Magnetotelluric soundings in NE Brazil: Constraints for dual subduction zones with opposite polarity beneath the NW Borborema province

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Abstract

The Borborema province, NE Brazil, occupies a crucial position for understanding the West Gondwana reconstruction during the Neoproterozoic. However, attempts of correlation with Africa are hampered because key links in the internal structure of the province have not yet been identified. A magnetotelluric study was undertaken along three profiles to image the deep electrical structure in the NW part of the province. Two-dimensional models show that despite several tectonothermal episodes that affected the region in the past, the large-scale signature of terrane assembly during Neoproterozoic accretion and collision is adequately preserved in one of the profiles. Two prominent resistive features dipping from the upper crust into the upper mantle in opposite directions were found, one dipping eastward from the trace of the Transbrasiliano lineament under the Parnaíba basin and the other dipping westward from the south-eastern part of the Tamboril-Santa Quitéria complex in the Ceará Central domain. These resistive features are interpreted to be due to remnants of former subduction zones, with the high resistivity consistent with dehydrated oceanic lithosphere depleted of sediments.

Introduction

The Borborema Province (Almeida et al., 1981) is a complex orogenic system in the northeasternmost corner of the Brazilian shield that was formed as a result of the convergence of the Amazonian, West African-São Luis and São Francisco–Congo cratons during the assembly of West Gondwana. Its present configuration is associated to the Brasiliano/Pan-African orogeny that took place during the late Neoproterozoic-early Phanerozoic age, where the province was strongly affected by deformational, metamorphic, and magmatic episodes (Brito-Neves et al., 2000). This orogeny affected the entire Borborema Province and was responsible for low- to high-grade metamorphism, emplacement of many granitic plutons, and development of continental-scale transcurrent shear zones, mainly striking E-W and NE-SW (Vauchez et al., 1995). Two major E-W shear zones divide the province into three segments, informally referred to as Northern, Central and Southern Domains (Van Schmus et al., 1995). Each of these main domains admits subdivisions in different subdomains characterized by some peculiar geological features and properties that allow distinguishing them from the adjacent subdomains. Also, superimposed on the Precambrian framework is a set of features resulting from the continental breakup that resulted in the opening of the Atlantic Ocean and the separation of South America from Africa in the Cretaceous. These include interior basins and basins from the continental margin (Brito Neves et al., 2000).

Although the litho-structural and geochronological characteristics of superficial rocks of the Borborema Province are reasonably well known, thanks to geological surveys, gravity and airborne geophysical surveys and significant advances fostered by geochemical and isotopic studies, deep crustal and uppermost mantle structure is relatively unknown. Consequently, dynamic processes involved in the formation and evolution of the province are still poorly understood. Contentious issues include the (i) identification of distinct geophysical signatures in lithospheric mantle blocks supposed to have independent origins and tectonic histories prior to accretionary events, (ii) importance of some lineaments within the province, suggested as representing either important crustal suture or shear zones of minor importance (Bezerra et al., 2011), (iii) identification of possible sutures related to ocean closure, crucial to understand the Neoproterozoic evolution of the province either as a collage of allochtonous terranes (Fuck et al., 2008) or as intraplate tectonism driven by far-field stresses reworking preexisting Archean–Paleoproterozoic crust (Neves et al., 2006).

Electromagnetic induction studies are being developed in the Borborema Province 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. The magnetotelluric (MT) method measures the electrical conductivity of the medium, which is sensitive to very small changes in minor but tectonically important constituents (fluids, graphite, melts, etc.) of the rock, and hence provides an alternative and complementary view of lithospheric structure to those given by other geophysical or geochemical approaches. The study reported here was carried out in the western sector of Northern Domain of the province, which lies north of the Patos shear zone and is primarily underlain by Paleoproterozoic basement including Archean nuclei with overlying middle to late Neoproterozoic supracrustal rocks and Brasiliano plutons (Van Schmus et al., 2008). The geoelectric structure beneath this region is investigated through MT imaging on three parallel profiles to understand NE-SW variations that could place lithospheric-scale constraints on geodynamic models of tectonic evolution.

Magnetotelluric study

MT is a passive geophysical technique that utilizes time-varying electromagnetic (EM) fields measured at the Earth's surface to image subsurface conductivity structure. The MT response depends on the Earth's electrical conductivity and on the frequency of the EM variations, with the deepest penetrations resulting from long recording time (data in lower frequencies) and resistive Earth material (more details on the MT method can be found in Simpson and Bahr, 2005; Chave and Jones, 2012).

