Supplementary material for: "Magnetotelluric evidence of crustal conductors in Parnaíba basin, NE Brazil"

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3D MT Forward modelling – characterization of mid-crustal structures

During the analysis of MT data, induction vectors inferred the presence of lateral variations of resistivity. The vectors pointed to anomalous concentrations of conductivity and the phase tensor ellipses were effective to point 3D structures in the middle crust.

To investigate the presence of mid-crustal structures within the crust we applied the 3D forward modelling and 2D inversion routines to test possible scenarios for Parnaíba basin. These were applied in addition to the 3D inversion as presented in the main text. The forward modelling was an important step of this work. It supports the hypothesis that we are dealing with 3D conductive structures within the crustal basement of Parnaíba basin.

To perform the 3D forward modelling we applied the following procedures:

1. We created a two-dimensional basin model in a three-dimensional cube. The depth of the basin varied from 3 to 4 km. The resistivity in the sedimentary package varied from 10 to 500 Ωm and the resistivity varied only in the y and z directions;
2. Several geological structures were simulated only in the crust region. The sedimentary package remained fixed;
3. MT data were calculated for same periods of observed MT data, between 0.001-50,000 s. To produce calculated data we used the forward modelling code associated to the inversion code of Rodi & Mackie (2001);
4. Phase tensors obtained from calculated data were plotted using MTpy software developed by Krieger and Peacock (2014). They were plotted in pseudo-sections where the vertical axes represent the period, the horizontal axes represent the position of stations and the colour scale represents Φ_{min} and skew;
5. An analysis of the behaviour of the phase tensor ellipses was performed for each model. Thus we could evaluate the response of the phase tensor to the structures modelled in the crust. The most similar response to the observed phase tensor data would be an indicative of the expected general geological setting for this area.

The following subsection details each test performed according to these procedures.

Two-dimensional basin with homogeneous crust

In this test we used a simple resistivity model (Fig. 1a) as specified above. With this resistivity model, a set of MT calculated data with same characteristics of observed ones was produced. Fig. 1b shows the pseudo-section of phase tensors corresponding to the model of Fig. 1a. Observe that the Φ_{min} angle decreases as resistivity increases. The normalized skew, shown in the second panel of Fig. 1b is zero in all ellipses as expected for a two-dimensional model. Also, it is possible to observe the appearance of some distorted ellipses on the east and west edges of the basin (assigned by dashed red rectangles), indicating the boundary between the basin and the basement. In the depocentre, where this boundary is mainly 1D, the phase tensor is very circular.

