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Numerical simulations of the current channeling effect on MT responses due to shallow conductive structures

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Abstract

MT data obtained at an alluvial valley in Argentina showed a strong telluric current channeling along its axis. This effect was reflected in the MT curves as a very low response for the TM apparent resistivity for periods longer than 1 s. The cause of this channeling remained unsolved although the existence of shallow conductive structures may be related to this effect. The purpose of this work is to analyze in detail the magnetotelluric response of this kind of structures. The main objectives are to identify the relevant geometrical and electrical features that cause the anomalous TM response and to study the sensitivity of the MT modes to characterize this kind of structures. Starting from a previous 2D TE inversion, we modified the structure in order to reproduce the behavior of the MT curves. 2D and 3D forward modeling of different shallow conductive structures were carried out and synthetic data from related structures were inverted using the 2D RRI code.

Keywords: Magnetotelluric; Current channeling; 2D forward modeling; 2D inversion

1. Introduction

One of the main applications of the magnetotelluric method is the characterization of sedimentary basins. The frequency-dependent apparent resistivity and phase are usually inverted following different methods. In the two-dimensional case, the TE and TM modes provide complementary information about the resistivity distribution in the subsurface, and the joint inversion of both modes is recommended (Berdichevsky et al., 1998). However, the presence of shallow conductive structures can produce a current channeling of the telluric currents that might result in an anomalous behavior of the apparent resistivity and the phase of a mode. In these cases, the inversion is performed with partial information using different strategies.

In this paper, a two-dimensional MT data set recorded in the region of Antinaco–Los Colorados Valley in the Province of La Rioja in the North–West part of Argentina (Fig. 1) is presented as an

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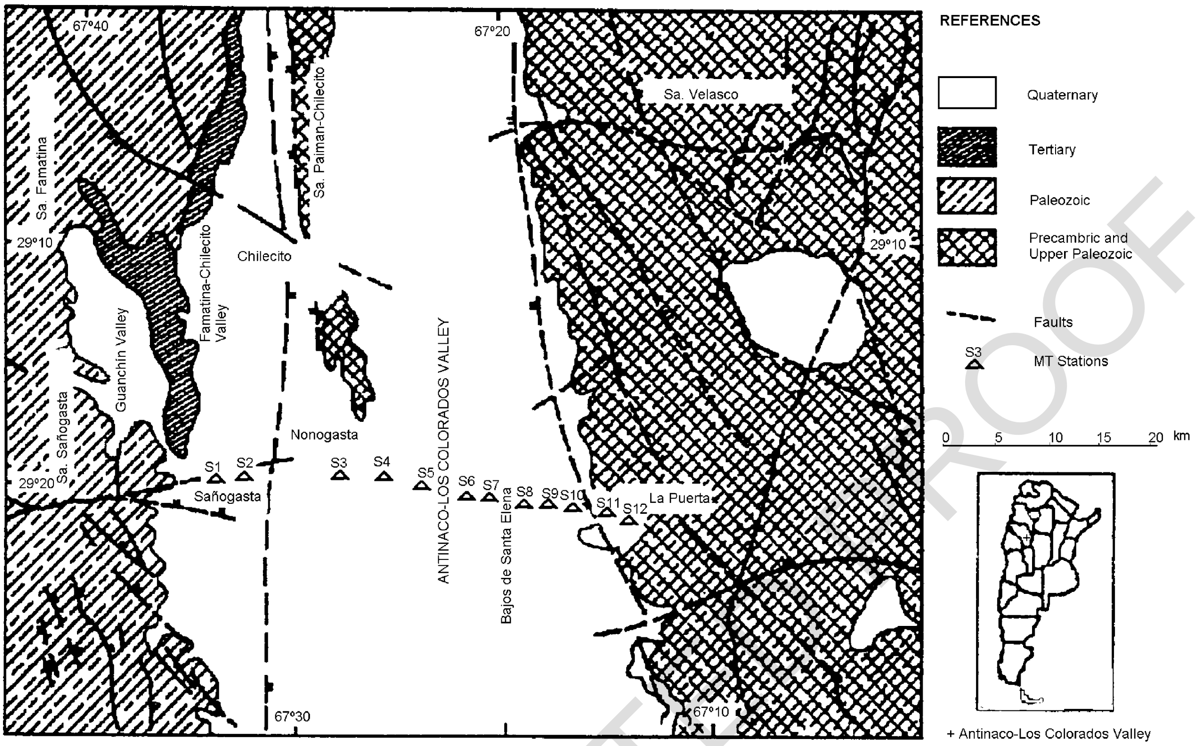


Fig. 1. Geological map of Antinaco–Los Colorados Valley.

example of this kind of data (from Pomposiello et al., 1998). The profile consists of 12 stations, and the measurements were collected in the range of periods from 0.1 to 8000 s. The most surprising aspect of these soundings was the anomalous behavior of the electric field in the East–West direction for periods longer than 1 s. Throughout six stations (S3–S8, Fig. 1), over 13 km, the electric field values measured in the E–W direction were lower in two orders of magnitude than the corresponding N–S values. Furthermore, the potential differences measured were in the resolution limit of the equipment. These facts clearly make evident the presence of a strong channeling of the telluric currents in the North–South direction, which coincides with the symmetry axis of the geological structure as well as the strike direction. The telluric field is polarized along the elongated depression filled with conductive sediments. This current channeling effect was reflected in the MT curves as a very low response of the TM apparent resistivity for periods longer than 1 s. Those values were in the order of 1 Ω m and even lower.

Different authors have studied the problem of the distortions in the magnetotelluric response due to shallow conductive structures. Particularly, the work by Berdichevsky et al. (1998) deals with the sensitivity of the TE and TM modes to detect shallow and deep structures. One result of that work indicated that the TM mode is more sensitive to the near surface structures and the TE mode may be more sensitive to the deep structures.

In the present work, we use the data from Antinaco–Los Colorados Valley as a starting point for the study of the current channeling effects caused by shallow conductive structures. In particular, we study the electrical and geometrical features a structure should have to generate the kind of electromagnetic response observed in the data. The dimensionality of the structure is analyzed; that is, if the electromagnetic response is basically due to a 2D structure or is a probable 3D effect. The main goal of this work is to identify the relative importance of the parameters that cause the low TM apparent resistivity response.

Starting from the previous 2D inversion model, we performed 2D forward modeling of related structures using the finite difference code included in the RRI (Smith and Booker, 1991). We focused our attention on the set of stations where the effect was notorious, from S3 to S8, and we studied modifications to the model in order to reproduce the behavior of the measured data.

The sensitivity of the MT data to detect and characterize this kind of structures was studied through the 2D inversion of the theoretical response corresponding to representative models that present the effect.

Finally, the response corresponding to 3D structures was analyzed, in order to look for a similar behavior in the MT curves. The calculations were performed using the PW3D code (Wannamaker et al., 1984; Wannamaker,1991). The 2D interpretation of the 3D responses along different profiles was carried out.

2. Previous results from the 2D inversion

In this section, we review the main results of the 2D inversion of the field data (Pomposiello et al., 1998).

