Preliminary results of ongoing GDS survey in Center-Southeast Brazil

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Abstract

Transient geomagnetic variations recorded by an array of 55 stations in Center-Southeast Brazil are analyzed to infer the configuration of internal induced currents in and around the southern São Francisco craton and northern Paraná basin. The data were subjected to robust regression analysis to derive vertical transfer functions presented as real induction arrows following the GDS method. A preliminary thin sheet conductance model was developed to explain the variety of conductive anomalies evidenced by the induction arrow maps. The principal structures revealed by the study are: (1) two crustal anomalies on the western side of the array, one correlated with a narrow gravity low and tentatively interpreted as a subvertical deep shear zone filled with sediments in its upper part, the other coincident with a positive gravity anomaly and probably associated with mafic intrusions of the Iporá igneous province, modified at depth by hydrothermalism during the volcanic activity; (2) two deeper anomalies, probably at upper mantle depths, on the eastern side of the array, one coincident with a positive geoid anomaly that could be generated by temperature rise or denser material, the other positioned in a region characterized by Early Cenozoic tholeiitic dyke swarms and possibly related to hydrothermal material introduced in the lithosphere. These two latter anomalies are located close to the border of the array and need stations further S-SE to better define the current concentrations associated with these induction features.

Introduction

Geomagnetic deep sounding (GDS) is an electromagnetic method that uses natural geomagnetic transient variations to image the Earth's interior in search for large lateral electrical conductivity contrasts. Data are collected by an array of magnetometers that are operated simultaneously in the study area. The method can be used to map local geologic structures, as well to investigate large-scale conductivity anomalies of continental scales (see Arora et al., 1999, for an example of application in North-Northeast Brazil).

A magnetometer array study is presently being undertaken in Center-Southeast Brazil, within and around the southern São Francisco craton and northern Paraná basin. A total of 29 Flinders digital fluxgate magnetometers (Chamalaun and Walker, 1982) are available for this study, within a collaborative project between INPE and Flinders University. This paper describes the first results of data processing, with presentation of the transfer functions in the form of real induction arrows, and a preliminary non-uniform thin sheet model, which maps the lateral extent and estimated depth-integrated conductances of regional anomalous structures.

Method

An effective way of summarizing the main induction effects in a GDS survey is through the vertical field transfer functions (T_{zx} and T_{zy}) relating the Fourier transforms of the anomalous vertical (Z_a) and the normal horizontal (X_n and Y_n) field components at any particular frequency:

$$Z_a = T_{zx} * X_n + T_{zy} * Y_n + \varepsilon$$

where all quantities are complex and ε is the residual error.

The normal vertical field component is negligibly small for quasi-uniform sources and hence the observed Z at each site can be considered to be entirely of anomalous origin (Z_a). The numerical estimation of the vertical transfer functions is achieved by using robust regression techniques (Egbert and Booker, 1993).

The most convenient way to display and isolate the information contained in the transfer functions on the conductivity distribution in the vicinity of the measuring sites is through maps of real and imaginary induction arrows. The magnitude of the real induction arrows is given by:

$$S_r = ((\mathrm{Re}(T_{zx}))^2 + (\mathrm{Re}(T_{zy}))^2)^{1/2}$$

whereas the corresponding azimuth is obtained from:

$$\theta_r = \tan^{-1} (\mathrm{Re}(T_{zy}))/\mathrm{Re}(T_{zx}))$$

It is a usual practice to reverse the azimuths so that the arrows point at right angle to current concentrations, helping to define the strike directions of the conductive structures.

The information on the geometry and electrical parameters of the anomalous structures can be gleaned by 3-D trial-and-error forward modeling of the GDS response in both spatial and frequency domains. In this paper, a 3-D thin sheet formulation (Vasseur and Weidelt, 1977) has been used to model the conductive structures indicated by the induction arrow maps.

Induction arrows

The measurements were carried out over two periods of roughly 6 weeks, in August-September and November-December, 2002. One station was recorded at the two periods and used as reference for calculation of geomagnetic transfer functions (Egbert and Booker, 1993). The magnetometers were deployed at 55 stations to measure the geomagnetic fields in vertical (Z) and two horizontal components resolved to the geographic north (X) and east (Y). They sampled the total field values of the three components at 1-minute intervals, with a resolution of 1 nT.

Figure 1 shows the layout of the magnetometer sites over a schematic outline of the major geological provinces in center-southeastern Brazil. The region is mainly composed of rocks of the Archean São Francisco craton and the Phanerozoic Paraná basin, with Neoproterozoic mobile belts of the Tocantins and Mantiqueira provinces surrounding the São Francisco block. The figure also gives maps of the real induction arrows for four periods, sampling the lithosphere below.