For this study, the horizontal components of the electric field (Ex and Ey) and the horizontal and vertical components of the magnetic field (Hx, Hy and Hz) were recorded at 81 sites along three SE-NW parallel profiles (with a 80-90 km offset between each profile), orthogonal to the major geological structures in the NW Borborema (Fig. 1). Profile A consists of 34 broadband sites (17 of which also included long-period data) in a total length of about 500 km, coincident with a deep seismic refraction transect (Soares et al., 2010). Profile B is 360-km-long with 18 broadband sites (9 with long-period) and profile C is composed of 29 broadband sites (15 with long-period) along a 400-km-long transect. Within each profile the sites are at roughly 15-20 km intervals. The data for profiles A and B were gathered from different field campaigns carried out during the years 2007-2010, whereas the data for profile C were collected in a single campaign during the second semester of 2011. Commercial single-station MT systems (Metronix ADU-06) were used to record broadband data (periods from 0.001 to 1024 s) and commercial remote-referenced MT systems (Phoenix LRMT and Lemi 417) were used for long-period data (period range from 10 to about 13,000 s). Recording time at each station was of at least 2 days with the broadband systems and of at least 2 weeks with the long-period systems.

Time series were processed using a robust code (Egbert, 1997) to estimate the complex MT tensor elements and magnetic (tipper) transfer functions. Because noise levels during the surveys were generally low, reliable broadband response function estimates were obtained at most sites in the period range 0.001 to 400 s. Some scattering at specific short periods can be associated with ambient cultural noise and, at period range of 1-10 s, attributable to the dead-band of low-amplitude signals. These corrupted responses were removed from analysis and interpretation. Sites over the Archean Tróia-Tauá massif showed a significant decrease in data quality, with station 3 in profile B only producing usable data up to 4 s and another station between the stations 2 and 3 in the same profile being completely discarded. In addition, there were recording failures in the electric field of station 12 in profile B and in the vertical magnetic field of station 42 in profile C. Due to the low signal amplitude of longer periods throughout the recording period of profiles A and B (extremely low solar activity during solar minimum and the low amplitude of geomagnetic variations at these very low geomagnetic latitudes; e.g., see Trivedi et al., 1997), only at a few sites for these profiles the responses were extended outside the range of the broadband equipment. On the other hand, the long period data at the sites of the profile C are of very good quality and produced acceptable MT response estimates up to 10,000 s.

2D inversion

The decomposed MT data for each profile were inverted using an algorithm that produces the smoothest model fitting the data within an expected tolerance (REBOCC, Siripunvaraporn and Egbert, 2000). Field data consisted of transfer functions responses for the 81 stations at mostly 38 periods extending from 0.0011 to 410 s. In profile C we were able to extend the analysis up to 10,000 s at some staions. Unreliable data with large scatter were removed from the dataset prior to inversion. To account for static shift effects and prevent the inversion from being dominated by data with unrealistically small variances, the inversions used error floors of 5% in the phases, 10% in the apparent resistivities, and 0.02 in the tipper. The starting models were either uniform half-spaces or a layered half-space determined from 1D inversion of the geometric mean of each site and all gave essentially the same final resistivity models. The preferred 2D inversion models shown in Fig 2 were obtained using a starting half-space resistivity of 100 Ωm. All models allow acceptable misfits between observations and model predictions with overall rms of 2.54 for profile A, 1.63 for profile B, and 2.62 for profile C, related to the assumed error floors.

Results and discussion

The broad range of tectonic and volcanic activity in the Borborema province, including periods of extension in the Paleoproterozoic, compressional deformation in the Neoproterozoic, and widespread emplacement of post-collisional granitoids from Neoproterozoic to Cambro-Ordovician, has contributed to the total expression of the conductivity signatures presented in the MT models.

Example of an conductivity signature attributed to the Paleoproterozoic extensional regime is the huge high conductivity anomaly beneath the Jaguaribe sub-domain in profile A. Low resistivity in the crust and upper mantle is inferred in many active and ancient extensional regimes (e.g., Jiracek et al., 1995; Bologna et al., 2006) and for paleo-events are ascribed to electronic conduction by highly conducting interconnected solid phases precipitated from carbon-rich volatiles (Nover, 2005). At the surface of the Jaguaribe sub-domain the rifting event is represented by the volcanic sequences of the Orós fold belt. Similarly, the predominantly sub-horizontal conductive anomalies at upper- to mid-crustal depths of the Médio Coreaú domain can be tentatively associated to Paleoproterozoic extension-related magmatism that were affected by low-angle thrusting and transcurrent deformation during the Brasiliano orogeny (Santos et al., 2008). At the surface the event is represented by the Saquinho volcanic sequence.

