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A TDEM survey to define local hydrogeological structure in Anthemountas Basin, N. Greece

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Abstract: *A detailed survey using Time Domain ElectroMagnetic (TDEM) soundings was conducted in Anthemountas Basin at the northern part of Greece, in order to delineate the intrusion of sea-water into coastal fresh water aquifer detected by drilling wells. We employed robust 1-D inversion algorithm because of high-level noise contamination of data caused by nearby airport. Inversion results were combined and plotted in pseudo 2-D, and 3-D sections. Geophysical interpretations correlate well with the existing geological and hydrogeological information. The results indicate that TDEM sounding method can provide accurate information in a highly conductive environment, even in the case of noisy data.*

Keywords: *1D robust inversion, TDEM, Re-weighted least squares, Saltwater intrusion.*

INTRODUCTION

TDEM methods have been utilized successfully in hydrogeological surveys, delineating aquifers, and mapping contamination of reservoirs (among others, Hoekstra and Bloom, 1990; Goldman et al., 1991). The earth is energized by abruptly shutting off the current in the transmitter. According to Faraday's Law, currents are induced in the subsurface, decaying with time and producing secondary magnetic field that creates a measurable voltage in the receiver (Raiche, 1984). In the coincident loop configuration, only one loop serves as a transmitter and receiver during the time-on and time-off period of the current, respectively. Unlike other geophysical sounding methods where the receiver-transmitter array must be expanded to explore deeper part of the geoelectric section, the depth of investigation for the TDEM method depends on length of recording window (Nabighian, 1979). The measurement of the signal at later times gives information related with the larger depths. The method is insensitive to inhomogeneities in the surface layers; most common reason that gives rise to bad quality data sets in all electromagnetic methods. Among the EM methods, this method has the best lateral and vertical resolution with regards to highly conductive targets (Kaufman and Keller, 1983).

A variety of data interpretation techniques have been proposed. Those include the imaging techniques

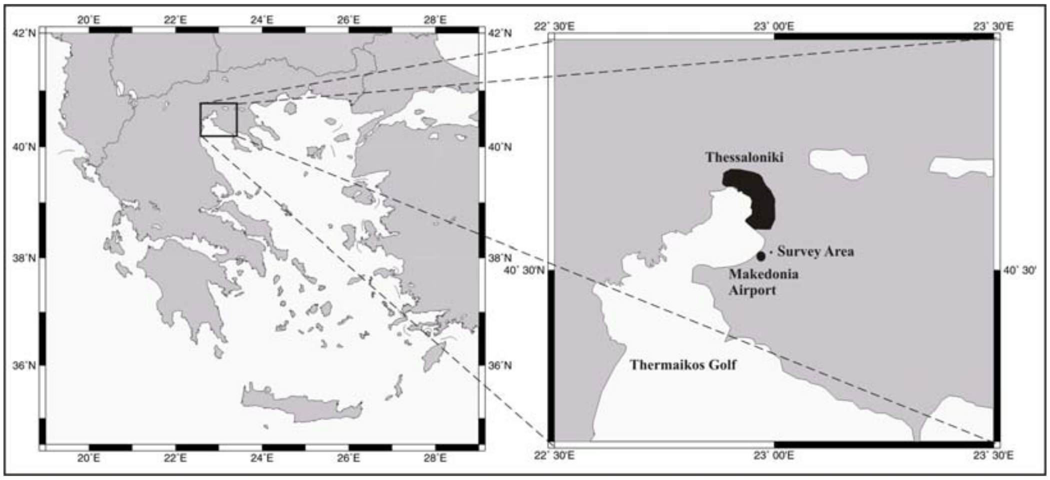

FIG. 1. General location map of the study area.

(among others, Lee, 1977; Tartaras and Zhdanov, 1996), conductive finite plate models (Pirttijarvi et al., 1998; Keating and Crossley, 1990) and inversion methods that use 1-D horizontally layered earth model (Constable et al, 1987; Goldman, 1988; Smith, Edwards and Buselli, 1994; Christensen, 1995).