In general, the magnitudes of the arrows are very small, especially at the center of the array, which implies that no meaningful vertical field is present. The absence of vertical field indicates that no significant lateral resistivity contrast occurs at the subsurface below or that the measurements were carried out just above the center of a major conducting feature.

At short periods, there is a reversal in the direction of the arrows between some stations on the western side of the array. The oppositely directed arrows are diagnostics of an elongated conductive structure running approximately N-S in that region. On the southeastern side, a more complex pattern is observed with arrows at oblique angles between several stations. In this case, it is not possible to define the conducting feature because the reversed pattern is very close to the border of the array.

With increasing periods, the induction picture undergoes a systematic change, with the arrows on the eastern side of the array swinging to a direction roughly perpendicular to the nearest coastline and the arrows on the western side pointing to SW. The transition zone on the center of the array (encompassing mainly the São Francisco craton the Brasília belt and part of the Paraná basin) is still characterized by a very weak response. The behavior on the eastern side suggests that induction features at very long periods tend to be controlled by the currents in the deep ocean. However, systematic rotation of arrows at different periods indicates that another conducting zone is present around this area. On the other hand, the behavior on the western side suggests the presence of another important current concentration in the western South America (shallower astenosphere?).

Thin sheet modeling

The thin sheet formulation considers that the conductivity anomalies are confined to a single layer at the surface of the Earth, which overlies a 1-D layered structure. In constructing the model, it must be observed that: the thickness of the sheet should be small compared both with the skin-depth of the diffusing EM wave in the layer immediately beneath the sheet at the considered period and the skin-depth for any material included in the sheet.

In agreement with these conditions, it was assigned a thickness of 5 km for the thin sheet, which allowed to incorporate the thick strata of inland and coastal sediments (mainly the Paraná, Campos and Santos basins), as well an ocean with different depths. The choice of the underlying layered-structure was based on geoelectrical models defined by long-period MT soundings at the study region (Bologna, 2001; Pádua, 2000).

For numerical computation, the area between 12-28^{o}S and 38-58^{o}W was divided into a grid of 32 X 40 cells with a node spacing of roughly 50 km. The geological features guided the boundaries of the variable conductance whereas the assignment of conductance values to the cells relied on the information from inland MT surveys and contour maps of isopachs and geological/geophysical data for the Santos and Campos basins.

The initial model could not explain some of the salient features of the observed arrows and was changed in a trial-and-error procedure in search for a better fit. Figure 2 shows the distribution of depth-integrated conductance values, whose induction responses reproduced satisfactorily the observed induction pattern. The comparison of the model and observed real induction arrows for the period of 68 minutes is shown in Figure 3. In general, the modeled arrows provide a reasonable fit to the observed ones, with the larger misfits being observed in the arrow directions at sites located on the eastern border of the array. This misfit may be attributed to a highly conducting zone along the contact between the São Francisco craton and the Mantiqueira province. Some other stations to E-SE, as well a finer grid spacing at this region, will be necessary to bring out this anomaly.

Discussion and conclusions

The 3-D numerical model, which incorporates the ocean effect and can account for the spatial and period dependence of the observed response, presents four source regions of enhanced conductivity in and around the study region. In Figure 2, these regions are indicated by the letters A, B, C, and D.

The anomalies A and B seem well constrained by the available GDS data. 2-D modeling along profiles (not shown) and the short distance of the sites that appear affected by these structures indicate that the source of the anomalies are likely situated in the upper crust. Anomaly A coincides with a narrow gravity low interpreted by Vidotti et al. (1998) as associated with a rift basin buried beneath the sedimentary strata and flood basalts of the Paraná basin. The effects of this anomalous structure are detected by geoelectrical data with periods up to tens of minutes, an indication that it must extend down the mid-lower crust. It is probably associated with a subvertical, deep shear zone, filled by sediments in its upper part. The conductivity enhancement can be related to interconnected brines or carbon concentration, in the form of graphite, along the faulted zone.

Anomaly B is located over the ultrapotassic-alkaline magmatism of the Iporá igneous province, in southern

Goiás. Its position and spatial extent to the SE are coincident with a positive gravity anomaly (Molina et al., 2000). It can be related to mafic intrusions, modified by hydrothermalism during the volcanic activity.

Anomalies C and D have a much larger effect than the former ones and are probably associated with deep-seated sources. It must be considered that both anomalies are positioned close to the border of the array and the GDS fit is not satisfactory. More data will be necessary to improve their spatial resolution. Anomaly C is coincident with a positive geoid anomaly (Molina and Ussami, 1999). It can be generated by a temperature increase or by denser material at larger depths, probably in the upper mantle. On the other hand, anomaly D is located in a region where tholeiitic dyke swarms were emplaced approximately 55 Ma ago (Bennio et al., 2003). It is claimed that the stretched lithosphere of the area allowed generation and upward migration of different magma types, with the dyke swarm indicating a phase of extensional tectonics. The geoelectrical anomaly could thus be associated with hydrothermal material intruded into the lithosphere.

