On the Resolution of the Darai Limestones by Two-Dimensional MT Forward Modeling

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The PNG data have been analysed to determine the presence of the lower Darai limestones. As a first step, Groom and Bailey decomposition method was applied, which indicated that the electrical structure was approximately two-dimensional and striking N120°. Accordingly, two-dimensional forward modeling of the rotated data was performed. The final model showed the resistivity distribution with alternating resistive Darai limestones and conductive Ieru stratigraphic units. In particular, the model exhibited the resistive lower Darai limestones along the whole profile, which was the question posed at the MT-DIW2. A sensitivity test was performed to ensure the presence of the lower Darai limestones was resolvable.

1. Introduction

The PNG data set, provided by Chevron Niugini Pty. Ltd. to the participants at the MT-DIW2, consists of 10 magnetotelluric sites from Papua, New Guinea and a geological cross-section as additional information. The MT data were recorded over a section of Darai limestones, below which there are conductive sediments. This structure consists of an imbricated system of SW-directed thrusts in such a manner that the anticipated sequence, from top to bottom, is as follows: Darai limestones, Ieru sediments, Darai limestones, Ieru sediments, and basement. As the Darai limestones were expected to be of higher resistivity than the conductive Ieru sediments, the magnetotelluric method was proposed as a good geophysical technique to resolve such a subsurface structure. However, previous inversions of these MT data yielded a thickness of the Darai limestones which was always thinner than that expected from geological data. In particular, it was thought that the lower Darai limestones were not detected by the MT data. The resolving power of MT data to detect the presence of the lower Darai was the question posed at the MT-DIW2. In this paper, we present our interpretation of the PNG data, which is summarized in a two-dimensional resistivity model along the profile. As evidenced by the model, our answer to the question posed at the MT-DIW2 is that MT data can detect the presence of the resistive lower Darai limestone.

2. MT Data Analysis

The MT sites were aligned along a 6 km NE-SW profile. The measurement axes for the horizontal components were NS and EW. The period range of acquisition was from 384 Hz to approximately 1800 s. Prior to interpretation, an analysis of the data was undertaken in order to determine the dimensionality of the underlying regional electrical structure. The Groom and Bailey decomposition method (Groom and Bailey, 1989) was applied following the scheme of Groom *et al.* (1993). The impedance tensor was rotated every 5° from 0° to 90°. A regional strike of N120° gave the minimum chi-squared error of misfit, and the minimum variation of the twist and shear angles versus the period, this behaviour failing only at short periods. Accordingly, the electrical structure was considered to be two-dimensional striking N120° (from the geology

the 90° ambiguity was eliminated). Furthermore, the geomagnetic transfer functions showed a behaviour from which a two-dimensional structure could also be roughly inferred. Thus, modeling was carried out from the impedance tensor components rotated 30°. Scattering in the apparent resistivities caused by static shift distortion was less than a decade. A correction for static shifts was made by fixing the depth of the basement, which was provided as additional data.

3. Two-Dimensional Modeling

The behaviour of the apparent resistivities and phases is similar at all the sites. The minimum at 60 s in both polarizations of the apparent resistivity curves is associated with the bottom of the thick lower Ieru conductive unit, below which there is basement. At periods longer than 1 s, there is a divergence between the two polarizations. The apparent resistivity curves are not parallel. Also, the phases diverge in such a manner that the minimum of the *B*-polarization apparent resistivity is, in general, lower than the one in the *E*-polarization. This suggests a lateral increase in resistivity at depth. For periods longer than 60 s, the apparent resistivity curves are again parallel, and the phases coincide. The model we constructed was obtained by trial-and-error fitting of the apparent resistivities and phases using the finite element algorithm of Wannamaker *et al.* (1987). A one-dimensional inversion of the *E*-polarization data from each site was undertaken, using Fischer and Le Quang's (1981) program, to provide an initial model. After several attempts, we obtained the final model shown in Fig. 1.

