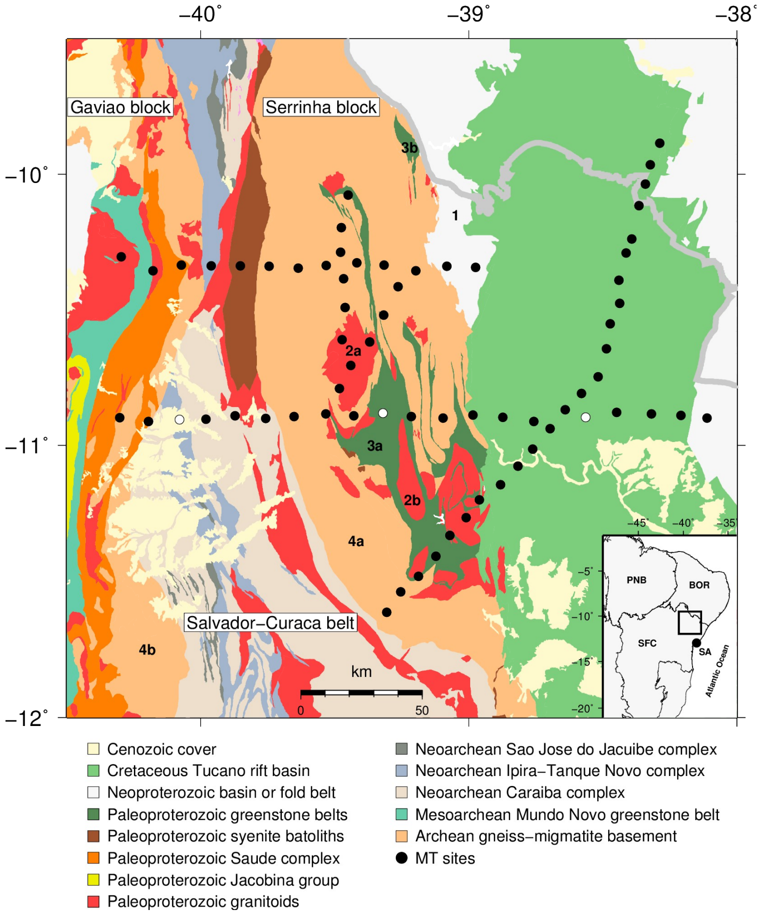

Figure 1 - Simplified geological map of the northeastern Sao Francisco craton: 1, Sergipano fold belt; 2a, Nordestina batholith; 2b, Ambrosio dome; 3a, Rio Itapicuru greenstone belt; 3b, Rio Capim greenstone belt; 4a, Santa Luz complex; 4b, Mairi complex. The thick gray line is the limit between the Sao Francisco Craton and the Borborema Province. Acronyms in inset figure are: BOR, Borborema province; PNB, Parnaiba basin; SA, Salvador city; SFC, São Francisco craton.