In the present work, we conducted a large-scale TDEM survey involving 35 soundings with the coincident loop configuration (50x50 m square loops at 50 m spacing) aligned on a rectangular grid. We performed 1-D interpretation scheme (Papadopoulos, 2003) and the interpreted results are correlated with existing geological data, providing useful information about the local hydrogeological conditions.

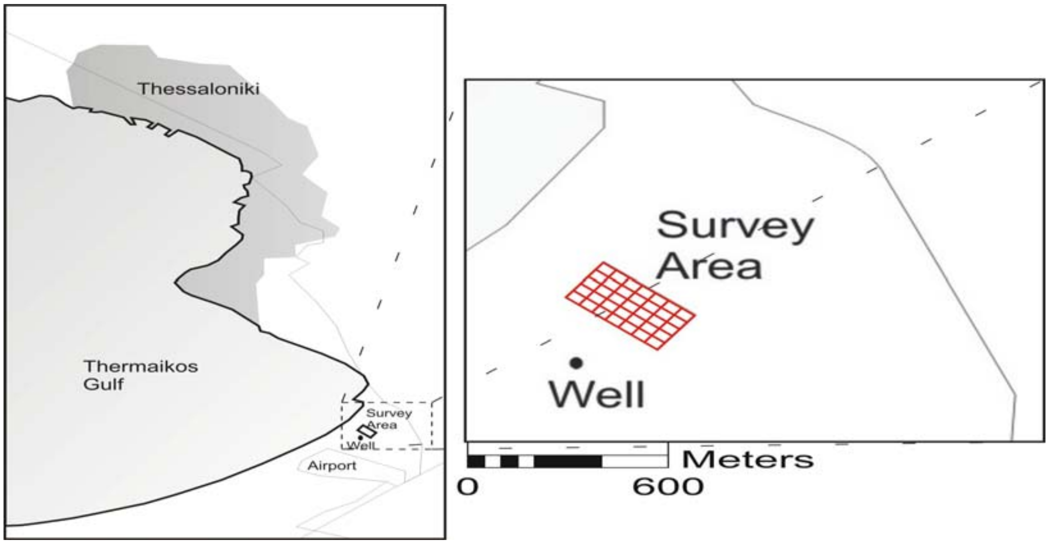

FIG. 2. *Left panel:* Extent of the Thessaloniki-Thermaikos Basin. *Right panel:* Magnified map of the survey area. Soundings are represented with red squares. Also shown the position of the well (black dot).

The airport of Thessaloniki is located a few kilometres southeast of the city, on the coastline of Thermaikos gulf (Fig. 1). It belongs to the basin of Anthemountas, which is a recent tectonic depression filled with younger sediments forming an extension to the wider basin of Thessaloniki-Thermaikos. According to Fytikas and Papachristou (2003) the stratigraphy of the region comprises of a) volcanic (dunites and peridotites) and/or metamorphic rocks with intense fracturing (gabbros and gneiss) of the basement encountered at around 1000 meters depth, b) the base conglomerate, c) Pliocene marine sandstones and green clays with limestone intercalations; river and lake sediments with lenses and layers of sand, silt, sandstones, marls, marly limestone and red-layers, d) Quaternary deposits of red silt, sand, conglomerates and breccia, and e) younger sedimentary deposits of terrestrial origin.

Coastal fresh water aquifers are often intruded by saltwater from the sea. The position and movement of this interface influences the location of wells and their rate of production. TDEM method provides a good way of sitting wells and monitoring salt-water interface migration. The saltwater layer becomes deeper and thinner in the landward direction.

The survey area is located between the city of Thessaloniki and the airport of Thessaloniki at approximately one kilometer away from the coastline and inside a farm of the Aristotle University. It is irrigated from wells in the farm, and the drilling water is saline.

In the vicinity of the area there is a drilling well, whose log is shown in Figure 3. The surface layer up to the depth of approximately 20 meters consists of clay. The underlying layers of 55 m thickness are comprised of gravel, clay and sand. There are gravels mixed with red clay from 75 m down to 110 m.

During summer, when the area is irrigated from wells, the surface concentration of salt increases, while during rainfalls the rain washes away the salt using a drainage system of channels communicating with the sea. Thus, surface layer has a major irregularity in salt concentration during the year, resulting in variation in resistivity of the top layers.

