2011-INCTET Progress Report on Magnetotelluric and Geomagnetic Depth Soundings in the Borborema Province and Adjacent Terrains, NE Brazil

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Abstract

In order to enhance our knowledge about the tectonic processes responsible for the geological evolution of the Borborema Province and adjacent regions, the *National Institute of Space Research* (INPE) and the *National Observatory* (ON) are conducting Electromagnetic Induction studies in northeastern Brazil, which are being supported by the *National Institute of Science & Technology for Tectonic Studies* (INCTET) project during the past three years. Such studies contemplate the deep geophysical probing of this region with Magnetotelluric surveys (MT) and Transient Electromagnetic soundings (TEM) along several geoelectric transects and an array of Geomagnetic Depth Soundings (GDS), which complement other geophysical methods. The focus of this study is directed to the identification of geoelectric variations in electric conductivity at distinct lithospheric depths and associations of geoelectric strikes and anisotropy with structural grain and stress patterns, particularly in the long ubiquitous structural features that cross the province and that constitute major geoelectric heterogeneities, at the near surface crust and also in the lower crust and upper mantle. The preliminary results indicate a lithosphere with a very variable electrical resistivity. The upper-mid crust shows up as a very resistive layer, overlying a less resistive lower crust and upper mantle. In some areas the mantle is very resistive, characteristic of a cratonic origin. Exceptions to a resistive crust are found under the Seridó belt, Jatobá rift basin and the Araripe intracratonic basin, marked by an underlying conductive crust. Laterally, the deeper portion of the crust and upper mantle is highly segmented in blocks with alternating juxtaposed higher and lower resistivities. This pattern is suggestive of highly deformed regions by transform dominated tectonic regimes, with the presence of contrasting mechanically strong cratonic-like keels against weaker zones likely subjected to delamination processes that might have produced magmatic related lithospheric re-fertilization by metasomatism.

Introduction

The *National Institute of Science & Technology for Tectonic Studies* congregates many geoscientists from several Brazilian research institutions with the purpose of studying the deep crust and upper mantle structures. It is multidisciplinary in its approach, merging different techniques and methodologies, which allow the study of the Earth's interior based on different properties of its constituting rocks. The focus of this research is the study of the crust and upper mantle of the Borborema Province and adjoining São Francisco Craton and Parnaíba Basin. The Borborema Province is a complex association of crustal blocks with differing ages, origin and geologic evolution, and which were amalgamated during the last orogenic event that took place in what is now the Brazilian territory, namely the late Neoproterozoic-early Phanerozoic Brasiliano orogeny, composing the Gondwana supercontinent. Therefore, Electromagnetic Induction studies are being developed with the goal of making a major contribution to a better comprehension of the actual articulation of the amalgamated crustal blocks and the role of large transcurrent lineaments in bringing these blocks together, through an integrated multi-disciplinary geophysical study.

Major objectives

Magnetotelluric (MT), Transient Electromagnetic (TEM) and Geomagnetic Depth Sounding (GDS) systems are being deployed, respectively, along several geoelectric transects with induction coils and lead electrodes, single-site electric loop at the surface, and as arrays with fluxgate magnetometers, for the deep geophysical probing of the present-day physical and chemical conditions of the Borborema lithosphere. The purpose is to make geophysical contributions by imaging the geoelectrical characteristics of the crust and lithospheric upper mantle. The collected and processed data yield maps of the distribution of electrical conductivity and directions of lithosphere anisotropy at different depths along profiles positioned perpendicularly to the prevailing structural directions. Furthermore, the study identifies areas of anomalous concentration of electrical currents in the crust and upper mantle and evaluates the spatial relationship of conductive layers, discontinuities and geoelectric anisotropy with the thermal state, mechanical, chemical and rheological lithosphere inferred from other geological and geophysical data.

Physical Principles and Data Processing

Magnetotelluric method (MT)

The MT method provides images of subsurface conductivity using natural, low frequency electromagnetic waves that diffuse into the earth's interior. The MT method requires the simultaneous time-series measurement of orthogonal components of magnetic (Bx, By, and Bz) and electric (Ex and Ey) variational fields. The ratio of the orthogonal horizontal components of E and B in the frequency domain is a measure of the Earth's electrical resistivity over a volume that increases with depth and width as the period increases. With pairs of orthogonal E and B fields, MT responses may be obtained in two polarizations, or modes. Above one-dimensional (1D) layered structures the two MT modes are identical, but for two-dimensional (2D) structures MT fields may be rotated to modes of electric field parallel to strike (TE mode) and perpendicular to strike (TM mode). Electrical current flowing along the strike direction defines the TE mode while the perpendicular response defines the TM mode. The TE mode data are usually more affected by 3D effects (finite strike length, off-profile structures) than TM mode data, although for certain situations the opposite can occur. The depth of penetration of the signal is controlled by the skin depth relationship that defines that the penetration increases as the sounding frequency and the electrical conductivity of the Earth's interior decrease. For this study, the five MT components are recorded using commercial remote-referenced broadband and long-period MT systems. Also, TEM data are acquired at some sites for static shift correction, allowing a more accurate interpretation of the MT sounding curves.