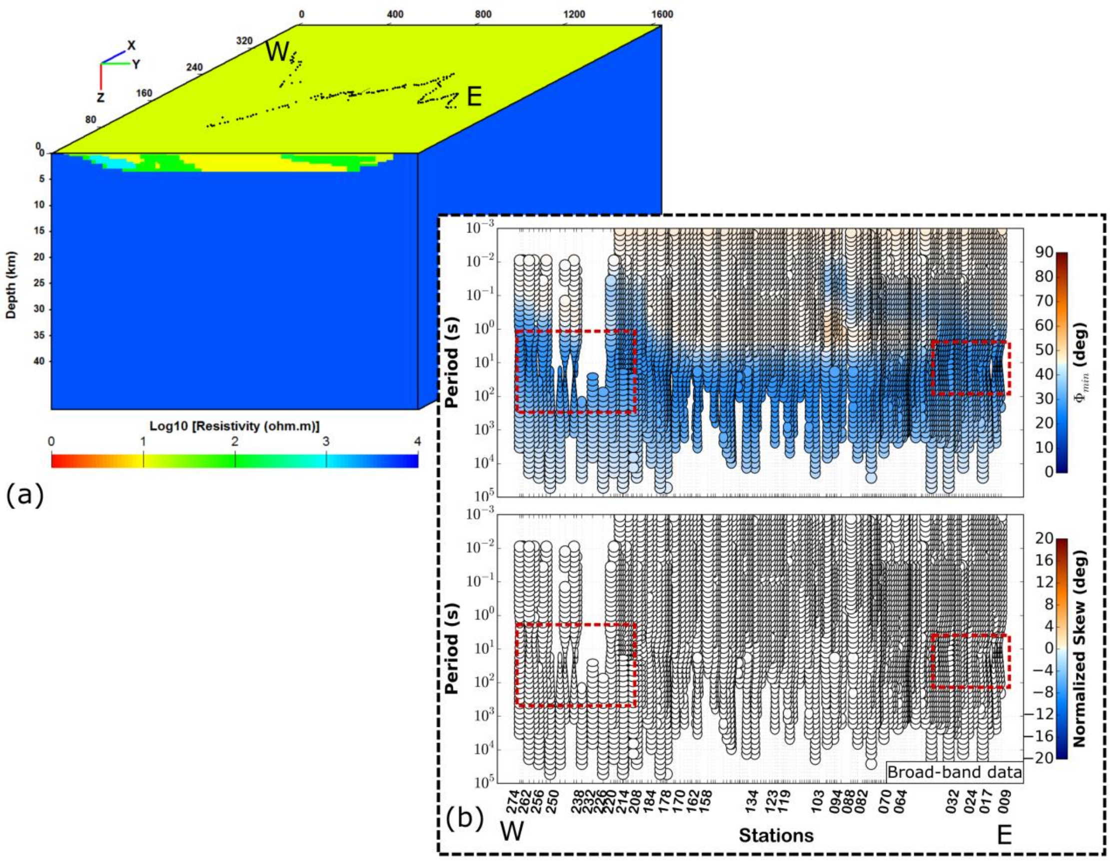

Fig.1. (a) Resistivity model used in the forward three-dimensional modelling. The model represents a simple two-dimensional basin. The black dots indicate the positions

of the calculated MT data in the model with same position and period range of observed data. (b) Pseudo-section of calculated phase tensors in functions of period and Φ_{min} (top) and skew (bottom). The red dashed rectangles highlight the distorted ellipses indicating the two-dimensional boundary between the sedimentary package and the basement.

Two-dimensional basin with heterogeneous crust

Supposing that the MCR interpreted by Daly et al. (2014) indicates the limit between upper and lower crust, this test intended to verify how the phase tensors would behave in such scenario. The limit between crusts is coincident with the position of MCR, at approximately 20 km. The upper crust was represented with a resistivity of 5,000 Ωm and the lower crust with a resistivity of 10,000 Ωm. This scenario is presented in Fig. 2a. Note that although there is a difference in resistivity between the two regions on the crust, the resistivity values remain high; above 5,000 Ωm. Fig. 2b shows the phase tensor pseudo-section corresponding to the model of Fig. 2a. It is not possible to verify large differences between the phase tensors shown in Figs. 2b and 1b, suggesting that the boundary between upper crust and lower crust would not detected by the phase tensors. The same test was done for vertical boundaries simulating different blocks in the crustal basement. This kind of structure also did not cause any effects in the phase tensor.