DATA ACQUISITION AND PROCESSING

A detailed TDEM survey was carried out using the Sirotem MKII unit (Buselli and O’Neil, 1977) for mapping the survey area. The coincident-loop configuration is applied by a square loop of 50 m side length. A number of 35 soundings were conducted at 50 m spacing, along a grid of 250x300 m in August 2002 (Fig. 2).

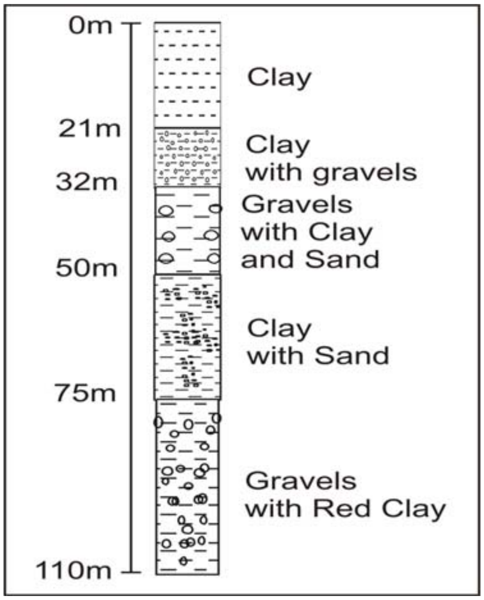

FIG. 3. The lithologic column of the well in the study area.