Geomagnetic Depth Soundings (GDS)

Geomagnetic Deep Sounding (GDS) is an electromagnetic method of geophysics, which is capable of imaging the Earth's interior in terms of electrical conductivity using natural geomagnetic transient variations. The ratio of vertical magnetic field (Bz) to the horizontal fields (Bx and By), known as GDS transfer function responses, also provides a measure of lateral changes in resistivity. The magnetic transfer functions are commonly represented by rotated real induction arrows, at a period mainly affected by mid and lower crust and upper mantle structure. The presence of lateral electrical conductivity differences at depth perturbs the flow of induced currents and produces frequency-dependent anomalies in the X, Y and Z components. The detection of such anomalies can be facilitated by correlating data from closely spaced sites, recorded preferably by an array of simultaneously operating magnetometers. The induction arrows can be interpreted based on the intensity and direction of the arrows; near null induction arrows indicate that the measurements are carried out just above a major conducting feature. The GDS responses are often plotted in map view in the form of induction arrows, facilitating a qualitative regional assessment of the degree of conductivity variations in the subsurface. The directions of the reversed real component of the arrows point towards more conductive regions. The method is particularly suited to map geological structures marked by large lateral conductivity contrasts.

Transient Electromagnetic (TEM)

The TEM system is an active method consisting of a battery- or generator-powered current transmitter that energizes a loop deployed on the ground, and where the depth of investigation depends on the actual size of the loop and the transmitted current, among other parameters. The current is cycled on and off in pulses of alternating polarity, producing a decaying magnetic field that depends on the conductivity of the medium. A receiver loop or a magnetic coil antenna is used to measure the secondary field decay. For this study purposes (static shift corrections), a vertical sounding mode (in- or out-loop) is used to measure the decay waveform in the time interval varying from several microseconds to milliseconds.

Data Processing

MT, TEM and GDS data are collected, analyzed and modeled using the most current equipment and technique. As the methods are particularly sensitive to the detection of any connected conductive medium, they give well constrained quantitative information about the depths to different transition zones. In terms of processing, modern techniques of robust data processing are applied to estimate the MT tensor functions and distortion analysis is used to evaluate if a 2D interpretation of the MT data set is valid. Usually, tensor decomposition gives acceptable fits to the measured impedance data. The final 2-D and 3D conductivity models provide vertical images that yield relevant new information on the current geophysical state of the crust and upper mantle under the study area, from which inferences can be drawn on different lithospheric processes. Induction arrows from the magnetic transfer functions can also be used to assess the dimensionality and the regional electric strike direction of the data. In a 2D scenario, induction vectors are orthogonal to the geoelectric strike. For sites not affected by large laterally positioned conducting features, orientation of the induction arrows is roughly parallel to the profile, and consequently perpendicular to the geologic strike. This analysis is used to support the results of the MT tensor decomposition and implies that a 2D description of the regional resistivity structure is a reasonable assumption. MT depth estimations can be hindered by near-surface distortions of the electric field amplitudes, causing a static shift in the impedance magnitudes. Usually, the static shift can be minimized using the results from TEM soundings. For sites where TEM data are unavailable, the static shifts are estimated as part of the 2-D inversion procedure for each profile. The approach used is to fit well the phase data at all stations and the apparent resistivities from stations without static shift, yet allowing a larger misfit to the apparent resistivity data of static-shifted stations. The static shift values estimated in this way can then be used to correct each site prior to depth estimation. Also, to remove the effects of galvanic scatters, the regional impedances can be determined by fitting the impedance estimates to a distortion model with an azimuth fixed at a general strike direction.