The model delineates five distinct units which correlate with the geological sequence. Below the surficial resistive blocks, associated with the upper Darai limestones, there is a dipping conductive zone, which corresponds to the upper Ieru unit, attaining a depth of 2 km under site 122. The resistivity contrast between the upper boundary of this dipping conductor and the upper resistive unit is the reason for the marked divergence between both polarizations. As a consequence, the minimum (at 60 s) for the *B*-polarization apparent resistivity is lower than that for the *E*-polarization curve. Between the upper Ieru conductive unit and the lower Ieru unit there is a resistive zone (500 Ω·m) which should correspond to the lower Darai limestones. The lower Ieru unit has an uniform resistivity of 2.5 Ω·m and is floored by the basement with a resistivity of 200 Ω·m.

Figure 2 shows the data and model responses for six regularly spaced sites along the profile. The RMS misfit has been calculated for all the sites and for periods ranging from 0.1 s to 100 s. The RMS misfit between the decimal logarithm of the data and model responses of the apparent resistivities is 0.056 for the *E*-polarization responses, and 0.086 for the *B*-polarization ones. The RMS phase misfit is 6.7 ° for the *E*-polarization phases and 9.7° for the B-polarization ones. These misfits show that the data are reasonably well-described by the model. The most significant disagreement occurs in the phases around 1 s (Fig. 2), where there seems to be a contradiction between phases and apparent resistivities, especially for the *E*-polarization responses. It should be pointed out that, in this particular model, one-dimensional modeling under every site fits the *E*-polarization data, whereas the *B*-polarization data are the most sensitive to two-dimensional structures. Moreover, the model fits well the inflection appearing in the *E*-polarization apparent resistivity curve between 1 s and 10 s, which is caused by the lower Darai limestones.