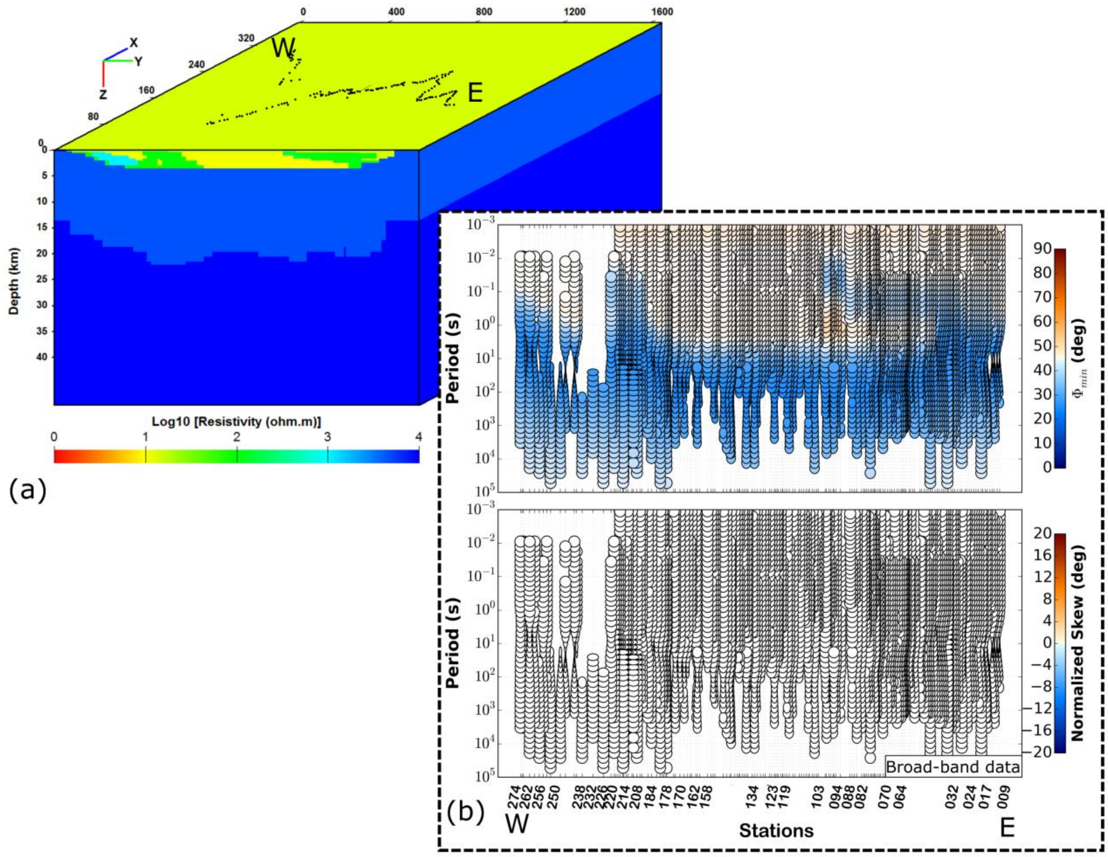

Fig.2. (a) Resistivity model used in the forward three-dimensional modelling. The model represents a heterogeneous crust underlying a two-dimensional basin. The black dots indicate the positions of the calculated MT data in the model with same position and period range of observed data. (b) Pseudo-section of calculated phase tensors in functions of period and Φ_{min} (top) and skew (bottom). It is not possible to observe any effects on the phase tensor caused by difference between lower and upper crust.

Two-dimensional basin with conductive layer in the middle crust

In this test we assumed the presence of a conductive layer of approximately 3 km thick (same as interpreted in the MCR) with depth's top of 23 km and 5 Ωm of resistivity. The model and the corresponding phase tensor pseudo-section are presented in Figs. 3a-b. Note that there are no large variations in the shape of the ellipses in the crust region, but we observe that the Φ_{min} values increase between 10 and 100s (assigned by the dashed red rectangle). This boundary characterizes the conductive layer inside the crust. In this test, it became clear that the ellipticity varies subtly inside two-dimensional layers, even with an abrupt change of resistivity. However, the Φ_{min} values change more noticeably. Also, the normalized skew remained equal to zero in all section, reflecting a 2D area.