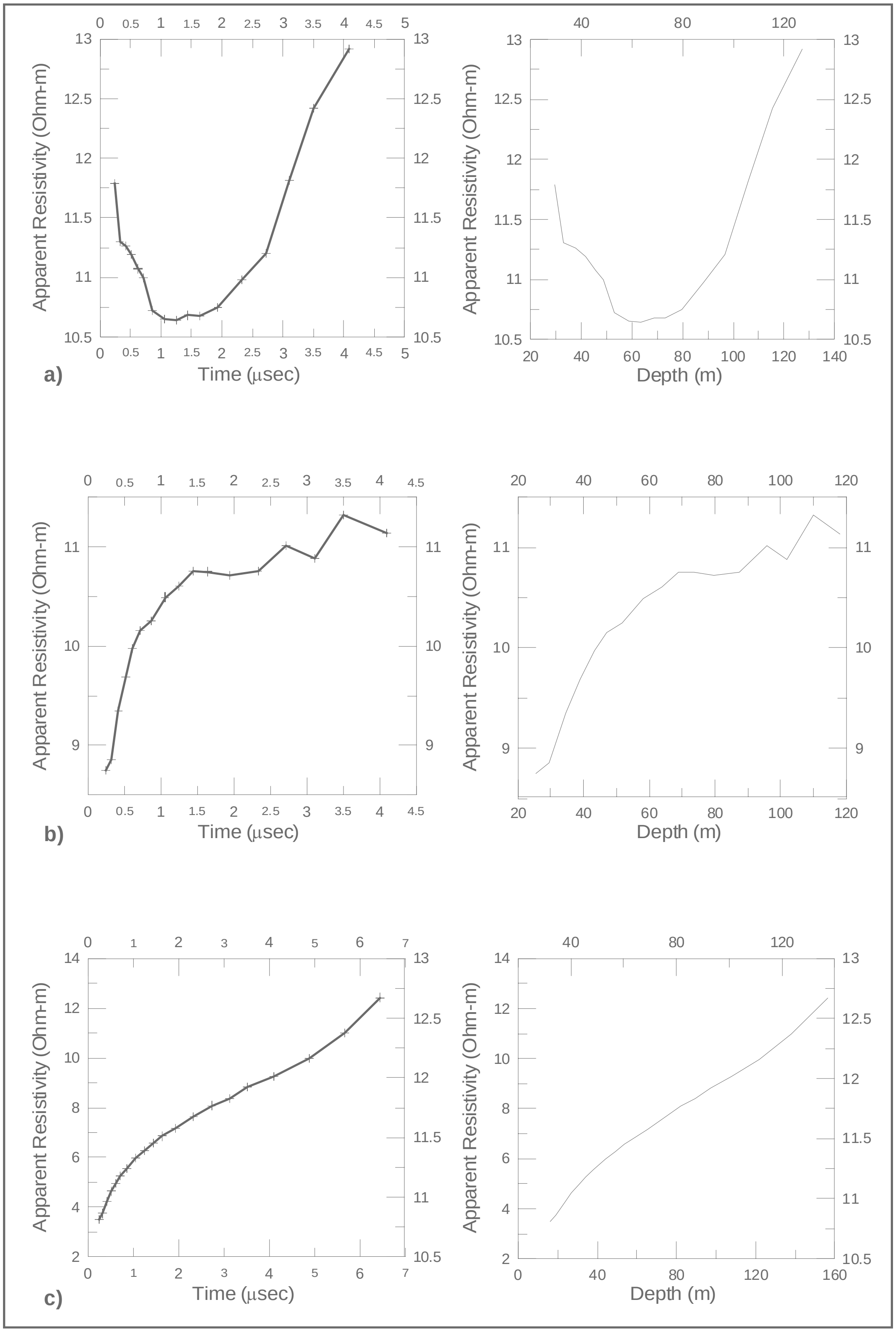

FIG. 4. *Left Panel:* Apparent resistivity-time curves. *Right panel:* Apparent resistivity as a function of pseudodepth for TDEM soundings a) Ant02, b)Ant03 and c) Ant24, respectively

Transient voltages of each sounding were transformed into apparent resistivity to aid in the qualitative interpretation and inversion, (Raiche and Spies, 1981). Apparent resistivity is the resistivity of a homogeneous earth that would produce the measured transient voltage at a single time. Figure 4 shows the transformation from apparent resistivity versus time curves into apparent resistivity versus pseudo-depth curves for three soundings.

Since the airport of Thessaloniki is very close to the survey area, electromagnetic noise due to control systems of the airport was expected to be relatively high. Typical recordings suffering from noise are presented in Figure 5.

We employed the robust 1-D inversion (Papadopoulos, 2003) for discrete numbers of layers, an automated technique for treating noise. Forward modeling calculations use Gaver-Stehfest inverse Laplace transform method (Knight and Raiche, 1982), modified for Sirotem MKII unit coincident-loop configuration by Karmis et al. (2003).

Inversion is based on hybrid damping factors least squares technique (Karmis, 2003). It is an iterative formula that minimizes ***q*** function of misfit given by

$$\boldsymbol{q} = (\boldsymbol{Wd} - \boldsymbol{Wf})^{T} (\boldsymbol{Wd} - \boldsymbol{Wf}), \qquad (1)$$

where ***W*** is the standard deviation matrix. ***d*** and ***f*** are the measured and synthetic data sets. Taylor series expansion of the model response gives

$$f = f^{0} + A.dm,$$