In order to see the influence of the lower Darai limestone, the responses from an alternative model, without this unit from site 106 to the NNE, have been calculated. This alternative model is in agreement with previous MT interpretations provided to the participants of the MT-DIW2. Considering all the sites and periods between 0.1 s and 100 s, the RMS misfit between the data and model responses of the apparent resistivities is 0.091 for *E*-polarization and 0.091 for *B*-polarization. The RMS phase misfit is 5.1° for *E*-polarization and 9.2° for *B*-polarization. This model not only gives a higher misfit for the apparent resistivities, but it does not display the inflection, between 1 s and 10 s, in the *E*-polarization seen in the observed data. Figure 3 shows
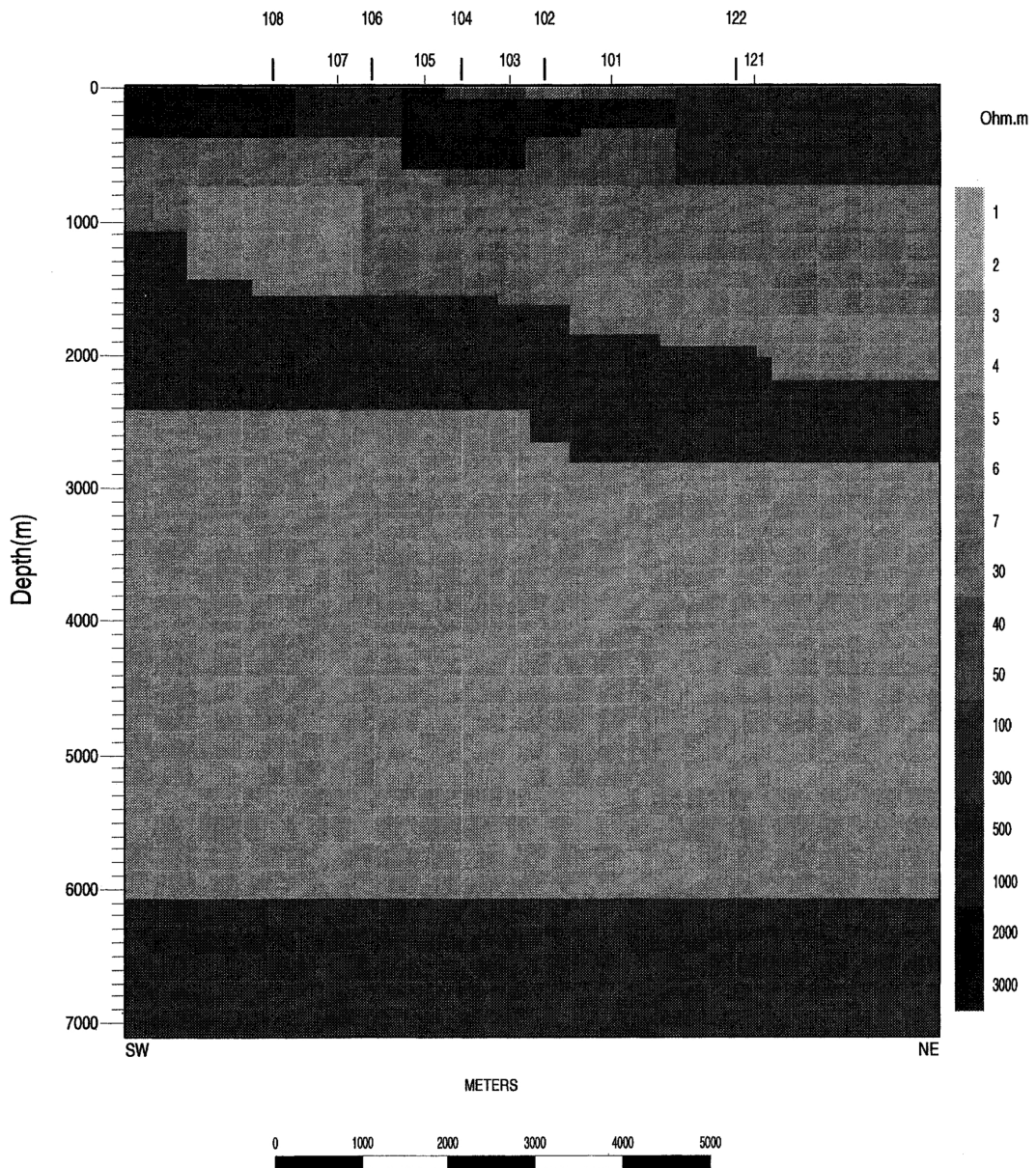
Fig. 1.   Two-dimensional resistivity model of PNG data.

the E-polarization response of this alternative model for site 104, which is representative of the misfit behaviour at all the sites.