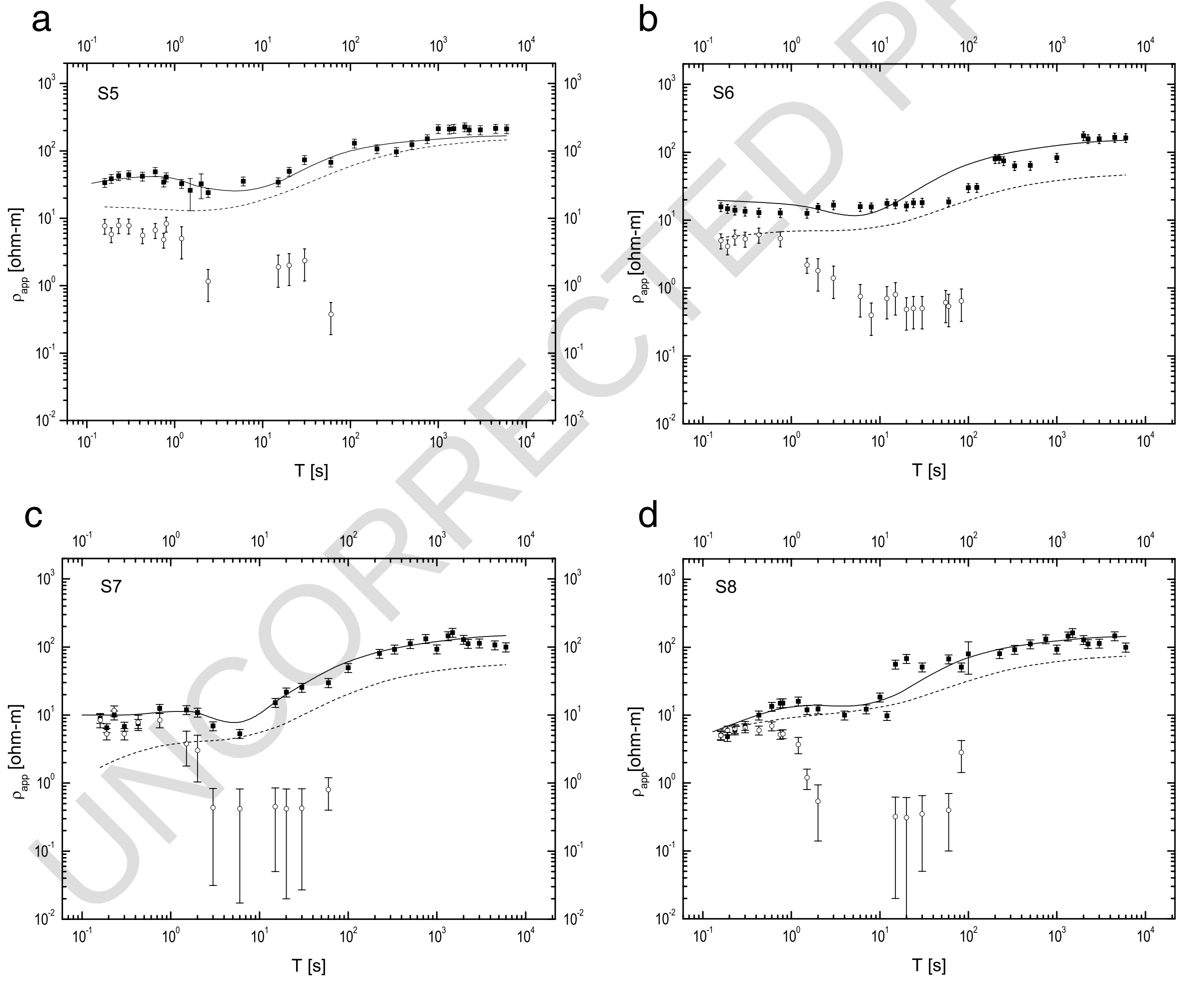


Fig. 2. TE (■) and TM (○) apparent resistivity data corresponding to station S5(a), S6(b), S7(c) and S8(d). The theoretical response of the model shown in Fig. 3 is displayed for the TE (—) and TM (- - -) modes.

As stated previously, we restrict our study to the stations located within the anomalous zone, which includes stations S3 to S8 (Fig. 1). As an example of the anomalous behavior observed throughout these stations, Fig. 2 shows the apparent resistivity data corresponding to stations S5–S8 for the TE and TM modes. The data corresponding to the TM mode for periods longer than 100 s present large distortions due to the current channeling effect, and it is omitted.

The inversion is performed using only the TE component because the TM mode is strongly affected by the current channeling. Furthermore, any attempt to include the TM data resulted in serious problems of convergence. The result is shown in Fig. 3. This inversion model allowed characterizing a sedimentary basin of 6-km thickness over a resistive basement. It revealed the presence of a shallow structure that consists of two conductive blocks (5–10 Ω m) separated by a higher-resistivity medium. The shallow conductive zones may be related to the high salinity areas corresponding to the Bajos de Santa Elena region (Fig. 1).

The fittings corresponding to stations S5–S8 are also shown in Fig. 2. The apparent resistivity inversion for the TE mode presents a normalized misfit of 1.35 and the fittings agree reasonable well with the field data. However, it is important to point out that the model obtained did not reproduce the TM apparent resistivity anomalous low response and the physical parameters which could produce this kind of effect remained at that stage not clear and requiered further investigation.

3. 2D analysis

In this section, we focus on the study of the geometrical and electrical features that should have a 2D structure to generate the current channeling effect observed in the data. We propose different 2D structures and calculate the electromagnetic response at the surface using the finite difference method code included in the RRI (Smith and Booker, 1991). The following parameters are studied: depth and thickness of the conductive structure, resistivity contrast with the medium and lateral extension of the conductive blocks.

Fig. 4a shows the first model. It consists of two 5 Ω m blocks (width: 5 km; thickness: 2 km; depth: 200 m) embedded in a 100 Ω m half-space. We calculated the electromagnetic response at sites O and P for different values of the distance between the blocks: $d = 6$, 4, 2 and 0 km (Fig. 4b).

The analysis of the TM apparent resistivity response (Fig. 5) clearly demonstrates that this mode has a high lateral sensitivity to detect this kind of 2D conductive structure. On site P, above the conductive block, the TM apparent resistivity curve was decreasing for all the d values considered, reaching values of the order and even less than 1 Ω m. It is important to

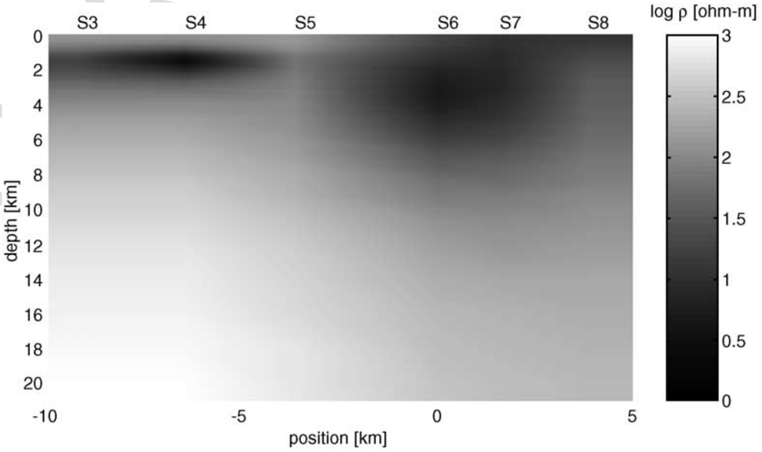


Fig. 3. 2D resistivity model.