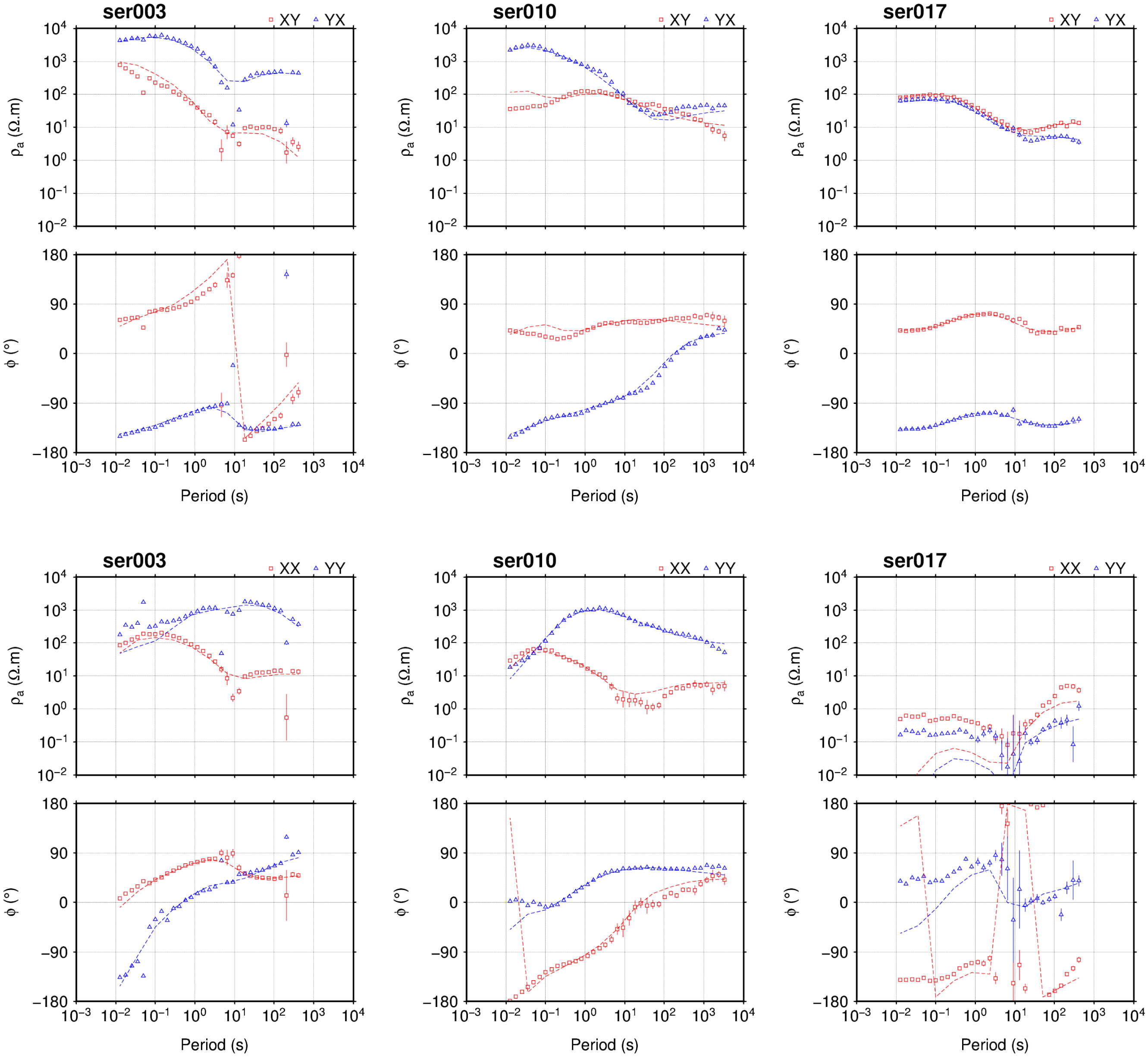

Figure 2 – Apparent resistivity and phase of three representative sites. Site ser003a is on the Salvador-Curaca Belt, in the western part of study area. Site ser010a is representative of the Serrinha Block, in the central part of the region, while the site ser017a is a typical response from the sedimentary Tucano basin. The upper panel displays the off-diagonal components. We can observe the phases of the xy- and yx-components leaving the quadrant at the sites ser003a and ser010a, respectively. At the site ser017a, responses are almost 1D for most part of the data. The lower panel shows the diagonal components. It can be seen that the diagonal are very well resolved for the sites ser001a and ser010a, with amplitudes of the same magnitude of the off-diagonal components. In the basin, as expected, diagonal responses are very weak. Dashed lines are the predicted responses from the 3D inversion using ModEM code.