Given the aforementioned contradiction between the apparent resistivities and phases, there is no two-dimensional model that fits both simultaneously. Nor do one-dimensional inversions of the E-polarization responses fit simultaneously the apparent resistivities and phases. The Hilbert transform relation between the apparent resistivities and phases (Kaufman and Keller, 1981) appears not to be fulfilled in the period band between 1 s and 10 s, which could indicate
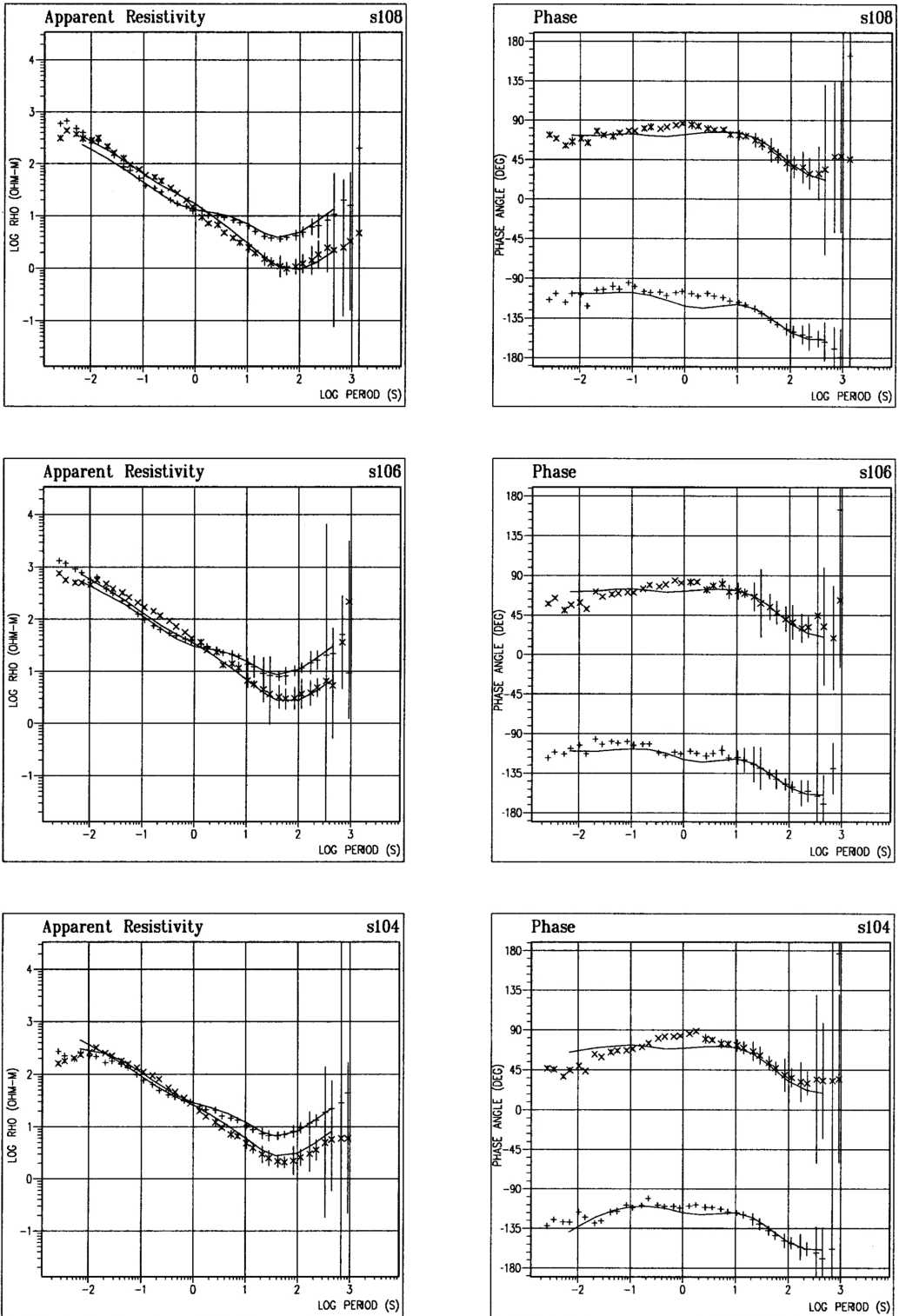
Fig. 2. Data and model reponses (solid lines) of six representative sites from the two-dimensional model of Fig. 1. Plus: *E*-polarization, cross: *B*-polarization.
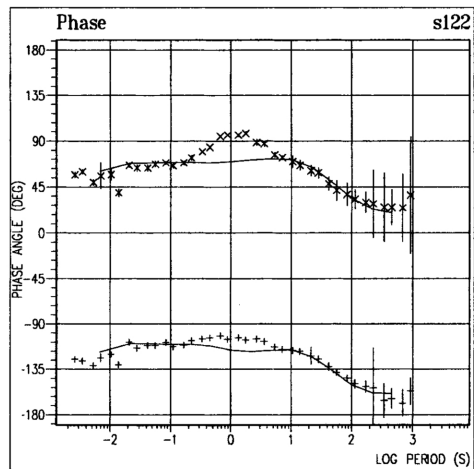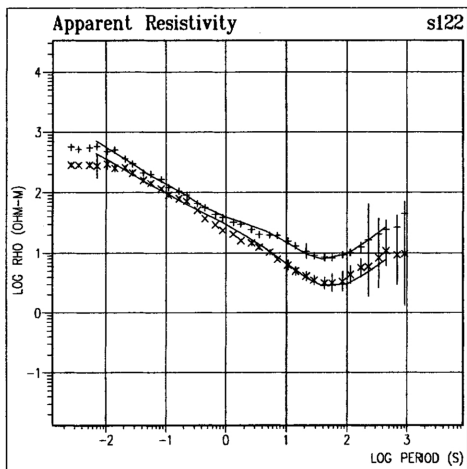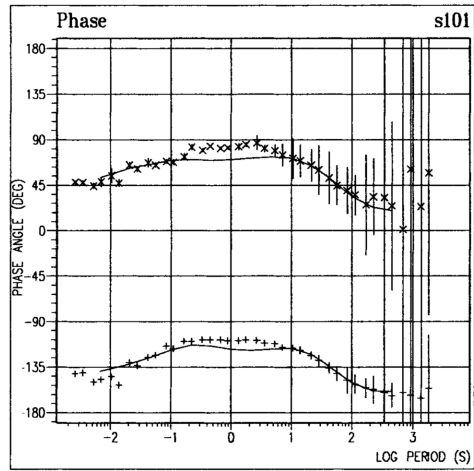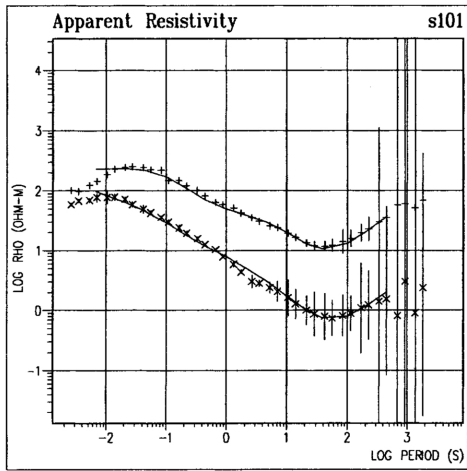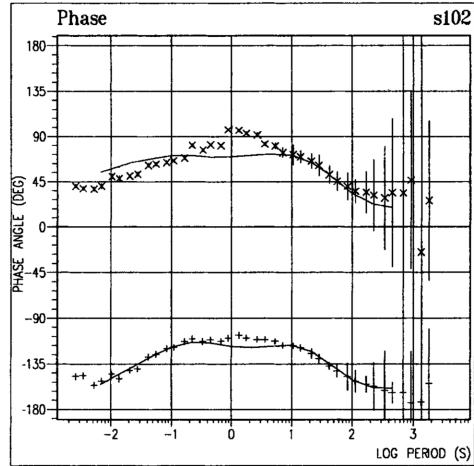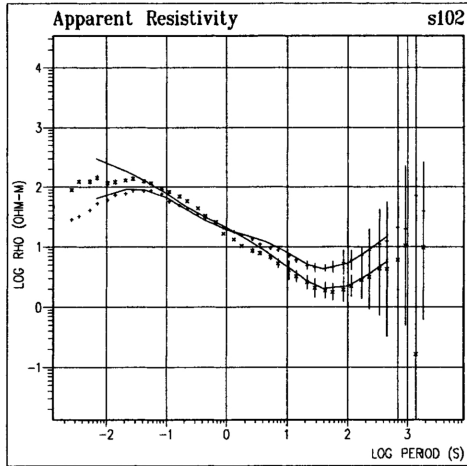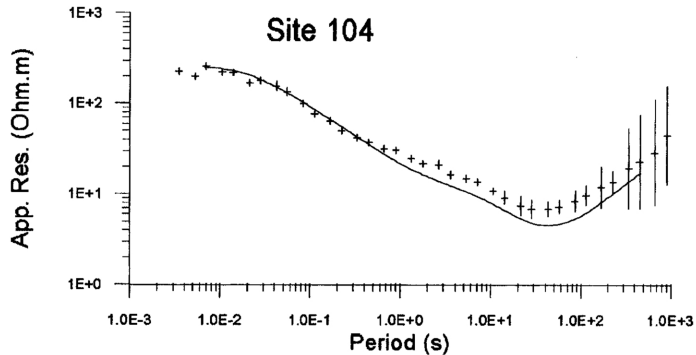
Fig. 2. (continued).