Summary of the activities

Magnetotelluric soundings

A total of around 300 MT soundings, carried out in fourteen profile segments and covering an extent of more than 3,500 km, at a regional scale given by the 20-30 km spacing between sites, has been collected so far. The MT transects were carried out across the major tectonic domains of the Borborema Province, namely the Médio Coreaú, Ceará Central, and Rio Grande do Norte, in the northern portion of the province, and the Transversal and Sul, in the southern and western part. The transects also continue to the south into the Sergipano Belt and the adjacent terrains of the northern portion of the São Francisco craton, and to the west into the São Luiz craton and Parnaiba Basin. Some particular geological features are crossed by the profiles, such as the shear zones that separate tectonic domains (Sobral-Pedro II, Senador Pompeu, Patos, Pernambuco, and Jaguaribe), sedimentary basins (Jatobá rift basin and Araripe basin), and several important terrains (Riacho Gravatá, Cachoeirinha, Pernambuco-Alagoas, Alto Moxotó, Alto Pajeú, Serrinha).

As seen in figure 1: two long profiles cross the states of Piauí and Ceará, in a WNW-ESE direction sub parallel to the northern sea shore; four profiles are in Rio Grande do Norte; three profiles run across Paraíba, Pernambuco in a north-south direction sub parallel to the eastern sea shore; two profiles are in Alagoas and Sergipe, several small profiles are in the Serrinha terrain; and a long profile runs in a EW direction in northern Bahia.

Subsequently to the preliminary processing steps, vertical sections of conductivity variations were produced for each profile, as shown for the two northern profiles in Figures 2 and 3. Such sections present electrical resistivity of the crust and upper mantle of the Borborema Province and adjacent areas, as vertical images down to 200-250 km depths.

GDS modeling

Additionally, geomagnetic vertical-horizontal transfer functions are used in GDS modeling of the regional geoelectric distribution and of the “sea coast effect” that disrupt MT data near the sea shore. To obtain the geoelectric vertical sections, 2D inversions are performed on the decomposed data by using an inversion algorithm. However, it is expected that both data, the MT and GDS, are influenced by the conducting sea water of the adjacent Atlantic Ocean. In this work, the effects of the ocean in the observed data are estimated by using a 3D code to calculate the surface response of different models, having the main features based on available information from geological and geophysical data. The geoelectrical structure for the ocean ward part is derived from regional bathymetry information and an estimation of the conductance of seawater saturated sedimentary successions deposited in the onshore portions of the Potiguar and Pernambuco-Paraíba basins. Apparent resistivity and phase curves derived from the 3D model in several sites along and outside the MT profile are thus compared with the expected 1D response. The result shows that the split in the MT responses between the two modes, TM and TE, will appear at longer periods at sites located at more distant sites from the nearest coast, depending on the station location, up to a distance of about 200 km.

Anisotropy

Another important result might come from observations of electrical anisotropy. It provides complementary approaches to estimate mantle deformation and ultimately address a wide range of geological and geophysical problems. Electrical anisotropy may be generated in the upper mantle either by a preferred interconnection of a highly conducting mineral phase (such as graphite) within foliation planes that mark past tectonic events, or by strain-induced hydrogen diffusion along olivine crystals oriented by present-day plate motion. As the depth to an electrically conductive anisotropic-layer is well constrained, long-period magnetotelluric (MT) soundings are then used to resolve the ambiguity in interpretation of seismic anisotropy measurements. Therefore, in the present study, MT data are also analyzed using the most current techniques to get band-limited strike directions for periods most sensitive to different lithospheric/ asthenospheric depths. Because the MT responses at long periods are sensitive both to deep and to distant structure, a careful analysis can be made to separate the effects of electrically anisotropic structures in the crust and in the upper mantle. Selected geoelectric strikes at typical depths of the crust, upper lithospheric mantle and deeper lithosphere/asthenosphere can then be compared with seismic anisotropy for interpreting structural deformation below the study area.

Preliminary results

The preliminary results indicate a lithosphere with a very variable electrical resistivity. The upper-mid crust shows up as a very resistive layer, down to 10-15km, overlying a less resistive lower crust and upper mantle. In some areas the mantle is very resistive, characteristic of a cratonic origin. The areas that show a deep lithosphere keel are the São José do Campestre Massif, Sergipana belt and Alto Moxotó Terrain. Exceptions to a resistive crust are found under the Seridó belt, Jatobá rift basin and the Araripe intracratonic basin, marked by an underlying crustal conductive zone. Laterally, the deeper portion of the crust and upper mantle is highly segmented in blocks with alternating juxtaposed higher and lower resistivities. Geoelectric discontinuities mark some particular geological features such as the shear zones that separate tectonic domains This pattern is suggestive of highly deformed regions by transform dominated tectonic regimes, with the presence of contrasting mechanically strong cratonic keels against weaker zones subjected likely to delamination processes that might have produced magmatic related lithospheric re-fertilization by metasomatism. The observed geoelectric strikes are possible indicators of compressional-extensional stresses. The directions of the geoelectric strikes and of the induction vectors show similarities with the tectonic grain, particularly at higher frequencies, associated with the upper crust.