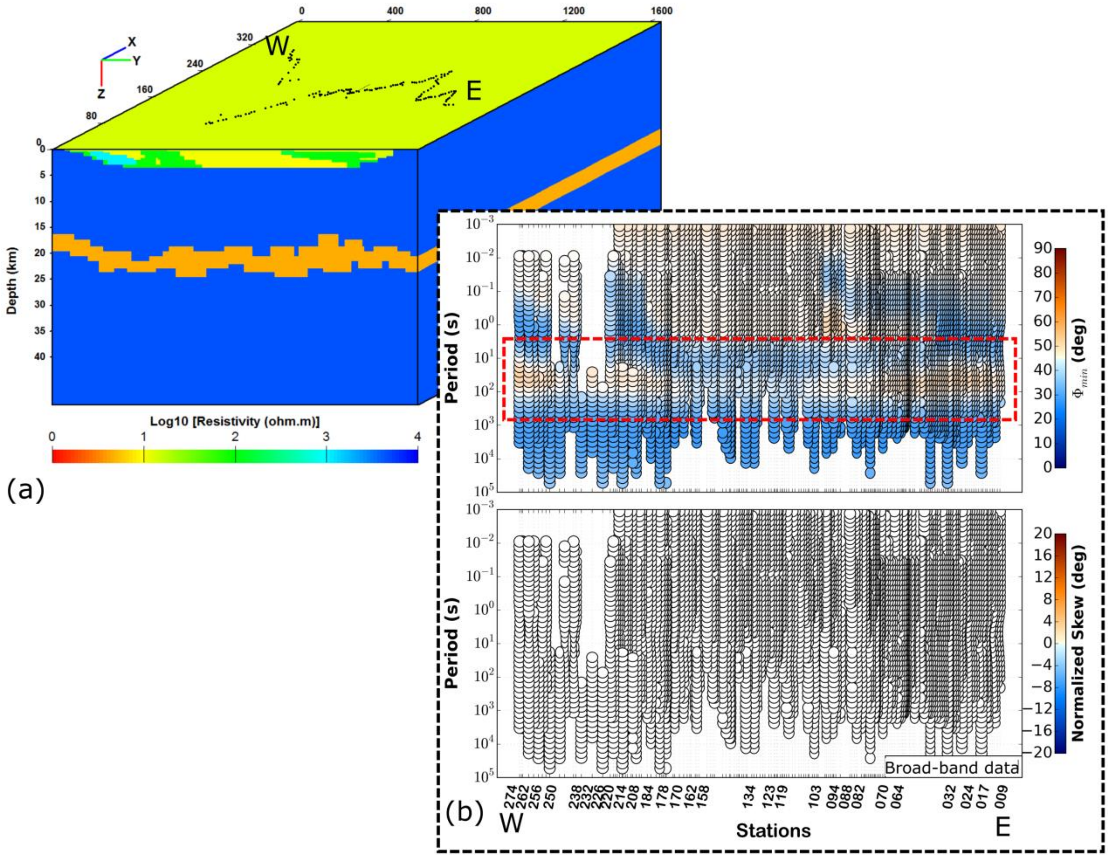

Fig.3. (a) Resistivity model used in the forward three-dimensional modelling. The model contains a conductive layer of 5 Ωm inside the mid-crust. The black dots indicate the positions of the calculated MT data in the model with same position and period

range of observed data. (b) Pseudo-section of calculated phase tensors in functions of period and Φ_{min} (top) and skew (bottom). The dashed red rectangle highlights area where d Φ_{min} is affected by the conductive layer.

Two-dimensional basin with three-dimensional conductive bodies in the mid-crust

In this test, the resistivity model contains three-dimensional conductive structures, of 5 Ωm, inside the middle crust underlying the two-dimensional basin. The conductive structures are situated in the central region of the profile simulating conductive blocks inside the crust. This structure is located at 18 km deep with a thicknesses varying from 3 to 5 km, as shown in Fig. 4.a. In this test, we observed relevant differences in the phase tensor ellipses shown in Fig. 4.b. It is possible to notice that between 10^1 and 10^3 s (red dashed rectangles), more ellipses appear distorted with normalized skew values different in from zero. These distorted ellipses and the high absolute values of normalized skews are associated with the presence of the three-dimensional conductive bodies surrounded by a resistive crustal environment.