Fig. 3. *E*-polarization data and model response for site 104 when the lower Darai limestones have been removed from site 106 towards the NNE.

errors in either the apparent resistivities or in the phases in this period range. Thus, it appears that the presence of the lower Darai limestones depends on which data (apparent resistivities or phases) are considered. The inflection in the *E*-polarization apparent resistivity curves appears clearly in all the sites of the profile, with a good correlation between them, and becomes smoother towards the NNE part of the profile. In contrast, the phases are more irregular from one site to other. Moreover, 1-D inversions of the *E*-polarization apparent resistivities always resulted in a lower misfit than the phases. These features would lend support to having more confidence in the apparent resistivities and, consequently, we think that, in this case, the apparent resistivities are more reliable than the phases. Accordingly, the conclusions in this paper are based on this assumption.

4. Sensitivity Test

A sensitivity test of their model parameters has been carried out to determine how well the MT data resolve the lower Darai limestones according to the model of Fig. 1. This has been made in two steps. First, given that the apparent resistivity of the 1-D model below every site coincides with the *E*-polarization of the 2-D model of Fig. 1, the 1-D analysis of the equivalence for the 1-D model below every site has been carried out. The equivalent 1-D models, giving the lower boundaries of the Darai limestone parameters (resistivity and thickness) have been obtained from the proper eigenvector combinations (Johanssen, 1977; Pous *et al.*, 1985, 1988; Pedersen and Rasmussen, 1989). Such an approach is expected to provide an approximate estimation of which parameter combinations are resolvable.

Second, 2-D models, according to the 1-D equivalence analysis, were constructed, and possible 2-D equivalences were investigated taking into account both polarizations. We considered two models being equivalent when they satisfy the following two conditions: 1- the RMS misfit between their model responses is less than a maximum value; 2- the responses maintain the inflection in the *E*-polarization of the apparent resistivity between 1s and 10 s, associated with the presence of the lower Darai limestones. The criterium for the maximum RMS misfit was set at 0.070 for both polarizations of the apparent resistivities, which is the order of the RMS misfit between the data and responses of the Fig. 1 model.

Figure 4 shows the typical behaviour of the eigenvector associated with the smallest eigenvalues involving the parameters of the lower Darai limestones. The first one shows a high amplitude for the component associated with ρ_4, which is the resistivity of the lower Darai limestone. The resistivity lower boundary from the 1-D equivalence analysis is 20 $\Omega\cdot$m. However, even though
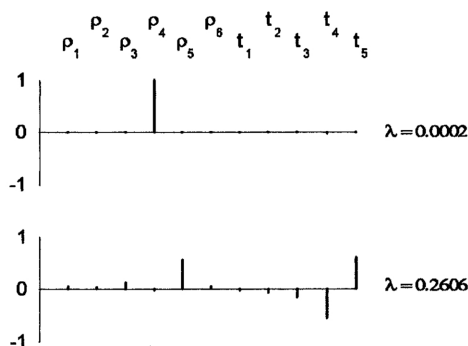
Fig. 4. Eigenvectors associated with the smallest eigenvalues (λ) involving the parameters of the lower Darai limestones. (These correspond to 1-D model beneath site 106).
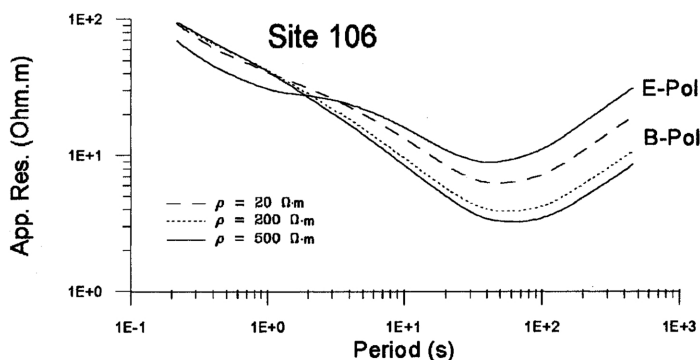