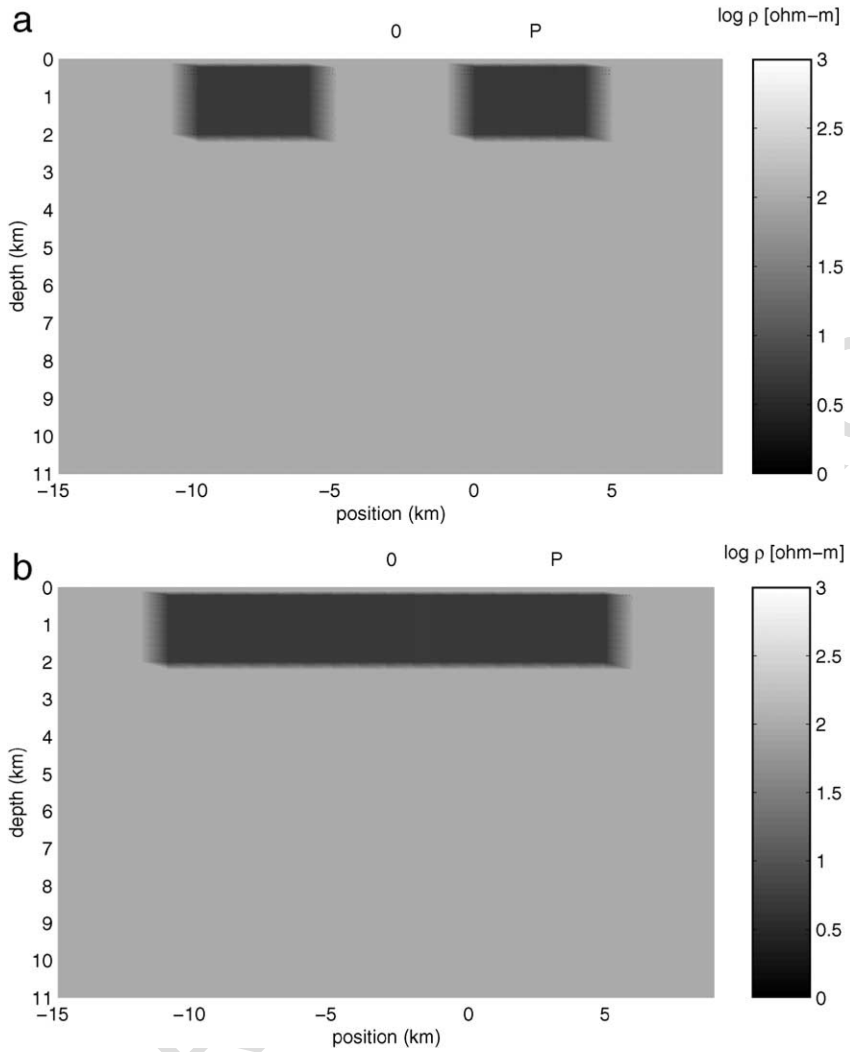


Fig. 4. Theoretical 2D models. The parameter d indicates the distance between the conductive bodies. (a) $d=6$ km.; (b) $d=0$ km.

note that when the width of the blocks increases the decreasing behavior diminishes.

The results obtained at point O allow us to conclude that if there is not a conductive body below the station, the TM apparent resistivity does not present the distortion associated with a current channeling. This conclusion is evident from the analysis of the TM apparent resistivity pseudosections (Fig. 6). In the data measured, the current channeling effect was observed in six consecutive stations along 13 km. Taking into account the results of the 2D models discussed above, it is feasible to consider a extended conductive structure for the following calculations.

The next step was the study of the depth dependence of the conductive structure. From the previous model (Fig. 4b), different depths were considered: 200, 400, 800, 1600 and 3200 m and the theoretical response calculated at points O and P. From the TM apparent resistivity results (Fig. 7), we can conclude that the conductive block must be clearly shallow. Besides, there is a gap between the model corresponding to 200 m and the others. This model was

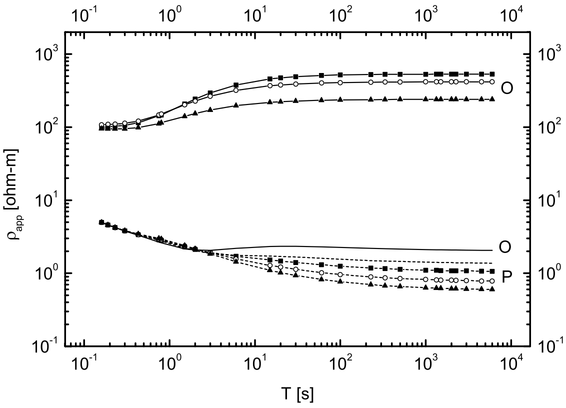


Fig. 5. TM apparent resistivity responses at points O (—) and P (- - -) for Fig. 4 models. ▲, $d=6$ km; ○, $d=4$ km; ■, $d=2$ km; No symbol, $d=0$ km.

the only one that showed TM apparent resistivity values in the order of 1–2 Ω m for periods longer than 1 s. Even the 400 m model showed a remarkable higher behavior, reaching values in the range of 5 Ω m in this range of periods. This result was observed at points O and P.

In order to verify the feasibility of the geoelectrical features of the model proposed, it was very important to analyze the TE apparent resistivity curves because in the data, the TE mode did not show a rugged decreasing behavior (Fig. 2). Fig. 8 shows the results. It is possible to observe that the TE apparent resistivity minimum value is approximately 5 Ω m at 1–3 s period; however, it then recovers and finally reaches 100 Ω m at longer periods (1000 s).

The TM apparent resistivity thickness dependence for model 4b at point P is showed in Fig. 9. It is interesting to note that for 0.5 and 1 km structure thickness the TM apparent resistivity shows a slowly decreasing shape, but then it is possible to observe a little recovery. For 2 and 4 km structure thickness, the decreasing behavior is more notorious and is observed even in the longest periods. The TM apparent resistivity curve is satisfactory for these thicknesses for the resistivity contrast between the conductive body (5 Ω m) and the medium (100 Ω m). We chose 2-km thickness for the calculations involved in the study of the resistivity contrast.

Fig. 10 represents the TE and TM apparent resistivity response for different resistivity medium values: 25 and 50 Ω m and the previous one (100 Ω m). The analysis of the results indicates that the TM apparent resistivity decreasing behavior was observed in all cases, but it is more important when the resistivity contrast is higher. Also, the TE apparent resistivity response was similar in all cases, showing a slow decreasing behavior at shorter periods (until 2 s), but then recovering and reaching the resistivity medium value at longer periods.

Previous geoelectrical surveys in the Valley (Osella et al, 1999) indicated the presence of aquifers with high concentration of salts in the area. In order to study the influence of this kind of structure, we decided to model a 500-m thickness block of 1 Ω m. The model is shown in Fig. 11a. The corresponding MT curves are displayed in Fig. 12a and b, and we can conclude that the effect is still important.

The last 2D models studied consists of two 1 Ω m blocks of 500-m thickness separated 4 km (Fig. 11b). The electromagnetic response is shown in Fig.12c and d and presents the same characteristics as previously calculated for the two 5 Ω m blocks. The same arguments for the TM apparent resistivity lateral sensitivity are applied to this case.

