Magnetotelluric Studies in NE of Brazil: Parnaíba basin and Adjacencies

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Abstract

As a part of a national project proposed by the Institute of Geotectonic Studies (INEG), with headquarters at the University of Brasília and participation of several institutions in from the Northeast and Southeast of Brazil, MT time series recorded at 49 stations along a profile crossing eastern border of the Parnaiba basin, North-East Brazil, with a profile of about 450 km in total. Pseudo-section plots of the observed and calculated data for TM and TE modes shows the apparent resistivity and phase of data and revealed conductive features associated to the sedimentary formations of Parnaiba basin and characterizes well its edge. The pseudo section of the tipper magnitude suggests a predominant 1-D behavior within the basin, while at the southeastern sector of profile, another tectonic terrain composed of resistive rocks of 3-D behavior are associated to the Borborema Province and / or São Francisco craton. A dimensionality analysis was performed using the WAL invariants and it was observed that the data obtained from the study region have a predominant 3-D behavior.

Introduction

The profile of approximately 450 km intersects the state of Piauí and extends to the state of Maranhão in the north, and Bahia in the south. The area that covers the profile is inserted in parts of the Parnaíba basin, Borborema province and São Francisco craton (Fig. 1).

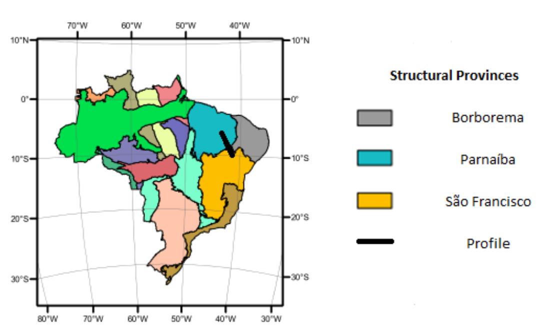

Fig. 1 - *Representation of geotectonic compartmentalization and MT profile in the region. Adapted from CPRM.*

The tectonic complexity of the Northeast of Brazil, originating from the continental rupture that separated South America and Africa and formed the South Atlantic Ocean, has led to an attempt to understand regional structuring and compartmentalization. The major tectonic divisions of the Northeast of Brazil are the Borborema province, the São Francisco craton and the Parnaíba basin. Characterized initially by Almeida et al., (1976,1977,1981) the Borborema province, bounded on the northwest by the São Luiz craton, on the west by the Parnaíba basin and on the south by the São Francisco craton, is a complex mosaic of crustal blocks of different ages, origin and evolution that were apparently amalgamated as a result of geological processes which were carried out in several stages over a wide period of time, but which owe their final configuration to the Brasilian Orogeny, occurring at the end of the Neoproterozoic and beginning of the Phanerozoic. The Brazilian cycle was composed of several tectono-orogenic events triggered at the end of the Upper Neoproterozoic, resulting in the formation of lithostructural units composed of magmatic, metamorphic and sedimentary rocks in the crust (Almeida et al., 1981).The São Francisco craton is the underlying boundary of the Borborema province and represents the structural bulkhead to which the northern domains were added.

This work aims to contribute to the knowledge of the geotectonic history of the region, being able to recognize structures such as lineaments, faults and suture zones by mapping variations of the conductivity in rocks, which are located from a few tens of meters to several kilometers.

The Parnaíba basin is located to the west side of the northeastern region of Brazil with an approximate 3,400 m maximum sedimentary thickness near its central position. It is an intracratonic basin where one finds Ordovician to Tertiary sedimentary deposits and intrusive and extrusive rocks associated to magmatic events from Jurassic to Eocretaceous ages.