Results obtained with the data merging of MT and GDS are used to constrain the borders of the tectonic terrains characterized by distinct geoelectric properties, mainly conductivity, strike directions and anisotropy.

The data collected under the auspices of the INCTET project have been used for thesis and dissertations by two doctoral and six undergraduate students (*scientific initiation),* and published in the proceedings of several national and international scientific meetings, as listed in the References.

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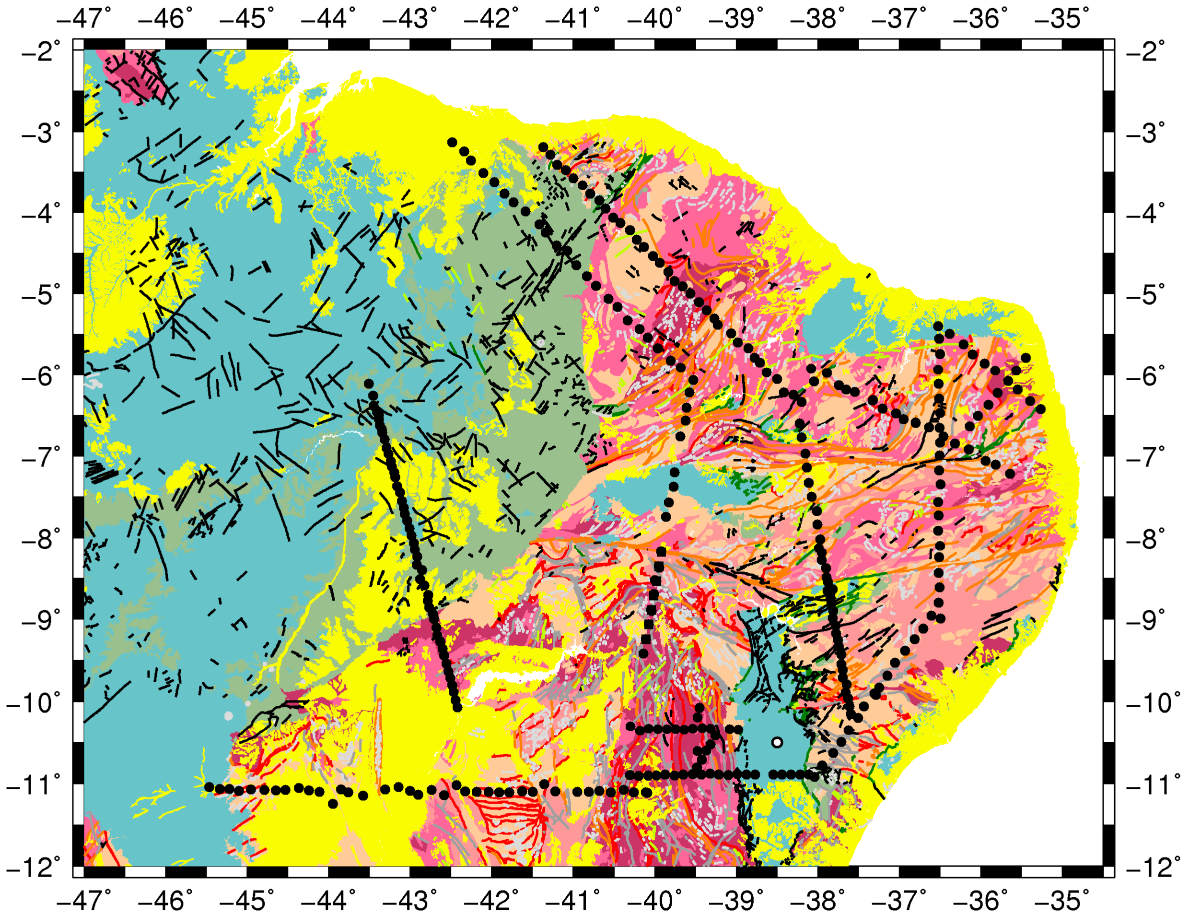

Figure 1 – Geologic map with geographic positions of the MT soundings (black dots) carried out in the Borborema Province and adjacent terrains.