Isolated conductors at crustal depths in the Ceará Central domain along profile A are concentrated in an area of low Bouguer anomaly which encloses a localized larger crustal thickness beneath part of the Tamboril-Santa

Quitéria complex. The crustal conductors are spatially coincident with some of the post-orogenic granitoids exposed at the surface. Presence of carbonate veins in a granitoid suggest that they may be related to CO2-bearing mantle-derived fluids (Santos et al., 2013). The increased conductivity can therefore originate from interconnected graphite-rich materials intruded in remains of post-orogenic igneous and metamorphic rocks. Similarly, isolated conductors beneath the Parnaíba basin in profile C can also be associated to post-orogenic granitoids. On the other hand, in profile A these conductors are located below and around the proposed magmatic arc where any possible evidence of Neoproterozoic collision-related sutures and subduction zones are expected to occur. In general, geoelectrical signature is controlled by the last tectonothermal event that may overprint or even completely obliterate at some places the signatures of earlier events. Along profiles A and C, any signature of potentially pre-existing Neoproterozoic structure formed during the collisional process has been virtually obscured by the pervasive post-collisional magmatism.

A different picture is observed in profile B, located to the south of the Tamboril-Santa Quitéria complex. Magmatism along this profile has not been so voluminous as to obliterate the geophysical signature of the collisional event (see Fig. 1). The conductor situated in the SE end of the profile in Fig. 2 is associated with the Paleoproterozoic extensional event beneath the Jaguaribe unit also recorded in profile A. The resistor at the NW end of the profile, also observed in profile C, is likely related to a cool and thick cratonic root (“Parnaíba block” of Cunha, 1986) hidden below the Parnaíba basin. The region where the Neoproterozoic collision is located involving parts of the Central Ceará domain and the Parnaíba basin is characterized by a gravity low associated with a probable crustal thickening. Also, the gravity data present short wavelength gravity highs approximately coincident with localized crustal conductivity anomalies (not shown in Fig.2). This can be taken as indicative of the presence of high-density, high-conductive intrusions in the crust associated with the Neoproterozoic magmatism.

However, the most significant features in the model of Fig. 2 are the presence of two moderate-to-high resistivity zones, dipping from the upper crust into the upper mantle in opposite directions in profile B. One of these resistive structures dips eastward from the western side of the Transbrasiliano lineament, whereas the other dips westward from the Ceará Central domain (south of the Tamboril-Santa Quitéria complex). The resistors merge each other in a single resistive block at depths of about 50 km.

The overall appearance of the MT model, with its several conductors and resistors, is quite similar to tomographic images of the mantle structure beneath the complex Indonesian archipelago, Southeast Asia (Hafkenscheid et al., 2001). In that case of an ongoing subduction system, positive velocity anomalies are associated to subduction along two separate trench systems. Similarly, the two high-resistivity zones in profile B may represent remnants of former subduction zones beneath the NW Borborema during the Neoproterozoic. MT results from different ancient and modern subduction/collision zones have shown that subducted plates are often imaged as highly-resistive slabs (Jones, 1993; Unsworth, 2010). The resistive slab corresponds to a dehydrated oceanic lithosphere depleted of sediments (Wannamaker et al., 1989), an interpretation justified by EM measurements on the seafloor (Key, 2011). In addition, the shallow subduction of the oceanic lithospheres observed in our model has been suggested as the dominant style of subduction during the Proterozoic and Archean (Abbott et al., 1994).

In summary, the MT data support the presence of fossil subduction markers beneath the NW Borborema province. Two subduction systems are identified in profile B: one dipping eastward from the trace of the Transbrasiliano lineament under the Parnaíba basin, the other dipping westward from the south-eastern part of the Tamboril-Santa Quitéria complex in the Ceará Central domain (Fig. 3).