Finally, we can summarize the 2D results remarking that a shallow model with the following parameters: resistivity, 1–5 Ω m; depth, 200 m; thickness, 0.5–2 km; and lateral extension of 15 km in a 100 Ω m host media presents the kind of electromagnetic response that can be associated with a current channeling.

It is not possible to assert that the 2D model proposed corresponds to the geological structure in Antinaco–Los Colorados Valley, but it is clear that a very shallow 2D conductive structure generates the type of distortion registered in the zone. Besides, the fact that the model was obtained through modifications to the TE apparent resistivity inversion model and is consistent with previous geophysical studies indicates that it is highly possible the presence of a structure with very similar characteristics in Antinaco–Los Colorados Valley.

4. 2D inversion of synthetic data

The usual procedure to analyze 2D MT data prioritizes the inversion of the TM mode (e.g., Wu et al., 1993). However, for the cases studied in this work, it is important to point out that in an actual situation a TM apparent resistivity low response might result in large errors for the TM data. In this section, we concentrate on the inversion of the synthetic data corresponding to the models displayed in Fig. 11 in order to analyze the sensitivity of each TE and TM modes to characterize the structures. Inversions of the TE data, TM data and both modes are carried out in order to compare the results and to discuss the applicability and accuracy of each one.

The inversions were performed using the RRI code (Smith and Booker, 1991). A relative error floor of 0.5 was considered for TM data and 0.1 for TE apparent resistivity and 0.15 for TE phase. Large uncertainties in the TM mode were considered in order to reproduce the high errors presented in the data. This is a consequence of the strong channeling of the telluric currents and the fact that the electric field measured might be in the limit of resolution of the equipment. Goals for the misfit of 1.1 were required at each theoretical station and an initial 100 Ω m half-space model was used.

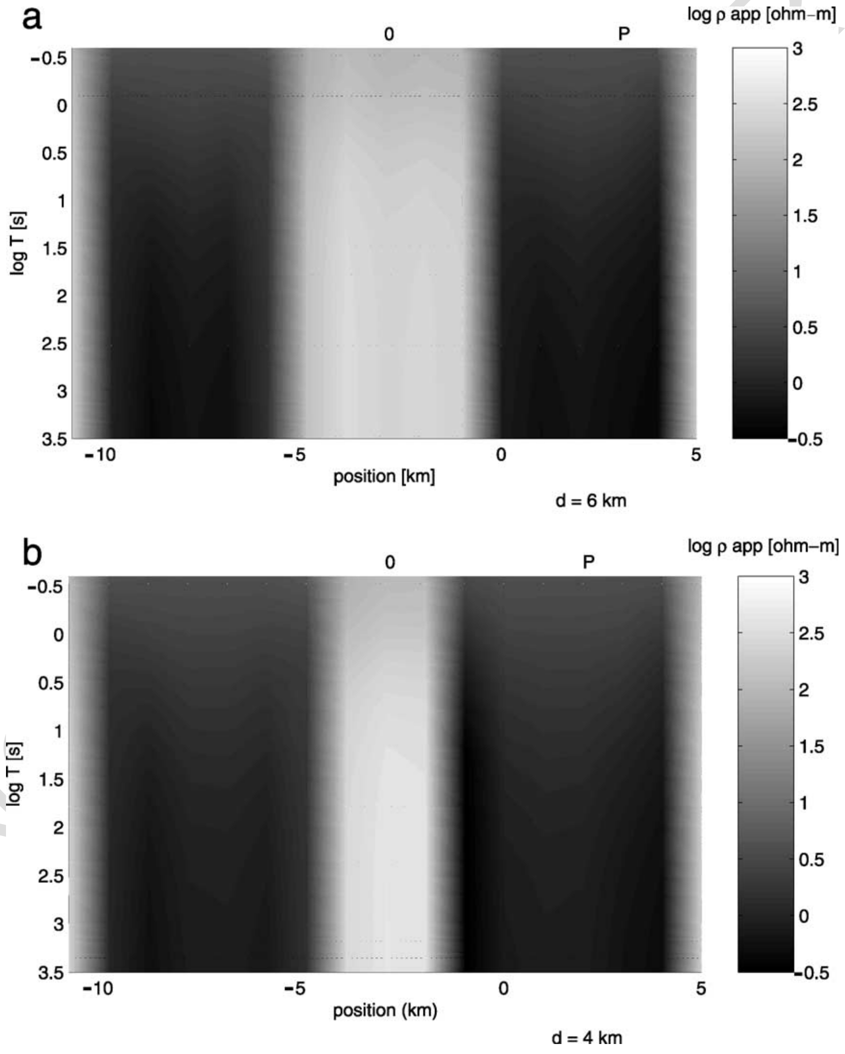


Fig. 6. TM apparent resistivity pseudosections corresponding to Fig. 4 models.

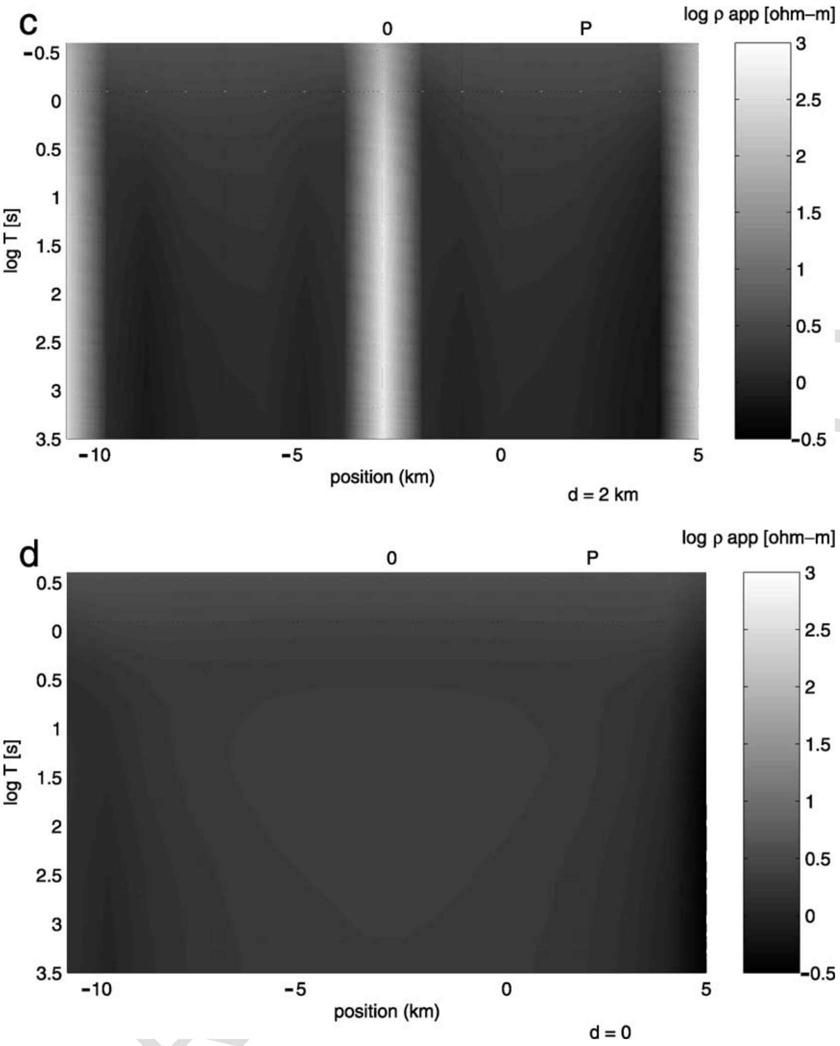


Fig. 6 (*continued*).