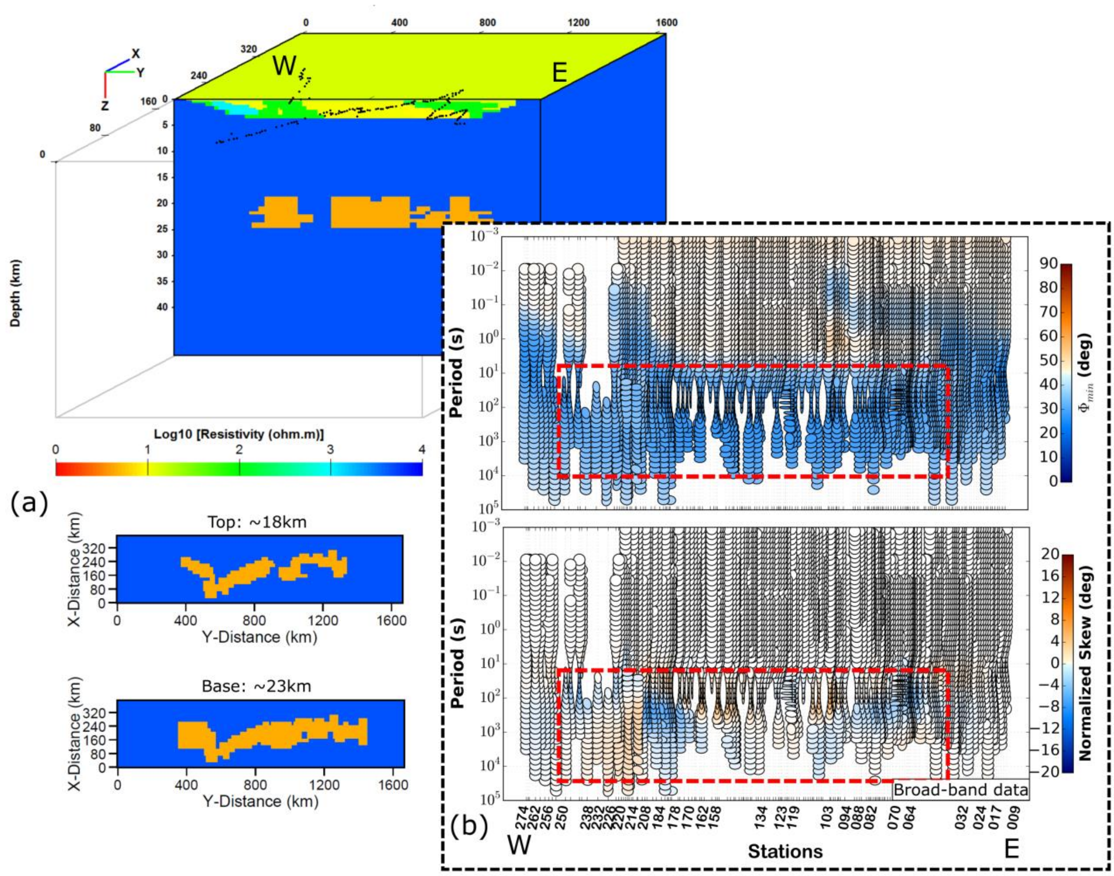

Fig.4. (a) Resistivity model used in the forward three-dimensional modelling. The model contains conductive three-dimensional structures of 5 Ωm inside the mid-crust. The black dots indicate the positions of the calculated MT data in the model with same position and period range of observed data. (b) Pseudo-section of calculated phase tensors in functions of period and Φ_{min} (top) and skew (bottom). The dashed red rectangle highlights the area where ellipticity, Φ_{min} and skew are affected by the conductive structures.

Two-dimensional basin with three-dimensional resistivity bodies

In this test, the resistivity model is similar to the previous one (Fig.4a) but here, the same three-dimensional structures are resistive instead of conductive, as shown in Fig. 5a. The resistivity of these structures is 10,000 Ωm. Fig. 5b shows the phase tensor pseudo-section of the corresponding model. In this test, it is not possible to observe relevant differences between the phase tensor ellipses shown in Figs 5b, 4b or 5b. With this test, it becomes clearer that MT data usually resolve conductors more clearly than resistors. Also, pronounced resistivity gradients between three-dimensional structures and the crust are necessary to create large phase tensor skew values.