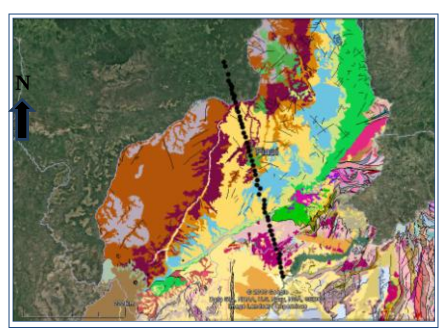

Figure 2 *- Adapted geology map 1:1000000 of the Piaui and Bahia (CPRM) and the profile. Station 04-10 are in Bahia state, 11-41 in Piauí and the remaining are in Maranhão state. Geological map indicates that stations 04-18 are over the igneous and metamorphic rocks unit, and the remaining over the sedimentary units of Parnaíba basin.*

The Parnaíba basin is a structural province of the Northeast that has been object of several studies; both for the petroleum potential and its relation with the main fault zones associated the Transbrasilian Lineament (Cunha,1986; Schobbenhaus et al.,1975; Milani & Zalán, 1999). In addiction, the understanding of the complex geology of the Borborema Province has been considered a key issue for the construction of supercontinent or paleocontinent models.

The stations were installed with a profile of about 450 km (Fig. 2) in total to record both long period and broadband MT time series which are the focus of this paper. Variation of two horizontal orthogonal components of the electric field (Ex and Ey) and three orthogonal components of the magnetic field (Hx, Hy and Hz) were recorded using ADU MT systems (Metronix, Germany) belonging to the Pool of Brazilian Geophysical equipment (www.pegbr.on.br). All measurements were performed using the magnetic north as x-direction, the y-direction pointing towards the magnetic east. Deviation between magnetic and geographic north (magnetic declination) is about 21 degree in the region.

Method

Magnetotelluric (MT) method is based on the idea that naturally induced electromagnetic (EM) field interacts with resistivity (or conductivity) variations of the subsurface structures. Therefore, observations of EM field on the surface of the earth can give some information about the resistivity composition of the subsurface geology. It measures simultaneously on the surface of the terrain magnetic and electric fields induced in the crust through natural signals. For frequencies smaller than 1Hz the natural signals are derived from the interaction of the solar wind with the terrestrial magnetic field, producing micropulsations of different periodicities. For frequencies greater than 1 Hz, the signals originate from electrical storms and generate spherics, having the earth´s surface and the ionosphere acting as wave guide. The mathematical formulation of laws describing the behavior of electromagnetic fields in an inhomogeneous conducting Earth (Zhdanov, 2009) is described by Maxwell's equations, which allow us to find the wave diffusion equation that describes the phenomenon, as the displacement current can be neglected considering both the frequencies involved in MT method and the range of resistivity values of Earth´s materials. The ratio between the horizontal components of the electrical and magnetic fields measured at the surface, called the impedance, is primarily dependent on the electrical conductivity distribution in subsurface.

The relations between E (electric) and H (magnetic) components may be given as follows,

$$E(f) = Z(f)H(f)$$

Where Z is 2x2 impedance tensor to be estimated. E and H are Fourier transformed data (Fourier coefficients).

The explicit form for each frequency is given as:

$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} Zxx & Zxy \\ Zyx & Zyy \end{bmatrix} \begin{bmatrix} Hx \\ Hy \end{bmatrix}$$

The impedance is usually represented by variations of its amplitude (apparent resistivity) and phase. Graphs of variation of apparent resistivity and phase as a function of frequency are the main results of an MT survey at a given location.

The relationship between the vertical and horizontal components of the magnetic field is the vertical transfer function vector or tipper. From it we obtain the induction vectors. These vectors are usually reversed so that the real vector points to conducting zones id the Parkinson convention is used (Vozoff, 1972). The magnetic field in terms of components and tipper can be written as:

$$Bz = \begin{bmatrix} Tx & Ty \end{bmatrix} \begin{bmatrix} Bx \\ By \end{bmatrix}$$

The impedance tensor and tipper vector are the main quantities used in the interpretation of MT data.

The depth of investigation depends on the depth of penetration of the electromagnetic wave (skin depth):

$$\delta = 0.5\sqrt{\frac{\rho}{f}}(Km)$$

Where ρ is the resistivity and f is the frequency of interest. The minimum frequency measured with the broadband MT system used in this study is around 0.00025 Hz. Assuming the average resistivity is 100 ohm-m, then skin depth reaches to about 300 km. However, subsurface is complex in terms of resistivity composition, thus, real probed depth will be usually much shallower than this level.