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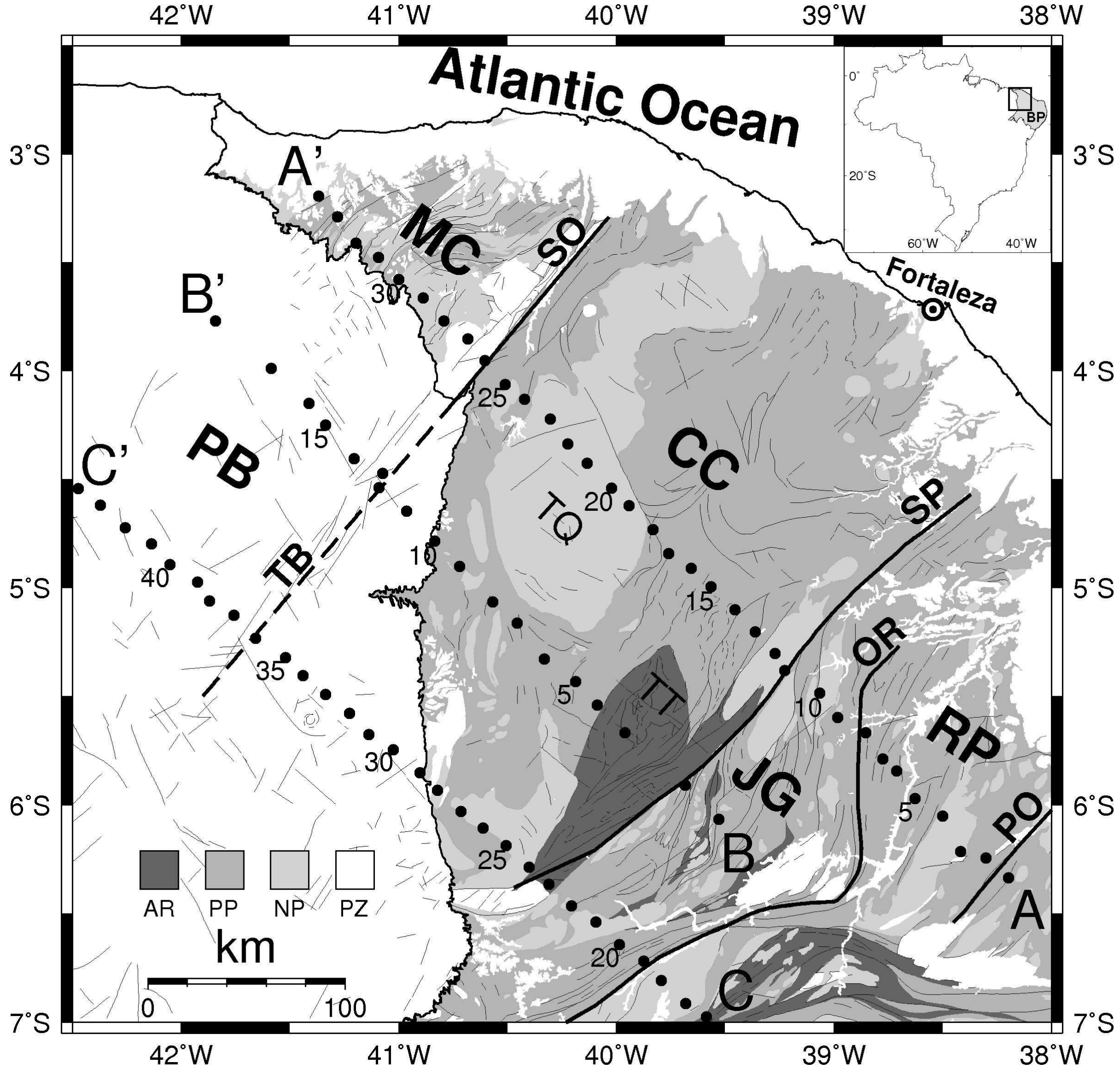

Figure 1 - Generalized geological map of the NW Borborema province in NE Brazil (from Bizzi et al., 2001), with the location of the MT stations along the profiles A, B, and C (numbered black dots). Geological domains are PB = Parnaíba basin, MC = Médio Coreaú, CC = Ceará Central, JG = Jaguaribe, and RP = Rio Piranhas. Main faults and lineaments are TB = Transbrasiliano, SO = Sobral-Pedro II, SP = Senador Pompeu, OR = Orós, and PO = Portalegre. Grey tones represent AR = Archean, PP = Paleoproterozoic, NP = Neoproterozoic (mainly granitoids), and PZ = Paleozoic. TQ stands for the Neoproterozoic Tamboril-Santa Quitéria complex and TT for the Archean Tróia-Tauá massif. Inset map shows the location of the study area in Brazil, with BP indicating the Borborema province.