where $\boldsymbol{f}^{0}$ is the the model response calculated from the initial guess. ***A*** is the sensitivity matrix and ***dm*** is the model correction vector. Subsituting the above equation into the equation (1) and solving for the model correction vector at *k th* iteration gives

$$dm_k = ((A_k W)^T A_k W + \lambda_k C^T C)^{-1} (WA_k)^T W dy_k \quad , \qquad (2)$$

where ***C*** is a matrix that handles the smoothness of the model, ***dy*** is a vector that contains the differences between the measured data and the model response.

Additional feature is the multi re-weighted least squares technique, using Morelli and Labreque (1996) methodology described for vertical electric sounding data. A trial-weighting matrix is calculated by using the equation

$${}_{trial}W_{i,i} = ({}_{old}W_{i,i}^{1/2} / e_i) \; [\sum_j ({}_{old}W_{j,j}^{1/2} e_j) / \sum_j {}_{new}W_{j,j}^{1/4} e^{1/2}) \qquad (3)$$

All new elements of the weighting matrix are chosen after examination of the trial and the old weights by the following criteria:

$${}_{new}W_{i,j} \begin{cases} {}_{old}W_{i,j} \rightarrow {}_{trial}W > {}_{old}W_{i,j} \\ {}_{trial}W_{i,j} \rightarrow {}_{trial}W_{i,j} < {}_{old}W_{i,j} \end{cases} . \qquad (4)$$

The weights are updated at all iterations until the L1-norm becomes equal to unity. L1-norm is defined as

$$.L1 = \frac{\sum_j ({}_{old}W_{j,j} e_j)}{\sum_j ({}_{new}W_{j,j} e_j)} . \qquad (5)$$

Less elements of ***W*** are modified by increasing number of iterations. L1-norm approaches unity and consequently the re-weighting process stops, otherwise the solution keeps tracking the noise contamination of the data. The Frechet derivatives are evaluated using perturbation technique. The misfit is calculated using average percent data error. All the initial guesses were set to 4-layers model. The depth-to-bottom was set to 150 m and the standard deviation for all data was set to 10%.