In conclusion, the array experiment has been useful in providing an overall picture of the electrical conductivity distribution in Center-Southeast Brazil. Due to limitations regarding quantitative interpretations of the GDS results, the vertical structure of the inferred anomalous zones can not be resolved by thin sheet modeling. However, the information provided by this study could be helpful in locating the transects of magnetotelluric measurements that would significantly improve the vertical resolution. Broad band magnetotelluric soundings along profiles running across the observed anomalies would be helpful in elucidating the tectonic and structural evolution of this part of the Brazilian shield.

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References

Arora, B.R, Trivedi, N.B., Vitorello, I., Padilha, A.L., Rigoti, A., and Chamalaun, F.H., 1999, Overview of geomagnetic deep soundings (GDS) as applied in the Parnaíba basin, North-Northeast Brazil: Rev. Bras. Geof., 17, 43-65.

Bennio, L., Brotzu, P., D'Antonio, M., Feraud, G., Gomes, C.B., Marzoli, A., Melluso, L., Morbidelli, L., Morra, V., Rapaille, C., and Ruberti, E., 2003, The tholeiitic dyke swarm of the Arraial do Cabo peninsula (SE Brazil): $^{39}Ar/^{40}Ar$ ages, petrogenesis, and regional significance: J. S. Am. Earth Sci., in press.

Bologna, M.S., 2001, Investigação magnetotelúrica da litosfera na província ígnea do Alto Paranaíba: Tese de Doutoramento, INPE, 172p.

Chamalaun, F.H., and Walker, R., 1982, A micro-processor-based digital fluxgate magnetometer for geomagnetic deep sounding studies: J. Geomagn. Geoelectr., 34, 491-507.

Egbert, G.D., and Booker, J.R., 1993, Imaging crustal structure in Southwestern Washington with small magnetometer arrays: J. Geophys. Res., 98, 15967-15985.

Molina, E.C. and Ussami, N., 1999, The geoid in southern Brazil and adjacent regions: new constraints on density distribution and thermal state of the lithosphere: J. Geodyn., 28, 357-374.

Molina, E.C., Ussami, N., and Marangoni, Y.R., 2000, Digital (5' x 5') gravity maps of the São Francisco craton and surrounding fold belts, margins and oceanic basins: CD-ROM with gridded data, explanatory texts and maps, IAG-USP, São Paulo.

Pádua, M.B., 2000, Estudo experimental de distorções geradas por linhas férreas eletrificadas em sondagens magnetotelúricas: Dissertação de Mestrado, INPE, 76p.

Vasseur, G., and Weidelt, P., 1977, Bimodal electromagnetic induction in non-uniform thin sheets with an application to the northern Pyrenean induction anomaly: Geophys. J.R. Astron. Soc., 51, 669-690.

Vidotti, R.M., Ebinger, C.J., and Fairhead, J.D., 1998, Gravity signature of the western Paraná Basin, Brazil, Earth Planet. Sci. Lett., 159, 117-132.