The results are displayed in Fig. 13. All the inversions converged to acceptable mean squared misfit, with values close to 1.1.

Fig. 13 reveals that the TE mode presents a higher accuracy in the imaging of the thickness than the corresponding TM mode inversion. However, in the case of the two conductive blocks, the TM inversion, despite the large errors involved, shows a better resolution of the width of the bodies. The joint TE and TM inversion allows characterizing very well the model corresponding to Fig. 11a (Fig. 13c), but fails in the imaging of the two conductive bodies presenting a conductive zone between the two blocks (Fig. 13f).

5. 3D forward modeling

The purpose of this section is to analyze the variation of the electromagnetic results calculated in the 2D forward modeling section when considering an elongated 3D body instead of the 2D

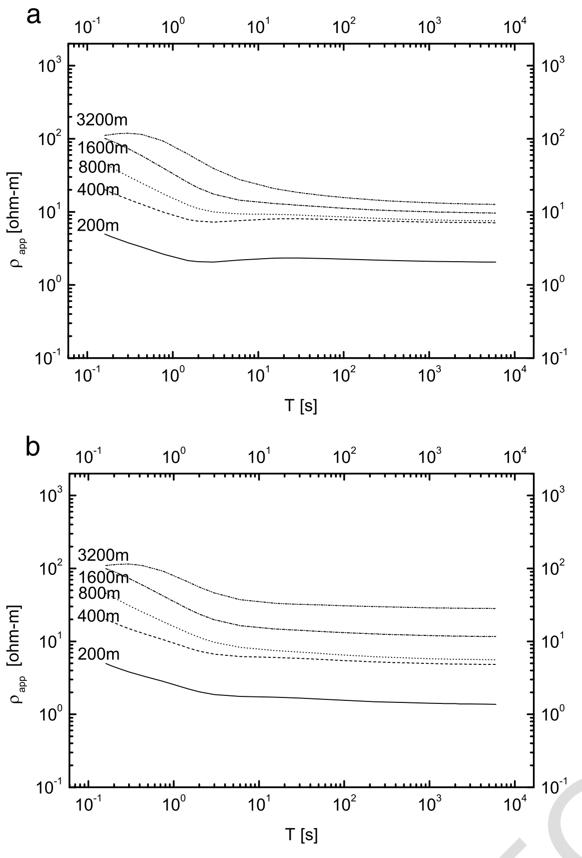


Fig. 7. TM apparent resistivity for different depths of the buried conductive structure at points O (a) and P (b).

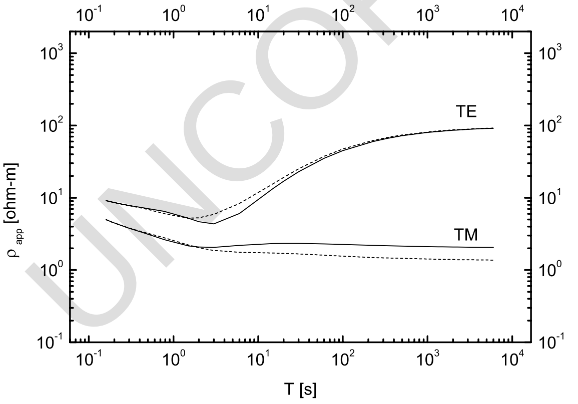


Fig. 8. TE and TM apparent resistivity response for Fig. 4b model at point O (—) and P (- - -).

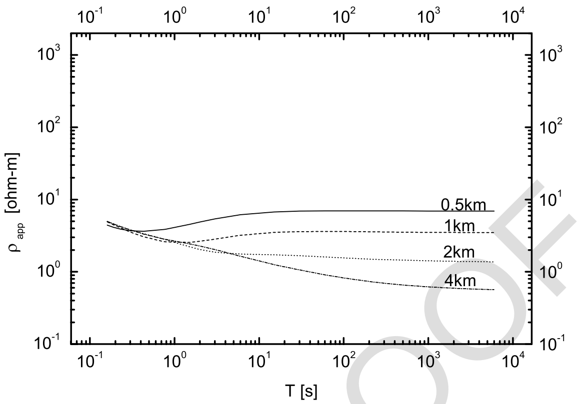


Fig. 9. TM apparent resistivity response at point P for different thickness of the conductive block.

models previously studied. The main goal was to determine if 3D effects could be responsible for the anomalous behavior of the TM apparent resistivity, or if it is basically caused by a 2D structure. In order to compare the results, a similar 3D structure was modeled. The model is shown in Fig. 14 and consists of a conductive body (resistivity: 0.5 Ω m; thickness: 500 m; depth: 200 m.) embedded in a 100 Ω m half-space. The lengths of the body are 32 km in the x̂ direction and 16 km in the ŷ direction.

The calculations were realized with the PW3D code (Wannamaker, 1991) and different profiles were

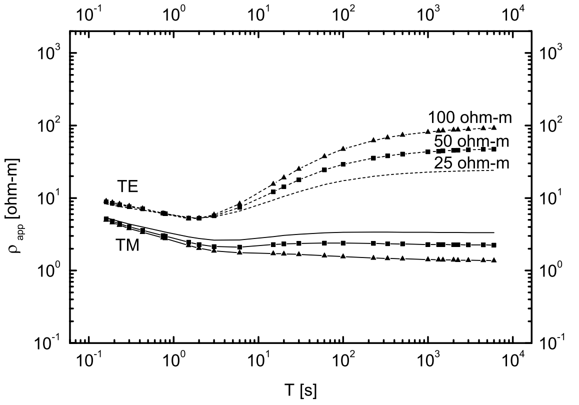


Fig. 10. TM (—) and TE (- - -) apparent resistivity at point P for different half-space resistivity. ▲, $\rho = 100$ Ω m; ■, $\rho = 50$ Ω m; No symbol, $\rho = 25$ Ω m