RESULTS AND DISCUSSION

Some typical examples of the interpretation are shown in Figure 6. The robust inversion algorithm treated the noisy data points as outliers by assigning them small weights to reduce their contribution on the inversion results.

The geoelectrical models afterwards were plotted in pseudo 2-D sections using interpolation to acquire a better presentation of the subsurface of the area. In figure 7 geoelectrical sections are shown for each profile. The results indicate two zones of very low resistivity,

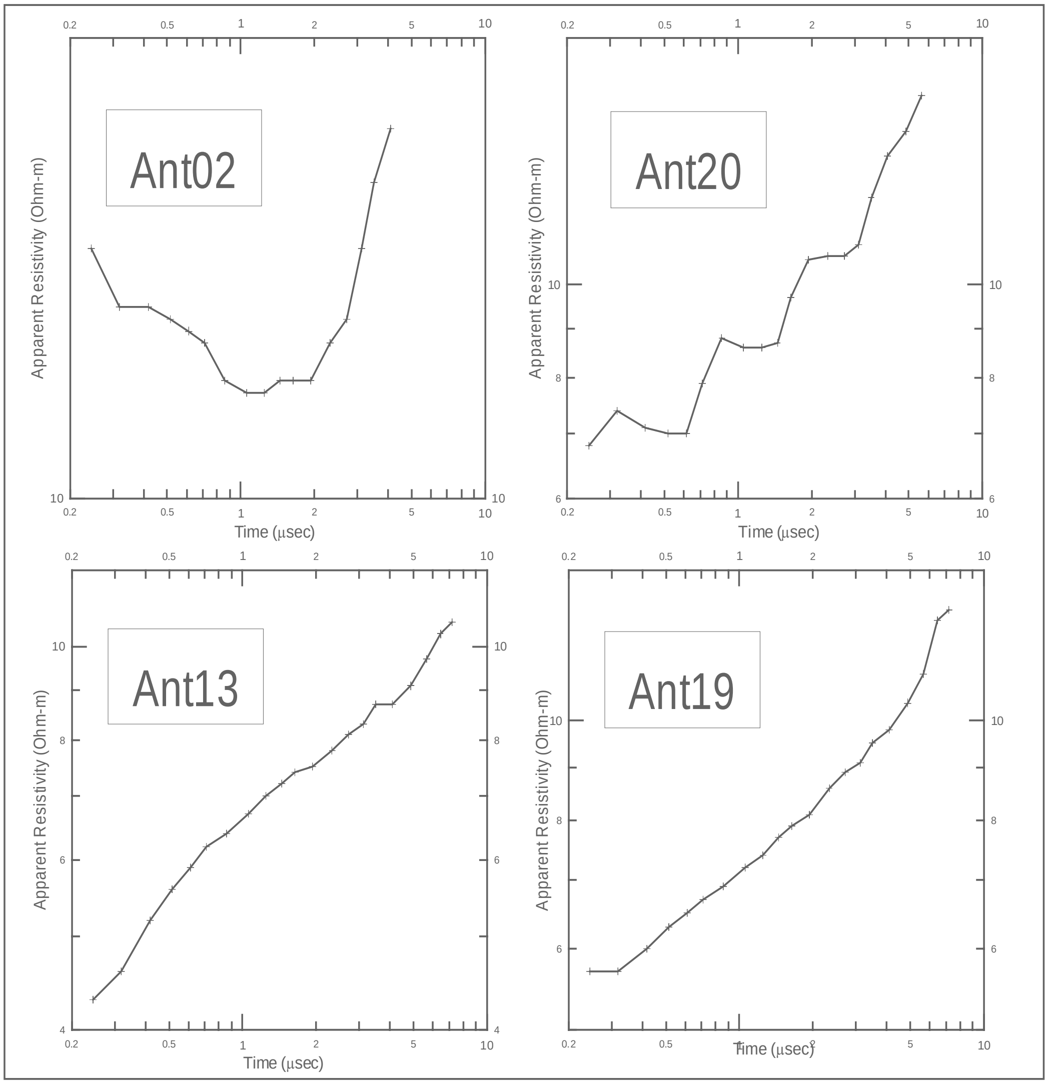

FIG. 5. *Top Panel:* Examples of TDEM soundings (Ant02 and Ant20) in the survey area with high levels of noise. *Bottom Panel:* TDEM soundings (Ant13 and Ant19) with relatively low noise levels.