For the MT data processing, starting from frequency domain transformation of time series, robust processing was applied to improve the estimation of apparent resistivity by eliminating outliers and reducing noise (Egbert and Booker, 1986). The robust processing of Egbert proposes a robust automatic analysis scheme that considers the systematic increase of errors with increase of energy, and that automatically reduces the weight of contaminated data. In contrast to the ordinary least squares, the program produces reliable estimates of transfer function or tipper, with realistic errors. The impedance tensor is calculated iteratively by analyzing the error of each sample. In practice, MT responses are calculated in independent and subsequently grouped frequency bands. Also the time series can be segmented into windows of different sizes. Different windows are applied for the same frequency band because the quality of the processing can vary from window to window.

In order to expose in a more compact way the results obtained so far, the pseudo sections presented here were constructed. The pseudo sections were elaborated with WingLink software and represent sections of apparent resistivity, phase and tipper magnitude as a function of period. The pseudo section is generated by the mathematical interpolation of the resistivity or phase values as a function of the period for each station along the entire MT profile. From the analysis of the pseudo sections it is possible to have a notion of the distribution of the electrical resistivity contrast in subsurface. However, it is emphasized that such distribution is not exact, since the data are not as a function of the depth, but of the period.

The WALDIM analysis code developed by Marti et al. (2009) was used to determine the dimensionality of the studied area. The code is based on a group of eight rotational invariants. The program classifies impedance into four main groups: 1D, 2D, 3D and a group composed of four superimposition models.

Results

The data quality seemed good since the curves of the apparent resistivity and the phase of impedance present smooth variations with narrow error bars in the majority part of the frequency range. An example of apparent resistivity and phase curve can be seen in Figure 3, referring to station 07 and 42, the first station within the Parnaiba basin and the second one, at the Borborema Province. The apparent resistivity values are lower for the station 42 within the basin.

The dimensional analysis by WAL invariants (Fig. 4) considered 7 decade-period bands from 10^{-3} to 10^{4} seconds, and thresholds for invariants 1.5 for I3 to I7 as 1.0 for Q. As can be seen in the table (Fig. 5), the results indicate for the most part a 3-D behavior, with a percentage of 45%, while 1-D obtained 10% and undetermined 16%. These results suggest 3-D regional dimensionality.

In the pseudo sections the station position is arranged along the horizontal axis and the periods in which the measurements were taken constitute the vertical axis (logarithmic scale). The apparent resistivity and phase values are the intersection between the location of the stations and each of the periods. Three pseudo sections were generated: TE and TM modes of apparent resistivity, phase and tipper magnitude versus period of the NW-SE profile (Fig. 6). Both in TE and TM modes one can observe a conductive environment most prominent at the northwestern portion of the profile, related to sedimentary formations of Parnaíba basin. At the southeastern portion, resistive rocks predominate and seem to be dipping under the basin, thus defining its limit. The resistive block is associated to the Borborema Province (or São Francisco craton) and possibly also constitutes the basin basement.

The pseudo section of the tipper magnitude displays lower magnitude at northwestern and central portion of the profile, while at the southeastern portion the magnitude has higher values reaching 0.9. The tipper results indicate that apart from small sectors, the Parnaiba basin is predominantly 1-D whereas 3-D structures are predominant at the southeastern sector, corresponding to the Borborema Province and / or São Francisco craton.