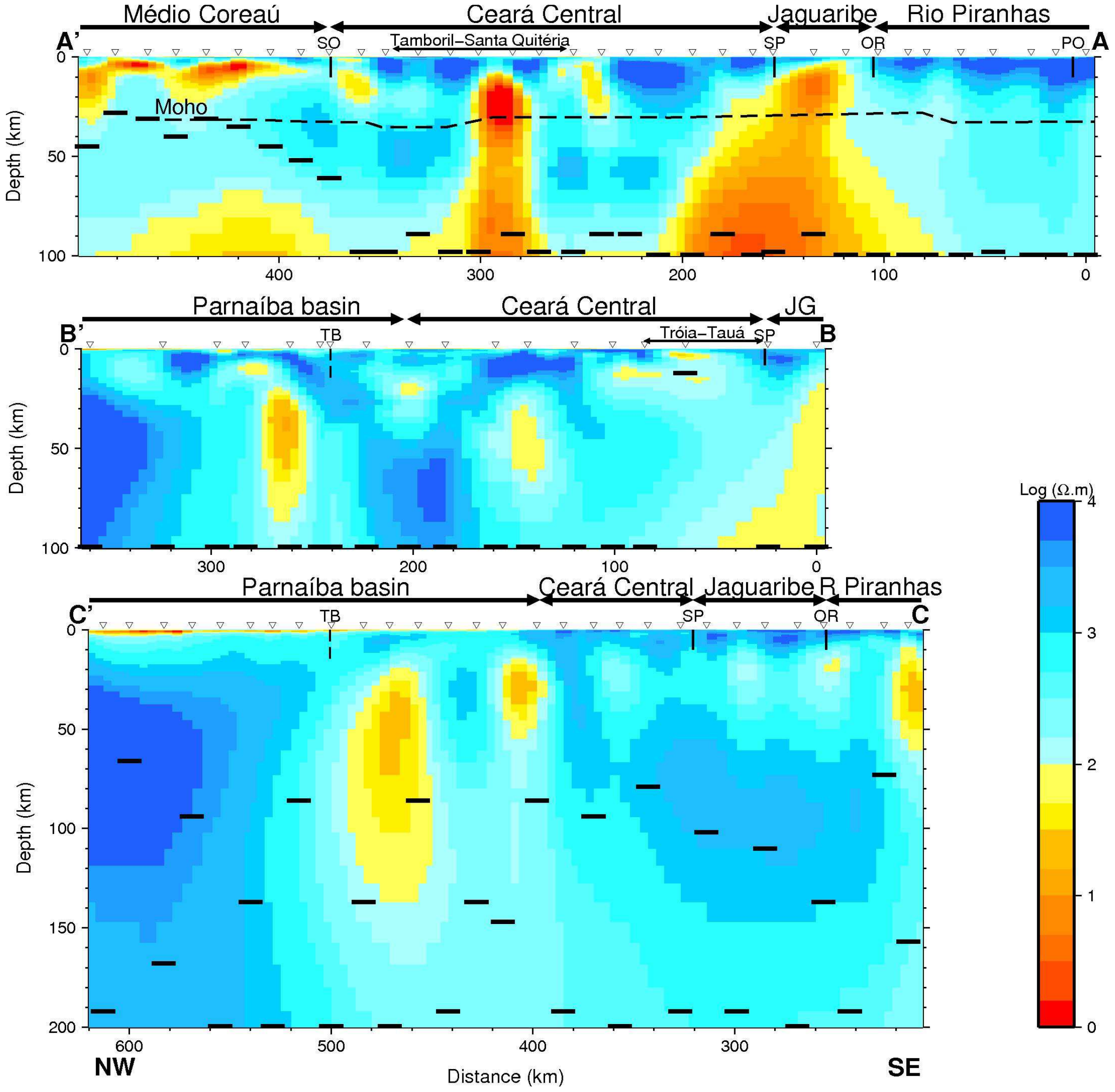

Figure 2 – 2-D resistivity models across the three profiles in the NW Borborema province derived by inverting the MT data, with indication of surficial limits of geological domains and main faults (SO = Sobral-Pedro II, TB = Transbrasiliano, SP = Senador Pompeu, OR - Orós, and PO = Portalegre). Inverted open triangles show the location of the MT sites. Dashed line in profile A is the seismic refraction interpretation of crustal thickness (Soares et al., 2010) and short horizontal black lines represent the estimated maximum depth of investigation beneath each site (following the procedure described in Padilha et al., 2013).