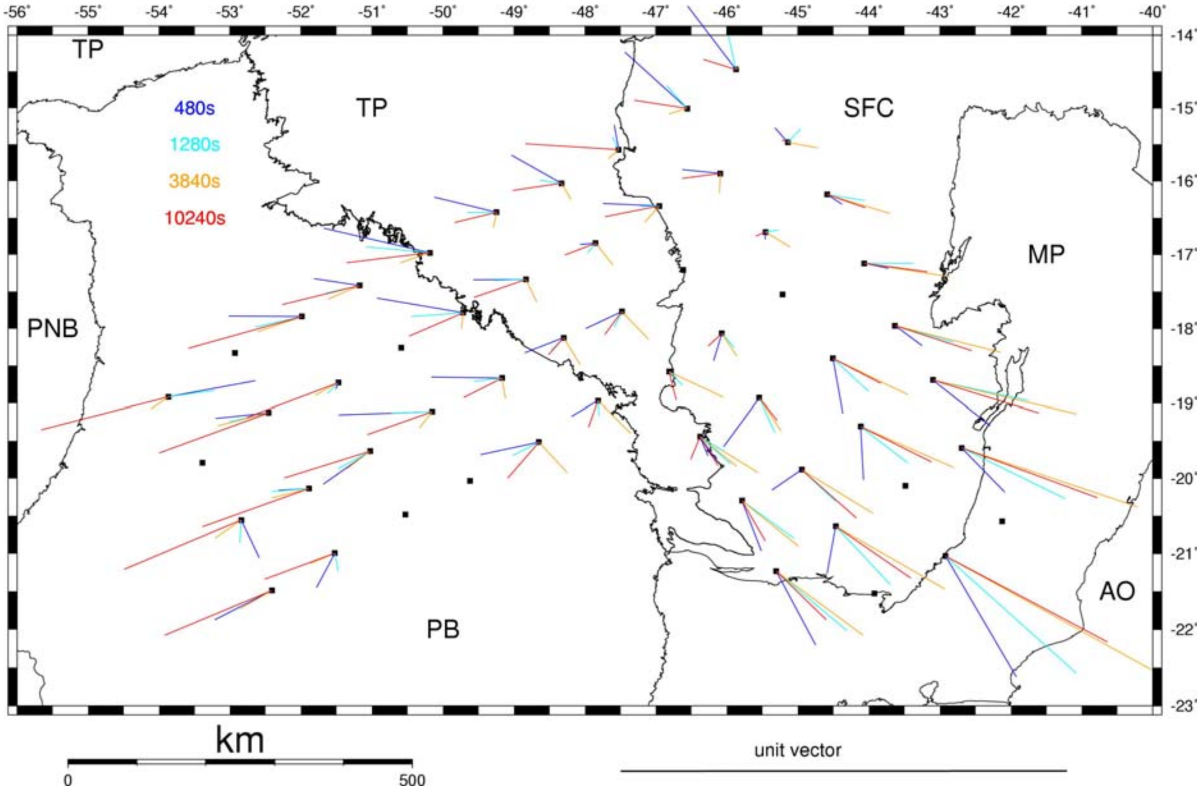

Figure 1 - Maps of real induction arrows, pointing away from the sites (black dots), obtained at the periods 480, 1280, 3840 and 10240 s. Sites with no arrows indicate poor-quality data not used in the study. For comparison, the unit length of the arrows is also shown in the figure. SFC stands for the São Francisco craton; PB, Paraná basin; PNB, Pantanal basin; TP, Tocantins province; MP, Mantiqueira province; and AO, Atlantic ocean.

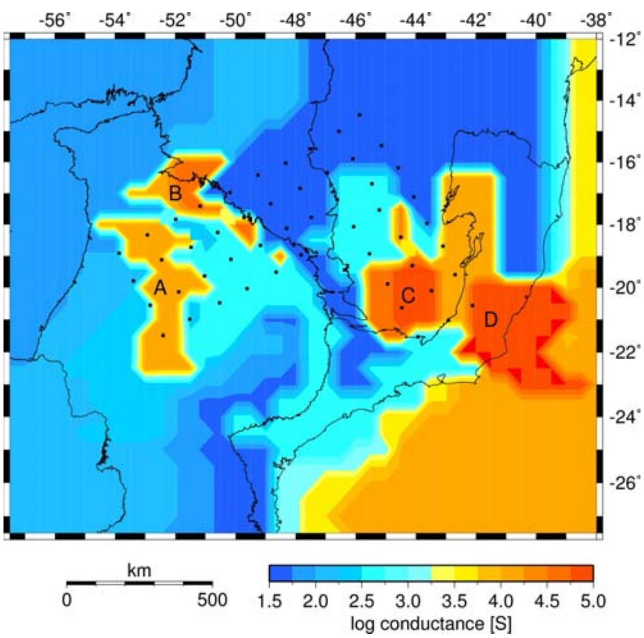

Figure 2 - The overall distribution of conductance values, in the logarithmic scale shown at bottom, obtained from the thin sheet model. The location of the stations (black dots) and the four main anomalies (capital letters) are also indicated (see text).

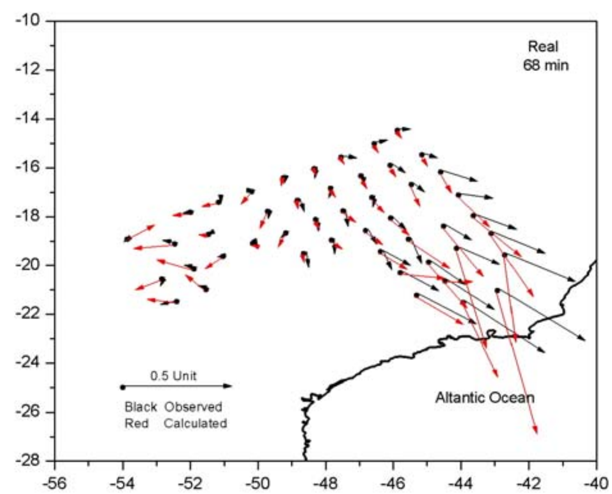

Figure 3 - Comparison of observed (black) and modeled (red) induction arrows for the period of 68 minutes. The modeled arrows are derived from the model shown in Figure 2.