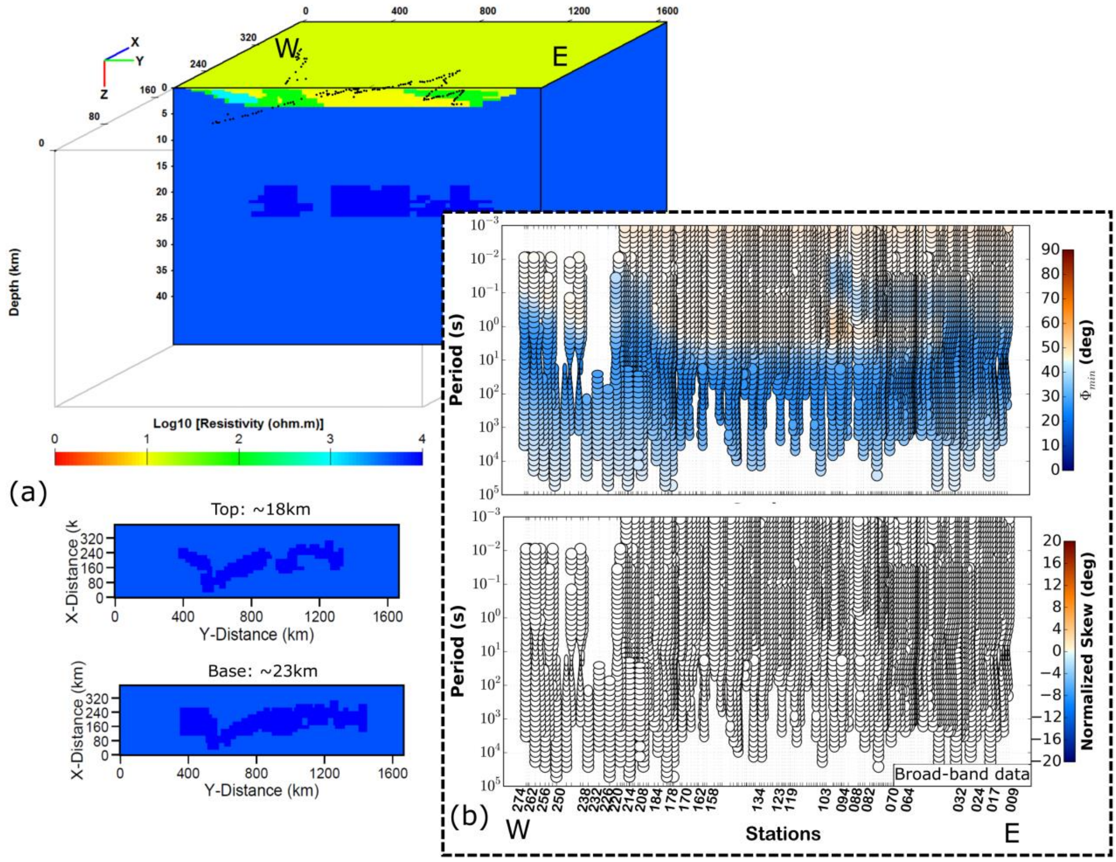

Fig.5. (a) Resistivity model used in the forward three-dimensional modelling. The model contains resistive three-dimensional structures of 10,000 Ωm inside the mid-crust. The black dots indicate the positions of the calculated MT data in the model with

same position and period range of observed data. (b) Pseudo-section of calculated phase tensors in functions of period and Φ_{min} (top) and skew (bottom). It is not possible to observe any effects on the phase tensor caused by the resistive three-dimensional structures.

The implications of interpreting 3D data with 2D inversion methods

The previous section established some criteria for interpreting the MT data. For a two-dimensional basin it is expected that the ellipses of the phase tensors align perpendicular to the more conductive structure. The Φ_{min} and skew values are associated with the conductivity and geometry of the subsurface. More conductive regions have higher Φ_{min} values. Three-dimensional structures are easily identified through phase tensors. The ellipses get quite twisted and the skew values are nonzero.

Now, what are the implications of applying 2D methodologies to interpret three-dimensional data in MT? To address this question the 2D MT inversion method proposed by Rodi and Mackie (2001) were applied in the calculated data obtained in the fourth test *("Two-dimensional basin with three-dimensional conductive bodies")* shown in Fig. 4a.

To apply the MT inversion of the calculated data (unrotated apparent resistivity and phase), the subsurface was discretized in two-dimensional rectangular cells, with a refined mesh in the shallower part and a more sparse mesh in the deep part of the model. To start the process, we used an initial homogeneous model characterized by an electrical resistivity of 100 Ωm. The error floor was set to 10 percent for the apparent resistivity and 5 per cent for the phase. The obtained estimative is shown in Fig. 6. It is possible to verify with this test that the sedimentary package of the model, characterized by the shallow low resistive region, was well imaged by the 2D inversion. However, we observed the appearance of some artefacts, especially in crustal depths, that were inconsistent with the original model (Fig.4a). The artefacts are characterized by the prolonged conductive structures that appear distributed in the crust, and some prolonged to the basin. This test showed that the two-dimensional MT inversion was inefficient in inverting three-dimensional data. It could not recover the conductive structures within the resistive crust creating large artefacts in the model that can trick the interpreter. With this, we suggest that the 2D inversion is able only to indicate the existence of three-dimensional conductive structures within a resistive region, however, without any precision.