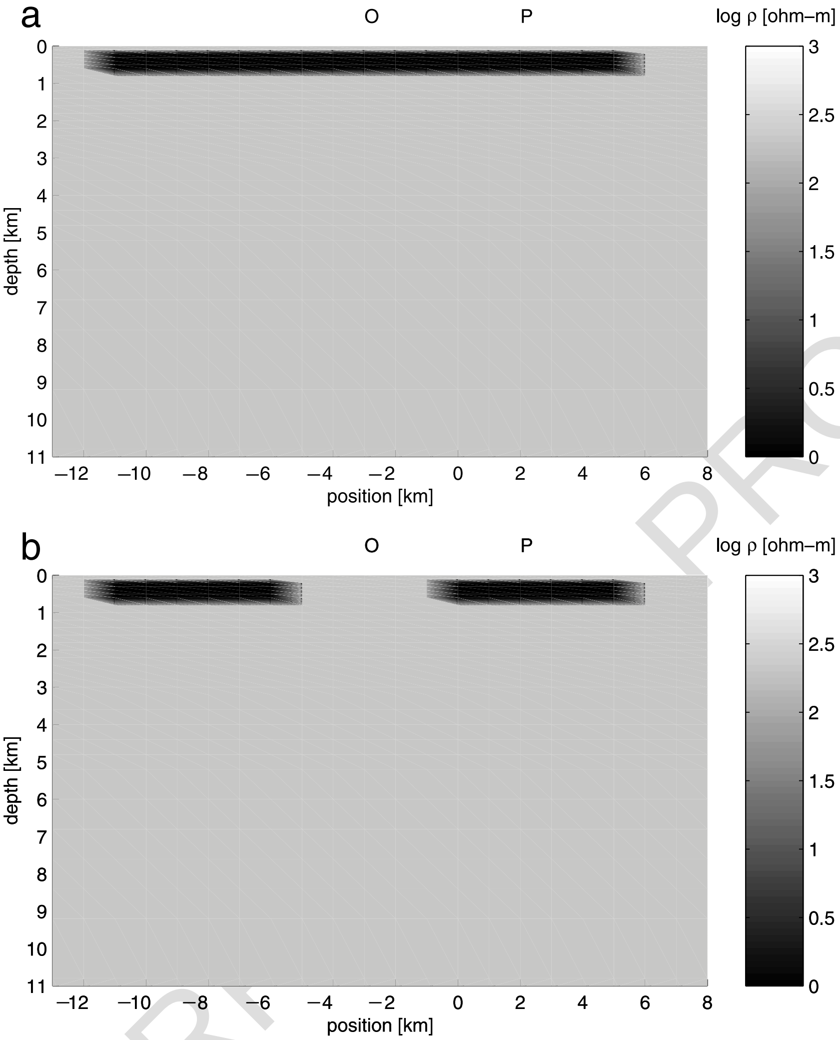


Fig. 11. Two-dimensional synthetic models.

obtained in each case: centered and parallel to the smallest axis (profile 1, Fig. 14), parallel to the smallest axis close to the edge of the body (profile 2) and, finally, centered and parallel to the largest axis (profile 3).

The apparent resistivity results are summarized in Fig. 15 where the corresponding 2D interpretation of the 3D electromagnetic data at relevant points is shown in order to compare the results from the 3D modeling with the previous 2D modeling.

The analysis of the first profile indicates that the corresponding TE apparent resistivity curves have a similar behavior to the 2D model, but the apparent resistivity values do not reach the electrical resistivity of the half-space. However, the TM apparent resistivity response is quite different from the 2D case.

From Fig. 15b and c, it can be concluded that the decreasing TM apparent resistivity behavior was not reproduced at any point. Note that in the case of Fig. 15c, the 2D profile 3 (Fig. 14) is parallel to the *x*-axis. Then in a 2D interpretation, the strike would be in the *y* direction. Then the TM mode would be associated to the component *Zxy* because the profile is rotated 90°, but the axes do not.

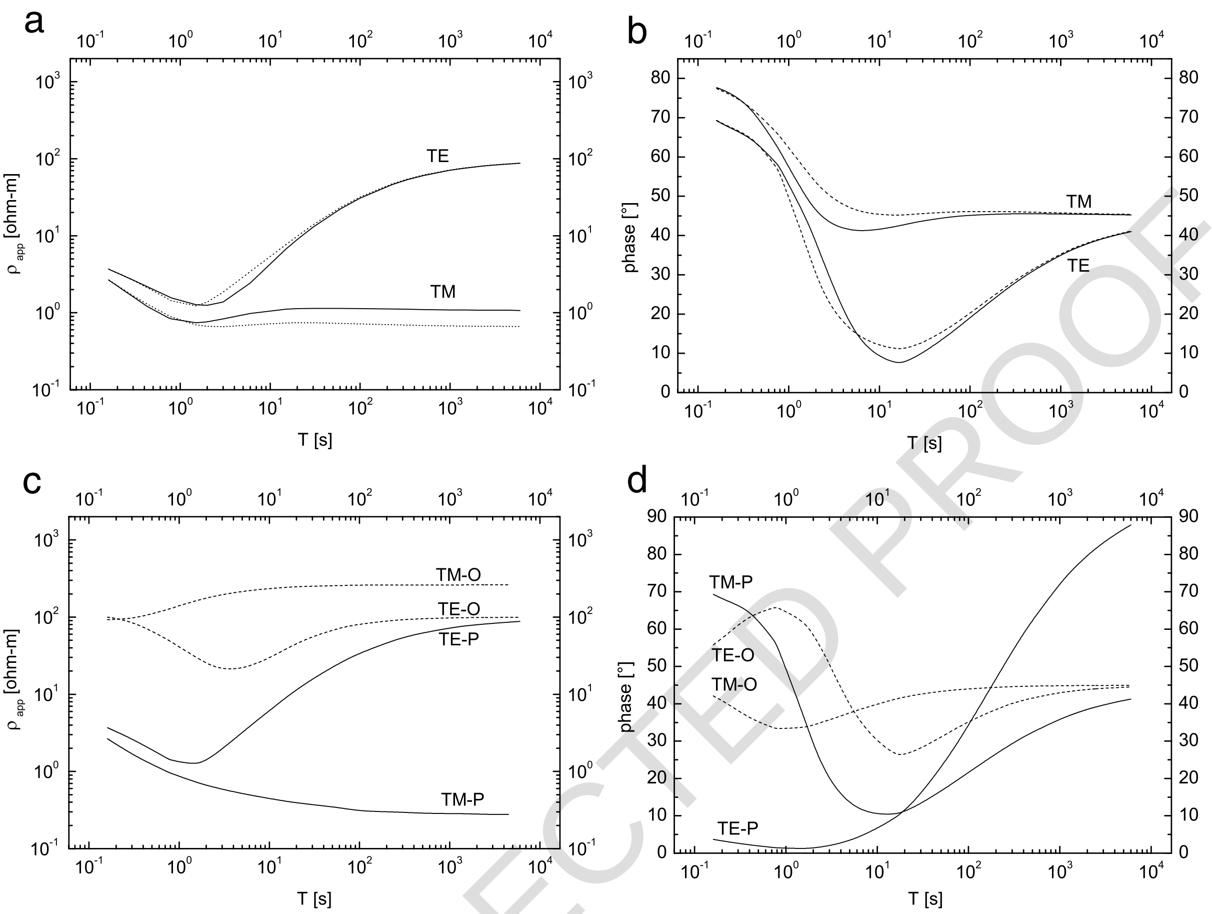


Fig. 12. Magnetotelluric response in models corresponding to Fig. 11 at points O (—) and P (- - -). The results for Fig. 11a model are shown in (a) and (b) and the results for Fig. 11b model in (c) and (d).

In summary, we can conclude that the 3D effects studied in this work are not the cause of the anomalous behavior of the TM mode.

6. Conclusions

In this paper, we have characterized the structures that can produce current channeling effects as strong as the one detected at Antinaco–Los Colorados Valley. This kind of effects produce anomalously low response in one of the components of the MT impedance tensor, not allowing performing the usual tensorial analysis. Then different strategy should be addressed in order to determine the features of the anomalies.