Fig. 5. B-polarization apparent resistivity responses for different resistivities of the lower Darai limestones. The E-polarization response is the same for all the models (upper solid line).

this low resistivity fits the E-polarization, it does not fit the B-polarization of the corresponding 2-D model. Figure 5 shows the 2-D response of the B-polarization apparent resistivities for site 106. The lower resistivity value, giving a 2-D RMS misfit less than 0.070 and maintaining the inflection, is 200 Ω·m.

The average thickness of the lower Darai in the model of Fig. 1 is 950 m. In accordance with the second eigenvector in Fig. 4, a combination of the parameters of the lower Ieru unit should be considered in order to obtain an equivalent model with the minimum thickness of the lower Darai unit. The lower boundary of the thickness from the 1-D equivalence analysis is, on average, 650 m, the parameters of the lower Ieru unit being 3.7 Ω·m and 5.6 km. After several attempts, the final 2-D model (with a RMS misfit less than 0.070 and the inflection in the E-polarization remaining between 1 s and 10 s) was obtained. However, this model gives a basement depth deeper than 8 km, which is not in agreement with the additional information provided (basement at about 6 km). Accordingly, the leveling due to the static shift was changed appropriately in order to obtain again a depth of 6 km for the basement. The resulted 2-D model is presented in Fig. 6. The RMS misfit is less than 0.070 and the E-polarization apparent resistivity response maintains the inflection. This model shows a resistivity of the lower Darai limestones of 280 Ω·m,
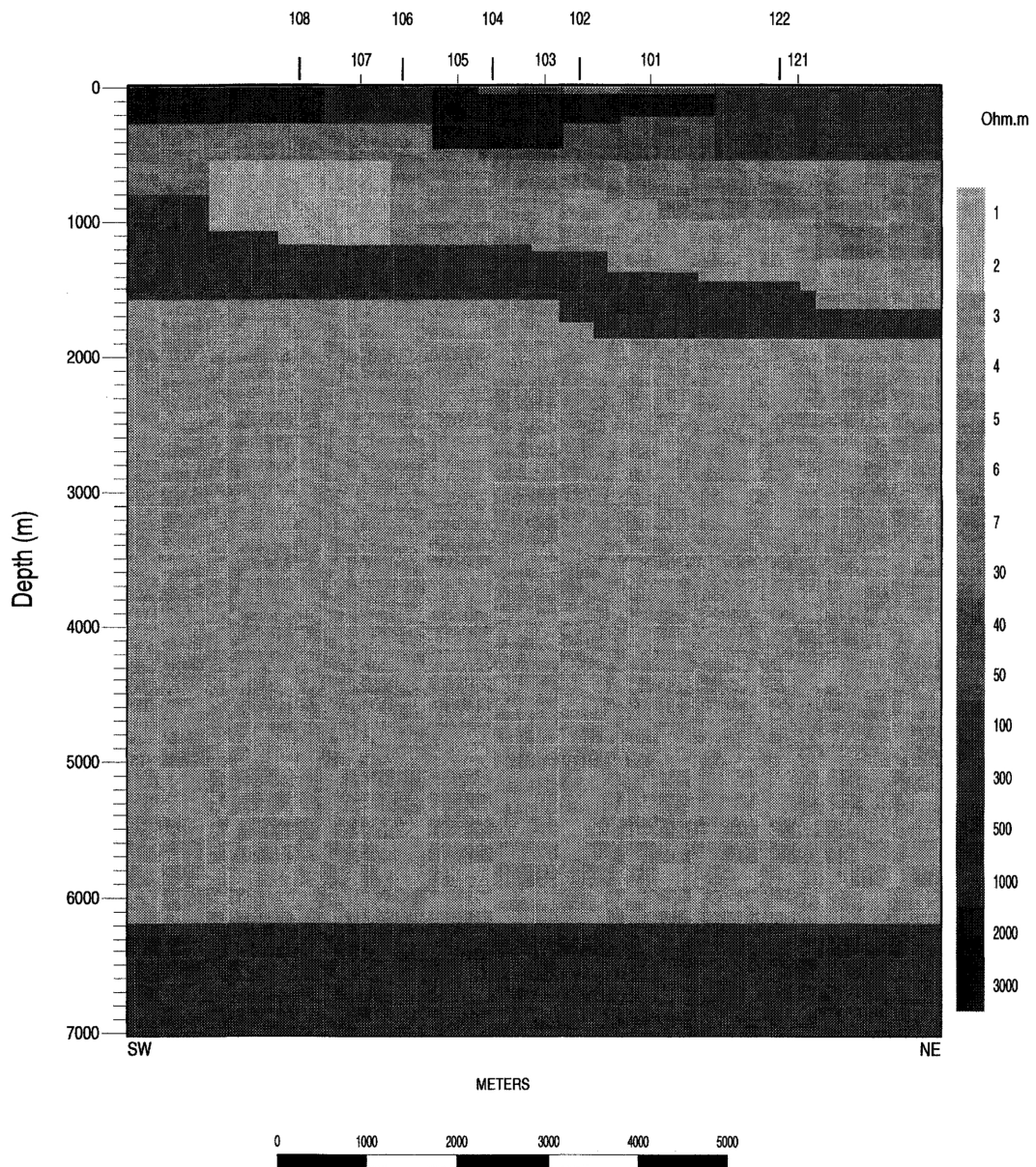
Fig. 6. Equivalent two-dimensional resistivity model.