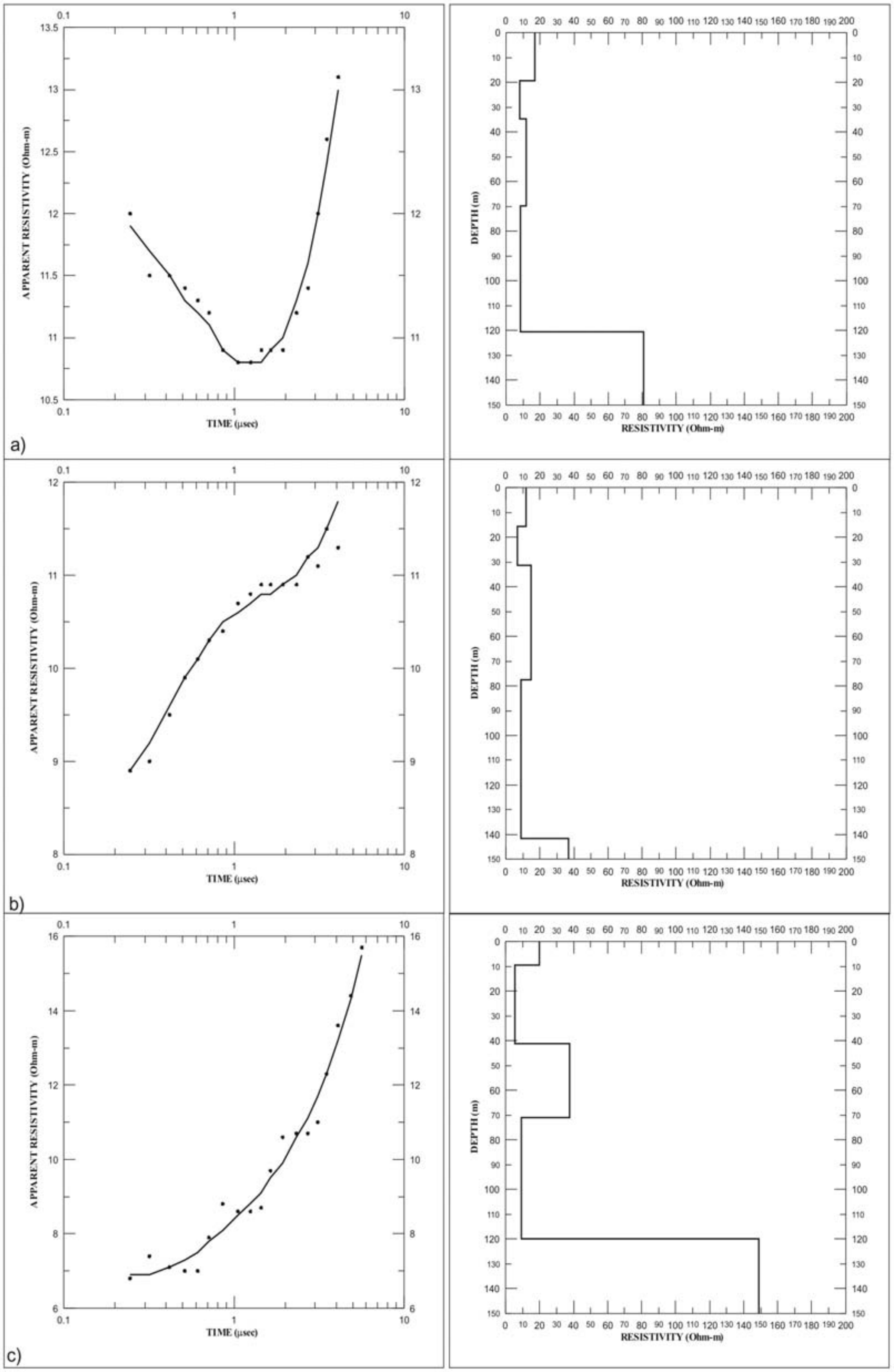

FIG. 6. The fit between measured and theoretical data (left panel) and the interpreted models (right panel) for TDEM soundings of Ant02 (a), Ant17 (b) and Ant20 (c), respectively.

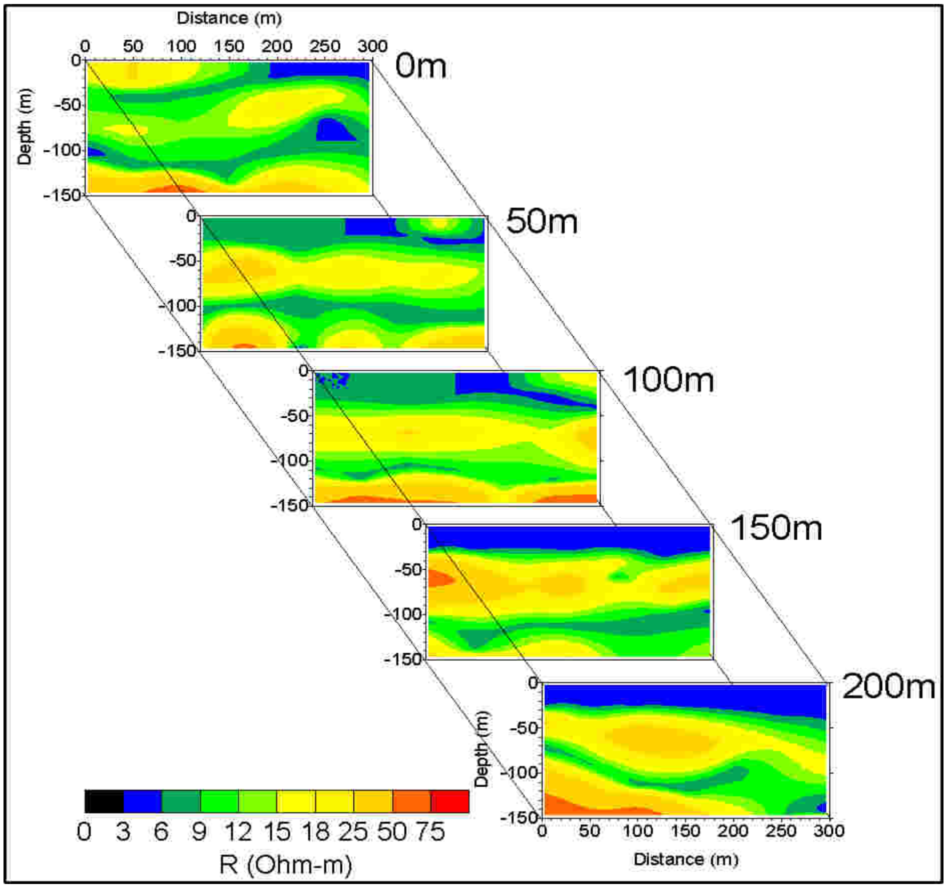

FIG. 7. Geoelectrical sections derived from the TDEM profiles.

the top layer of approximately 20 m and a deeper layer between 80 m and 110 m.

Results were also combined to construct a pseudo 3-D section of the subsurface resistivities. In the pseudo 3-D section of Figure 8 the layers of low resistivity were excluded, and there are two traverse profiles for better visualizing the third dimension.

According to the well log, the top layer consists of clay and mud. Hence, the high concentration in salt at the surface in combination with the top clay layer gives rise to the top low resistivity layer in all soundings.