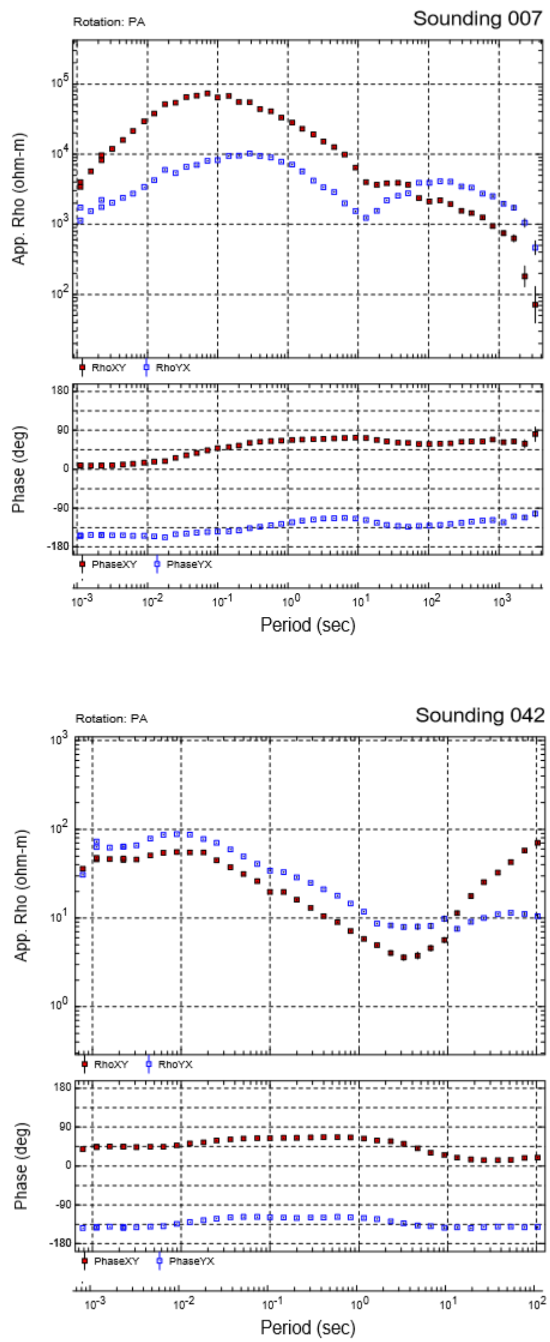

Figure 3 *- An example of the processed MT data of the stations 07 and 42, without static shift correction.*

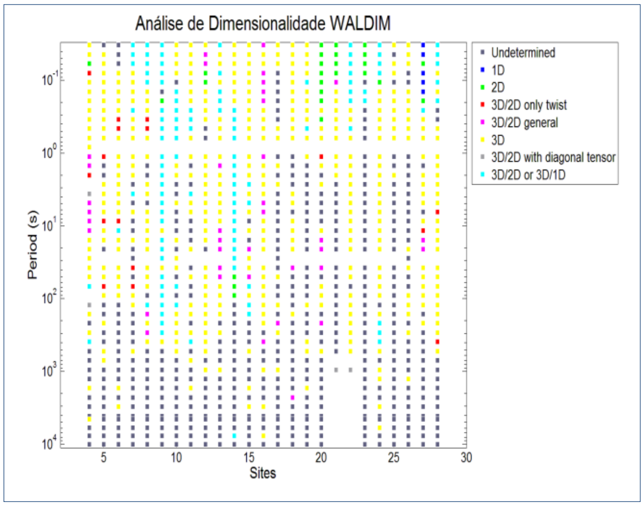

Figure 4 *- Dimensional and distortion analysis results by WAL invariants, where the dimensionality of the regional structure is 3-D.*

Dimensionality summary from the 49 EDI files:	
Total periods	1775
Undetermined cases	298
1 D cases	192
2 D cases	98
3 D/2 D twist cases	79
3 D/2 D cases	164
3 D cases	816
3 D/2 D diag cases	0
3 D/1D 2D cases	128

Figure 5 *- Table with WALDIM result for 49 stations.*

Conclusions

According to the obtained results, it can be inferred that there is a conductive body that appears in the two pseudosections at depths around 3.0 – 3.5 km taking into account the skin depth, and apparent resistivity values and periods involved. The edge of the Parnaíba basin can be identified by an abrupt change in resistivity values, characterizing a lithological change in which the sediments of the basin make contact with resistive rocks, possibly craton rocks. The different signatures of conductivity shown in the pseudo sections are related to a wide volcanic and tectonic activity in the region of the Parnaiba basin and adjacencies.

The profile is for the most part located in the Parnaíba basin, probably cutting a small part of the Borborema province and / or São Francisco craton, provinces with which it limits. In order to better characterize the limit of those of the tectonic provinces and the presence of conductive bodies, a 3 D inversion is indicated along with more geological and geophysical information.