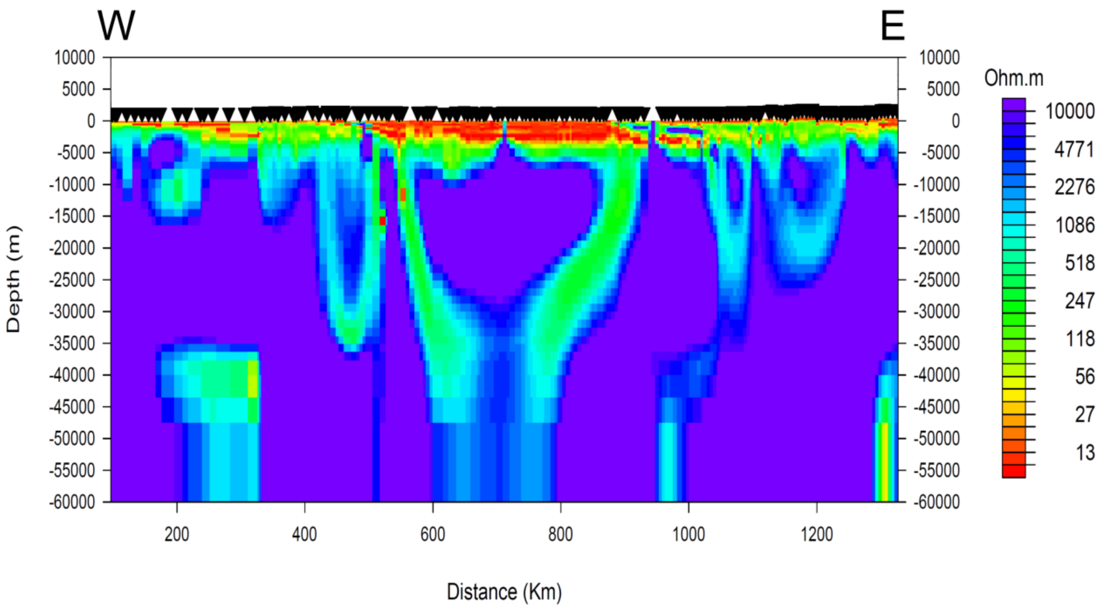

Fig.6. Forward modelling test to recover three-dimensional crustal conductive structures through two-dimensional inversion. The image show the resistivity distribution obtained through the two-dimensional inversion of the three-dimensional synthetic data produced by the model of Fig. 4a.

2D inversion of observed MT data

The 2D inversion was performed on all 176 observed Parnaiba MT stations, in the period range of 0.001-50,000 s with error floor set to 10 percent for the apparent resistivity and 5 per cent for the phase. To start the process, we used an initial homogeneous model characterized by an electrical resistivity of 100 Ωm.

The inversion model is showed in Fig. 7 and the pseudo-sections for observed and calculated data are shown in Fig. 8. The misfits, as expected, are only acceptable for short periods and for the apparent resistivity data. The nrms error is ~5.6. Thereby, the most reliable zone in this inversion model is the shallower region, which is possible to observe the boundary between sediments and basement highlighted by black dashed line. It is estimated a basement depth for this region varying between 3 and 4 km, which is compatible with seismic. However we observe clear artefacts in the inversion model, characterized by vertical conductors, which are inconsistent with the pseudo-sections of the observed data. These conductors are compatible with the artefacts that appeared in Fig. 6, caused by three-dimensional conductive structures inside a resistive environment. As suggested by the phase tensor analysis, the two-dimensional inversion also suggests the existence of three-dimensional conductive structures at mid-crustal depths of the Parnaíba profile.

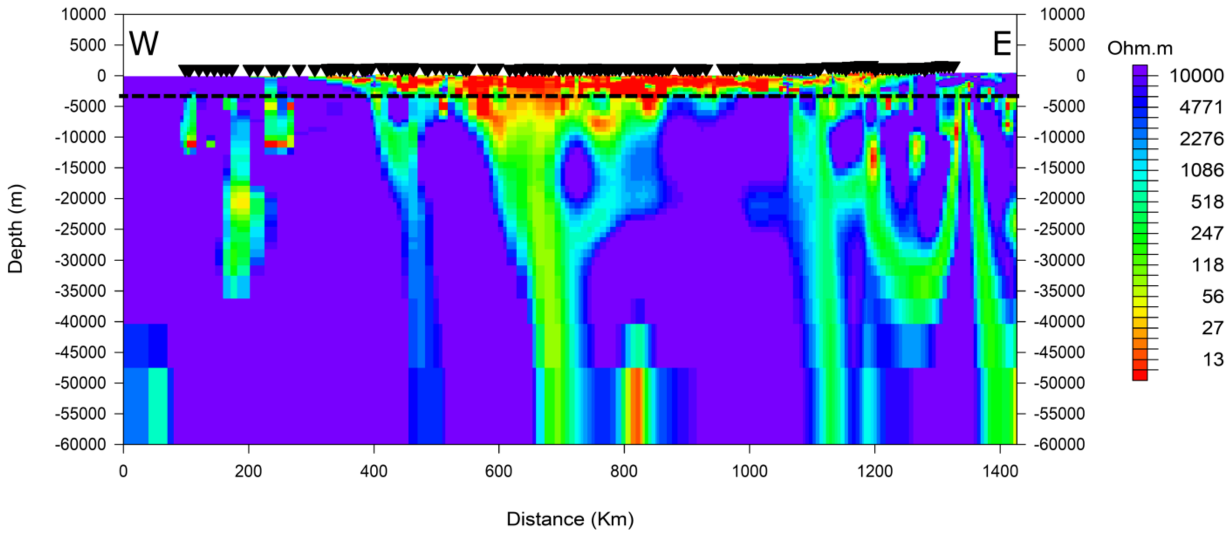

Fig.7. Resistivity distribution obtained through two-dimensional MT inversion. The black dashed line characterizes the boundary between the basement and the sedimentary package. It is possible to observe conductors in mid to lower crust.