Within this frame, we performed 2D and 3D forward modeling calculations to look for structures which produced this kind of anomalous behavior as a means to identify it in actual data, and we studied the approximations that can be obtained by applying inversion codes to synthetic data. We used the data from Antinaco–Los Colorados Valley as an example where this kind of anomaly was detected.

From the analysis of the forward modeling calculations, it can be concluded that the current channeling effect detected in Antinaco–Los Colorados Valley is due to a 2D structure. It was demonstrated that the MT apparent resistivity response for both modes corresponding to a shallow conductive structure (1–5 Ω m), embedded in a more resistive half-space (100 Ω m), presents the same character-

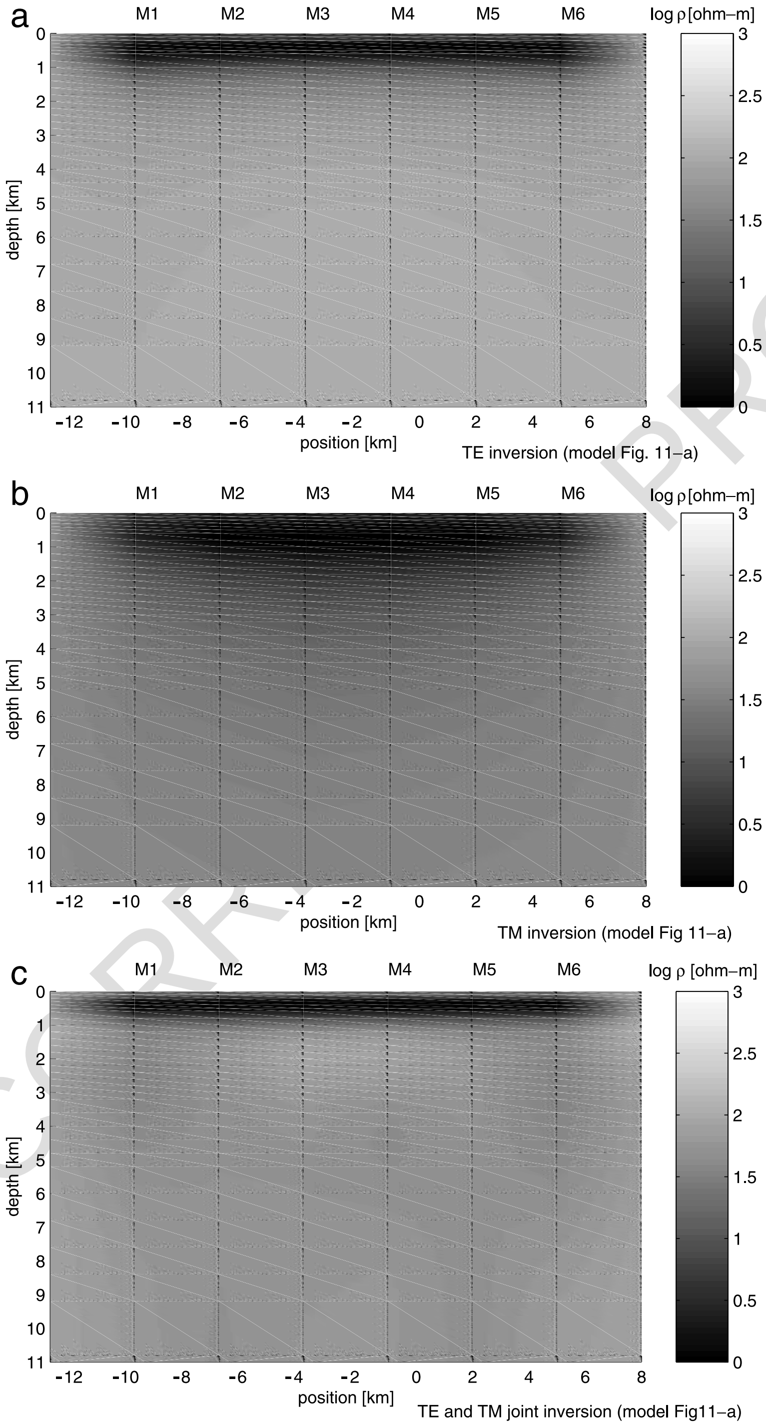
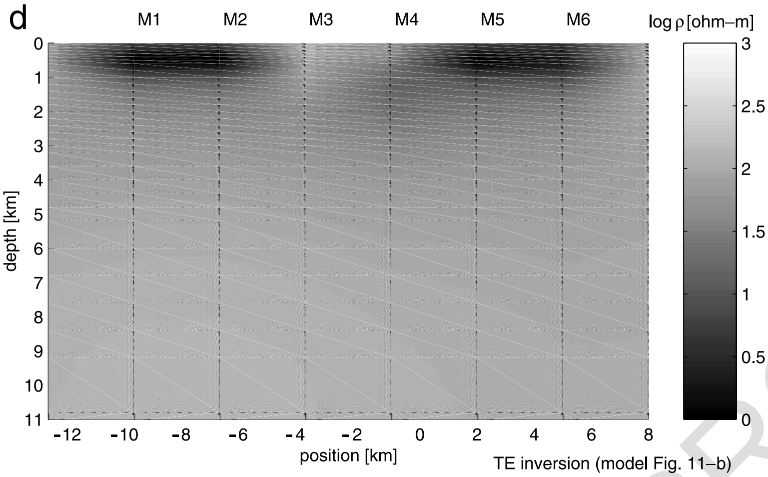
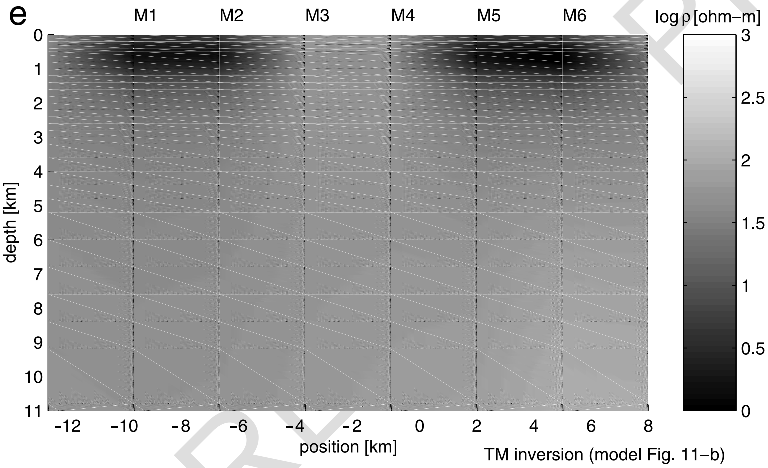


Fig. 13. 2D inversion of synthetic data corresponding to Fig. 11 models.