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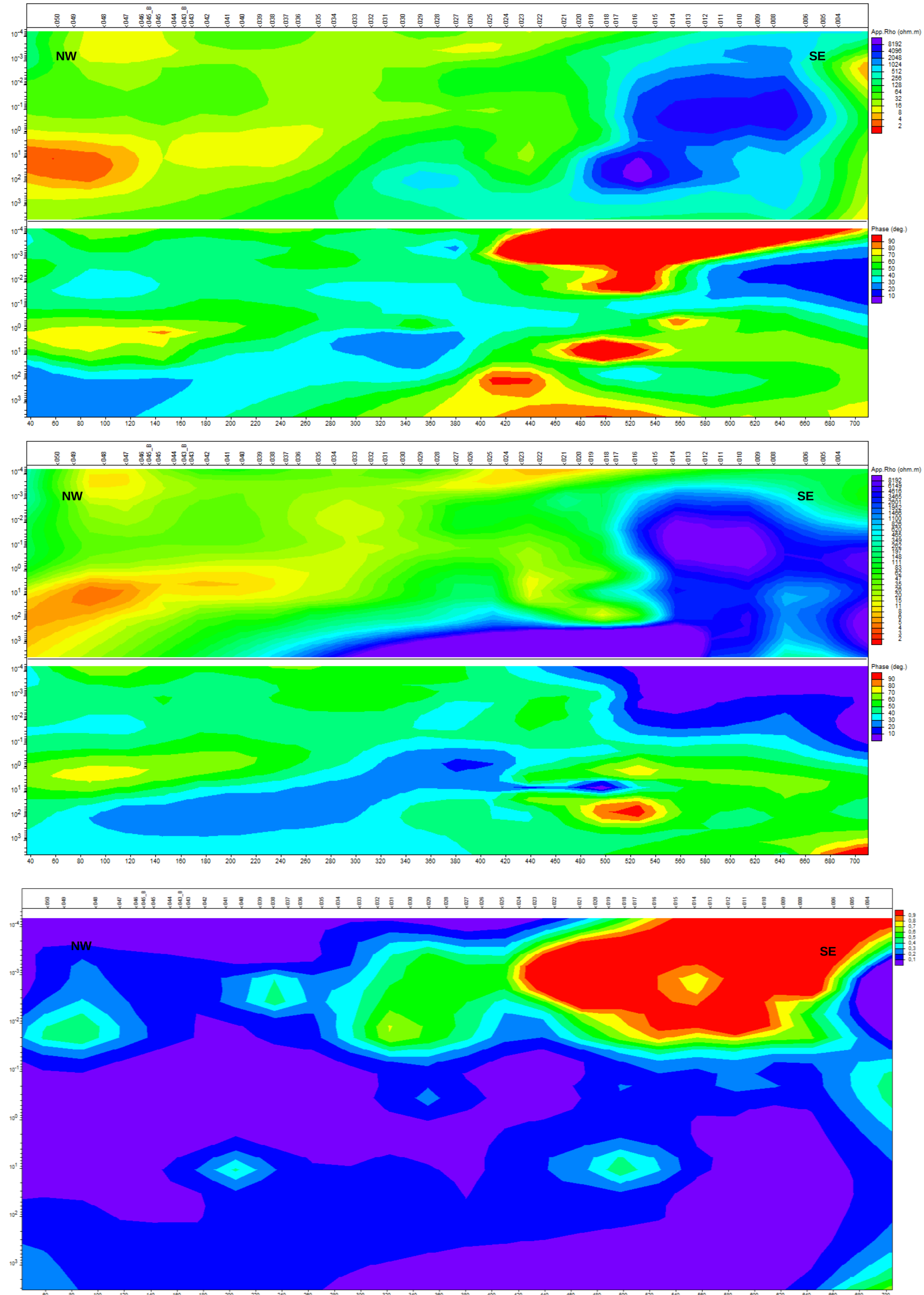

***Figure 6** – Pseudo sections: apparent resistivity and phase versus period for TE mode; apparent resistivity and phase versus period for TM mode; and tipper magnitude versus period, respectively. Distance is in km.*