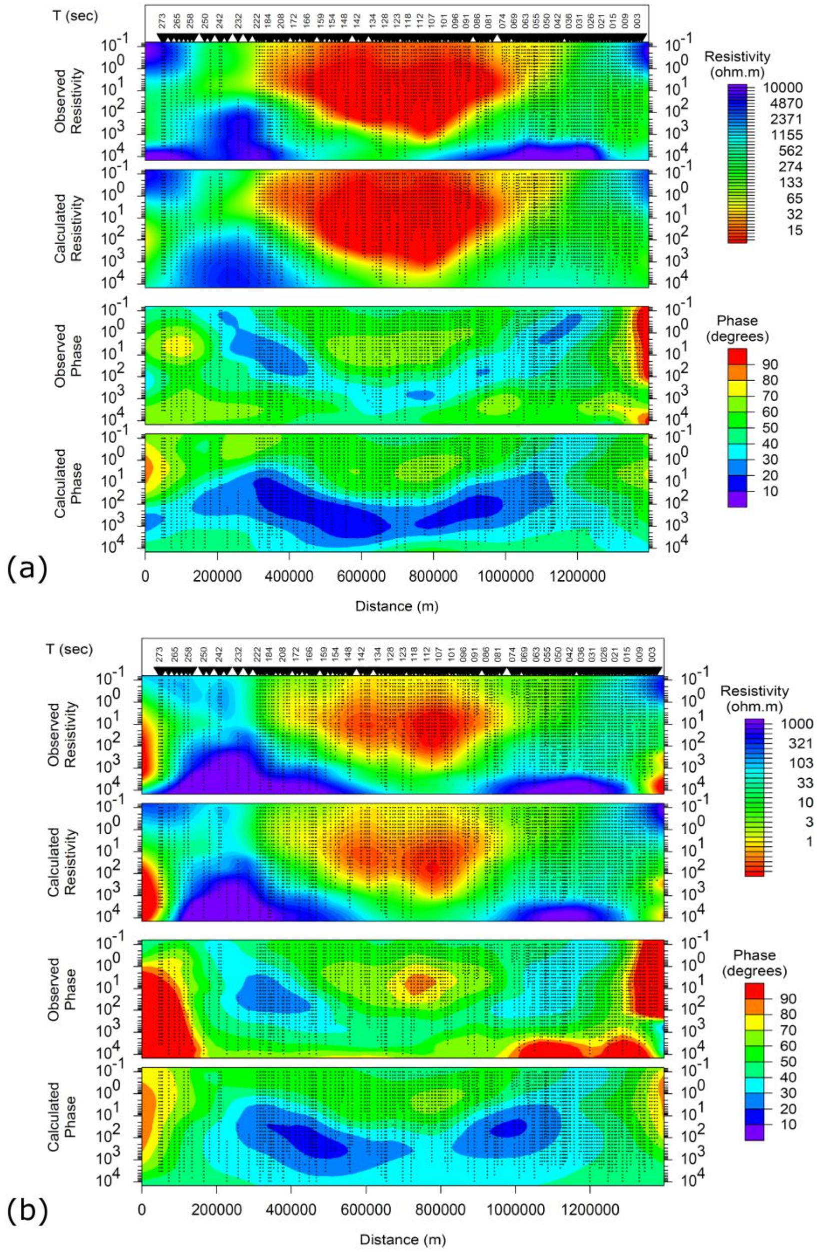

Fig.8. Set of MT data used in the inversion. The pseudo-sections illustrates: (a) TE observed apparent resistivity; TE calculated apparent resistivity; TE observed phase; TE calculated phase; (b) TM observed apparent resistivity; TM calculated apparent resistivity; TM observed phase and calculated TM phase.

References

Daly, M. C., V. Andrade, C. A. Barousse, R. Costa, K. McDowell, N. Piggott, and A. J. Poole, 2014, Brasiliano crustal structure and the tectonic setting of the Parnaíba basin of NE Brazil: Results of a deep seismic reflection profile. Tectonics, **33**, doi:10.1002/2014TC003632

Kelbert, A., N. Meqbel, G. D. Egbert and K. Tandon, 2014, ModEM: A modular system for inversion of electromagnetic geophysical data. Computers & Geosciences, v. 66, p. 40-53, doi:10.1016/j.cageo.2014.01.010

Krieger, L., Peacock, J. R. 2014, MTpy: A Python toolbox for magnetotellurics. Computers & Geosciences 72, 167–175.

Rodi, W. & Mackie, R. L., 2001. Nonlinear conjugate gradients algorithm for 2D magnetotelluric inversion. Geophysics 66, 174-187