The subsurface consists of layers with gravels mixed with clay and sand from the depth of 25 m and up to 80 m. These layers are considered as the fresh water aquifers. The second low resistivity zone is apparent below the depth of 80 m, with resistivities of 6-12 ohm-m. This layer consists of gravel with red clay, and is attributed to the saline water infiltration. Below that layer, the resistivity rises to higher values, between 30 and 90 ohm-m, which correlates well with the Pliocene formations which are known to exist in the wider area and are related to deep aquifers of fresh water (Vargemezis and Nagoulis, 1990). Thus, we could argue that the existence of deeper aquifers within the Pliocene formations in the study area is quite probable and, in that case, fresh water could be expected at depths more than 120 meters.

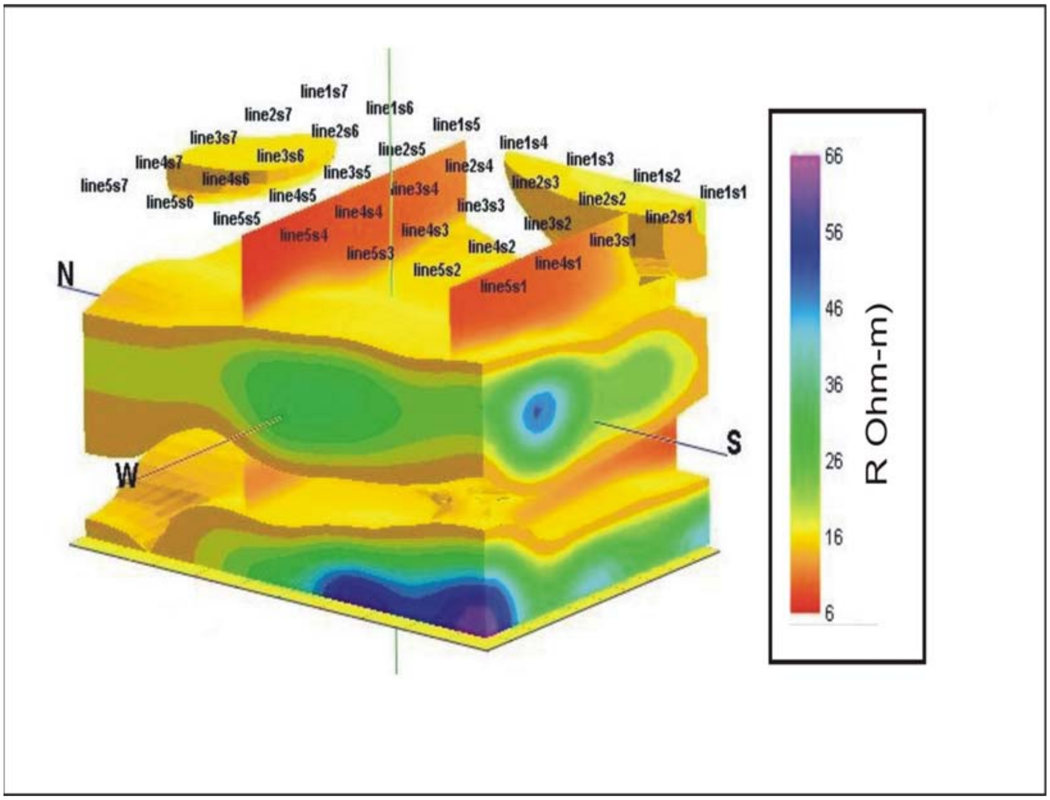

FIG. 8. 3-D presentation of the interpreted geoelectrical structure of the survey area.

In general, the interpretation results are in good agreement with the expected resistivity values for the layers appeared on the well log, and the 2-D profiles are consistent with the image obtained from the well.

Another matter for discussion is the productivity rate of the method. A crew of 3 persons has carried out fieldwork within two days. In general, the method proved to be significantly faster than the geoelectrical VES method that is traditionally used for this type of surveys. The processing and interpretation of the data using robust inversion was done rapidly and in an automated manner and no geological information was used as constrain for the inversion.

Overall the combination of the TDEM method with the 1-D robust inversion scheme produced results that are in good agreement with the existing information. This proves that the method is useful to delineate the hydrogeological conditions in the area of interest. It was also verified that the TDEM method and the suggested interpretation scheme are effective in highly conductive environments, even in the case of noisy data.

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