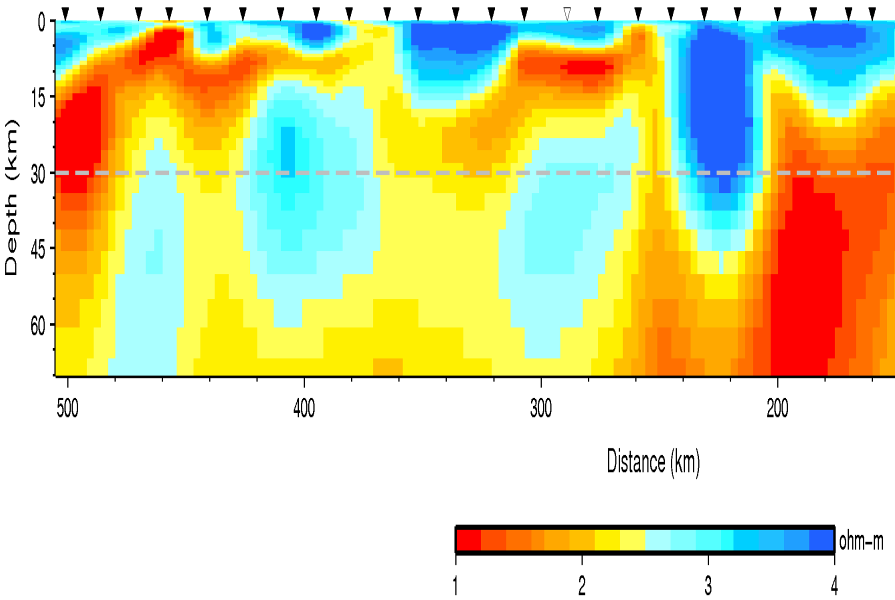

Figure 2 – Section of inverted broad-band TM mode data of the NW-SE profile across the Médio Coreaú and the Ceará Central terrains in NW Borborema Province. The bluish colors are for more resistive lithosphere whereas reddish colors are for more conductive zones. The dashed gray line indicates the position of the Moho defined by a seismic refraction model.

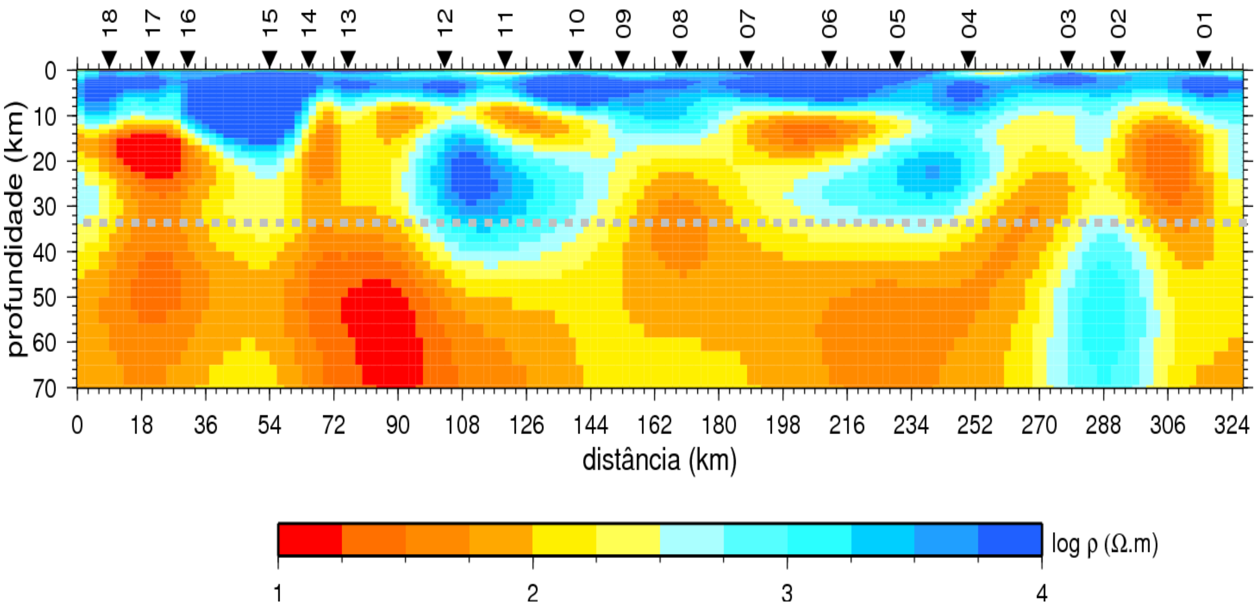

Figure 3 – Section of inverted broad-band TM mode data of the NW-SE profile across the Rio Grande do Norte terrain.