which is similar to the lower boundary obtained from the first eigenvector. The average thickness in the central part of the profile is less than 500 m and is located closer to the surface: beneath site 106, its top is at 1.2 km and beneath site 122 at 1.5 km. Now, the parameters of the lower Ieru unit are 2.3 $\Omega \cdot$m and about 4.3 km in thickness.

5. Conclusions

The *E*-polarization apparent resistivity data are the most sensitive data for detecting the lower Darai limestones, which are characterized by the inflection appearing between 1 s and 10 s. This inflection becomes smoother towards the NNE part of the profile, and at periods longer than 1 s the *B*-polarization apparent resistivity is lower than the *E*-polarization. These two features are a consequence of the NNE dipping of the embedded resistive unit, which corresponds to the lower Darai limestones.

Thus, we conclude that the lower Darai limestone is present along the whole profile. From the model of Fig. 1, in which the parameters of the lower Darai limestones are 500 Ω·m and about 950 m, a sensitivity test was carried out in order to obtain lower boundaries for these parameters. The equivalence analysis showed that the resistivity may vary independently, but the thickness depends on other parameters. After recalculation of the static shift correction, this thickness results mainly in a dependence with the depth of the lower Darai limestone. In accordance with the criterium used in the sensitivity test, the lower boundaries are 200 Ω·m for the resistivity (for the Fig. 1 model) and a thickness of 500 m when the lower Darai limestones are shallower (Fig. 6).

There seems to be a contradiction between the phases and apparent resistivities in the interval from 1 s to 10 s. Our conclusions are based on the assumption that the resistivities are more reliable than the phases. However, a new revision of the data and further data would be necessary to shed light on this contradiction and the possible distortion effects.

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