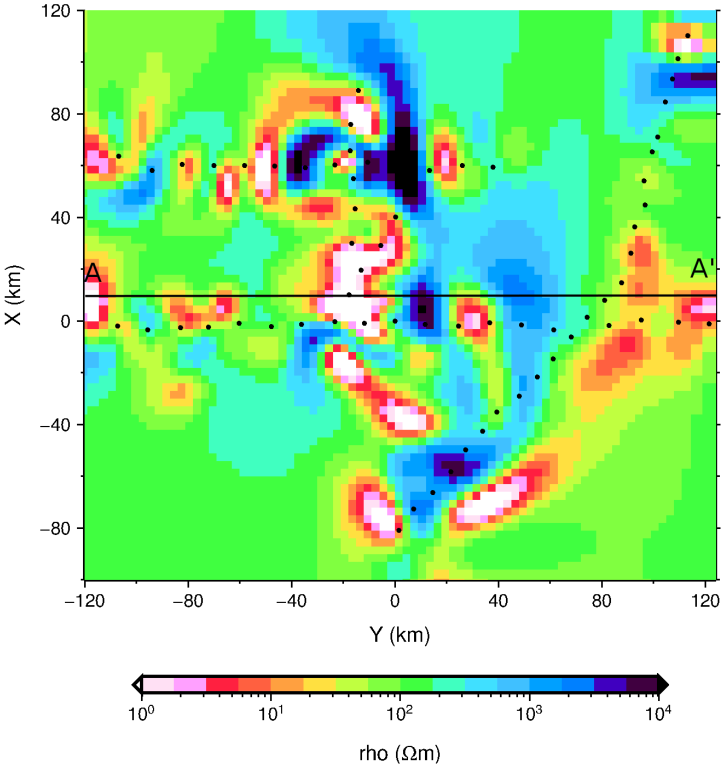

Figure 3 – Inverse model at depth of 10 km. Line indicates location of profile A-A' shown in Figure 4.

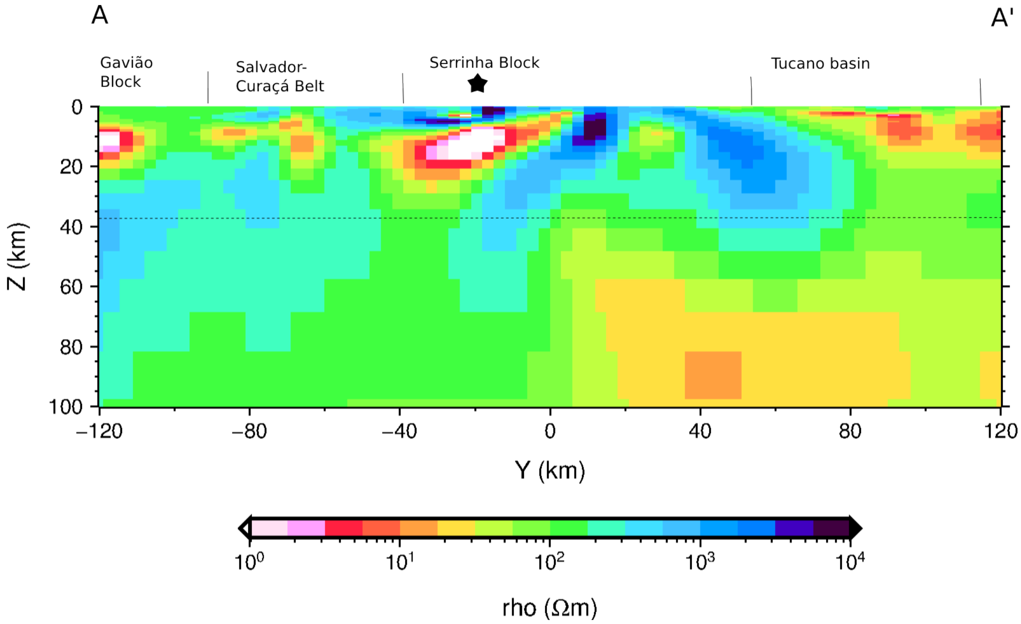

Figure 4 – Cross section along A-A'. The black star is the Brauna Kimberlite field. Dash line is the average Moho taken from regional seismological data (Feng et al., 2007).