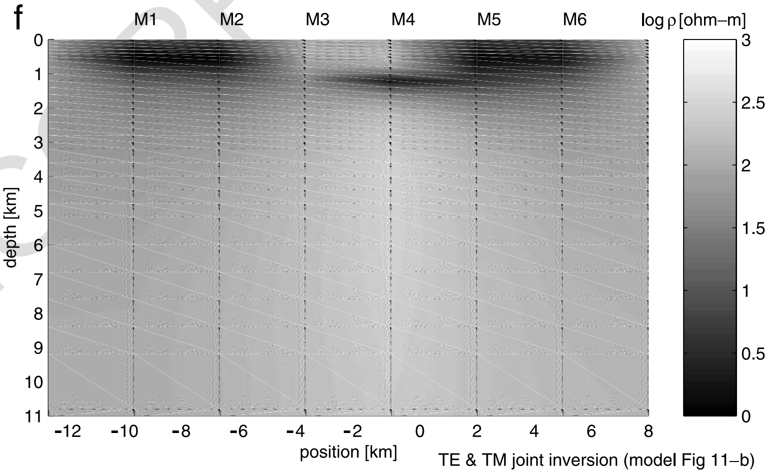


Fig. 13 (*continued*).

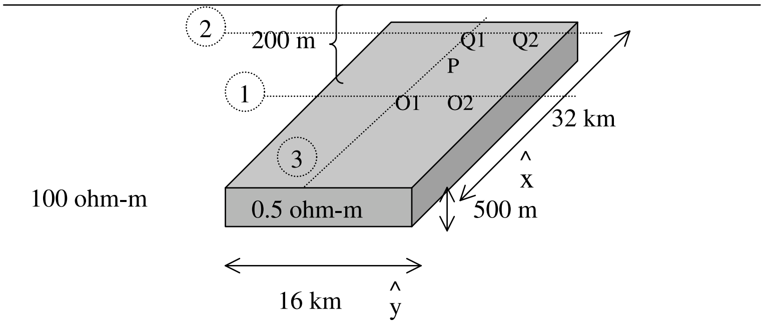


Fig. 14. 3D model. The coordinates of the points indicated in the figure are: O1=(0,0) km, O2=(6,0) km, P=(0,12) km, Q1=(0,14) km and Q2=(6,14) km.

istics that the data measured. The lateral extension of the structure must be as extended as the length of the profile where the effect is detected. This is a consequence of the high lateral TM sensibility. The structure depth turned out to be the most important parameter. Satisfactory results were obtained at depth of 200 m, and it is important to emphasize that the effect clearly diminishes when considering

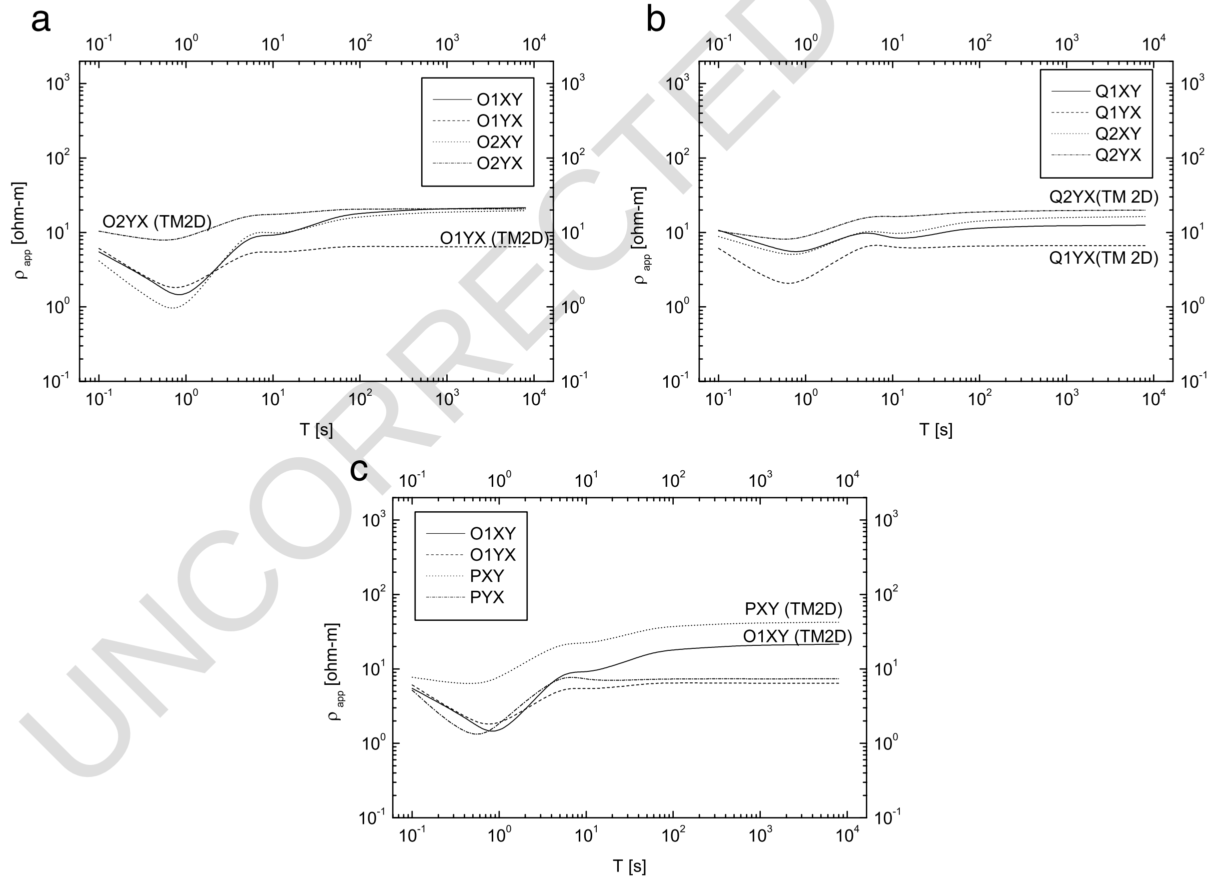


Fig. 15. Apparent resistivity curves in 3D model corresponding to Fig. 14, profile 1 (a), profile 2 (b) and profile 3 (c)

larger depths. The 2D inversion of synthetic data demonstrated that the TE inversions present a better resolution of the structure thickness and that the TM mode allows characterizing the width of the conductive structure with higher accuracy.

Acknowledgements

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References

Berdichevsky, M.N., Dmitriev, V.I., Pozdnjakova, E.E., 1998. On two-dimensional interpretation of magnetotelluric soundings. Geophys. J. Int. 133, 585–606.

Osella, A., Favetto, A., Martinelli, P., Cernadas, D., 1999. Electrical imaging of an alluvial aquifer at the Antinaco–Los Colorados tectonic Valley in Sierras Pampeanas, Argentina. J. App. Geophys. 41, 359–368.

Pomposiello, C., Osella, A., Favetto, A., Sainato, C., Martinelli, P., Aprea, C., 1998. Current channeling and three-dimensional effects detected from magnetotelluric data from a sedimentary basin in Sierras Pampeanas, Argentina. Geophys. J. Int. 135, 339–351.

Smith, J.T., Booker, J.R., 1991. Rapid inversion of two- and three-dimensional magnetotelluric data. J. Geophys. Res. 96, 3905–3922.

Wannamaker, P.E., 1991. Advances in three-dimensional magnetotelluric modeling. Geophys. J. R. Astron. Soc. 11, 1716–1728.

Wannamaker, P.E., Hohmann, G.W., Ward, S.H., 1984. Magnetotelluric responses of three-dimensional bodies in layered earth. Geophysics 49, 1517–1533.

Wu, N., Booker, J.R., Smith, J.T., 1993. Rapid two-dimensional inversion of COPROD2 data. J. Geomag. Geolectr. 45, 1073–1087.