The application of Time Domain Electromagnetic Method to characterize the Keritis Basin, in Western Crete, Greece

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Abstract: - Time Domain Electromagnetic survey (TDEM) was undertaken in the Keritis basin region of Crete, in order to obtain detailed information about the characteristics (geometry, etc) of the hydrogeological regime (aquifer) of the area. In order to define the stratification, as well the faults of the investigated area, 305 TDEM soundings were carried out. A strong correlation between the results of TDEM survey and boreholes exists and indicates: a) the applicability of TDEM method for solving hydrogeological problems, b) a high potential aquifer mainly hosted in the calcitic rocks of the area under investigation.

Key-Words: - Aquifer characterization, TDEM, transient electromagnetic methods

1 Introduction

Effective management of groundwater resources is a well known problem in several areas around the world. Its importance is designated to areas suffering from the lack of fresh water. Detailed study of available aquifers has great interest especially in islands. Crete is the biggest Greek island and is considered to be a semi-arid region. The average annual precipitation is estimated to be 900 mm, the potential renewable water resources 2650 m^3/yr and the real water used is about 485 million m^3/yr. The major water use in Crete is in irrigation for agriculture (84.5% of the total consumption) while domestic use is 12% and other uses 3.5%. The growing water demands make the water resources management extremely important for sustainable development [1].

Among the different geophysical techniques, the transient electromagnetic method has proved a valuable tool due its high sensitivity to conductive targets, impressive vertical and lateral resolutions and bigger depth according to constructed array geometry size [2,3]. Time Domain Electromagnetic (TDEM) survey encompass the generation of a primary magnetic field which is abruptly interrupted in order to produce induced eddy currents in the subsurface. These eddy currents will produce a secondary magnetic field which can be detected by an appropriate receiver coil on the surface. The value and the decay rate of the measured voltage can be used to estimate resistivities in various depths if appropriate inversion techniques used [3]. The final outcome comes in a form similar to dc electrical resistivity methods but having the advantages that mentioned earlier. TDEM soundings were conducted in Keritis basin at Western Crete, in order to obtain detailed information about the geometry of the different geological layers in the aquifer and depth to the basement. A total of 305 measurements were carried out. Data from existing boreholes in the broader area used to calibrate preliminary results.

The purpose of this study is to investigate the feasibility of TDEM method to clearly identify shallow structures. Comparing the results from TDEM measurements with boreholes' data at the investigated area lead to the same conclusions about the subsurface structure. As an evaluation case, we produce the delineation of an aquifer. Maps of resistivity values highly correlate with the general hydrogeological condition in the area. Numerical 3-D modeling results provide useful information about the distribution of subsurface conductivity, thereby enabling to recognize the main geological formations and the pattern of the aquifer bed. Aquifer presents a homogeneous geometry where its limits clearly identified as well as the direction of its discharge.

2 Method and materials

2.1 The TDEM method

The TDEM method has been used in hydrogeological studies over the last 15 years. The method is described in detail in several textbooks [2],[3],[4]. Therefore, only a short description is given below, in order to briefly discuss the essential features of the method.

The TEM method belongs to the category of controlled source EM methods. A typical TDEM system consists of a transmitter (Tx) loop and a receiver (Rx) loop with equal or less dimensions. The size of Tx loop varies according to exploration depth but without being the parameter that directly control the exploration depth as happened in other methods (e.g Vertical Electrical Sounding method). An increase in Tx loop initially affects (increases) the signal to noise ratio resulting to increase in exploration depth.

A current flowing through the Tx loop generates a primary, stationary field. By using an abruptly on-off switching sequence, currents are induced to the ground according to Faraday's law Due to Ohmic resistance of the subsurface, the current system will decay and further induce a secondary magnetic field. This field which is the transient response is measured in by induction coil (the Rx loop). The decay rate of the electromagnetic field depends on the distribution of the resistivity in the subsurface. In a conductive medium, the field decays slower comparing to a resistive medium. Based on this principle, the measured voltage on Rx coil can provide information about geoelectrical structures at several depths. In order to provide easier interpretation the measured voltage usually converted to apparent resisitivity, ρ_a, according to following formula:

$$\rho_a = \left[\left(0.05 \cdot \pi^{1/2} \cdot \mu_0^{5/2}\right) \cdot \left(r^2 \cdot R^2\right) / \left(E(t)/I \cdot t^{5/2}\right)\right]^{2/3} \quad (1)$$

Where μ_0 is the magnetic permeability, R=(L/$\pi^{1/2}$) is the radius of the Tx loop (L x L), r=(l/$\pi^{1/2}$) is the radius of Rx loop (l x l) S_{RX} is the Rx coil area and *E/I* is the voltage (signal) by current [5].

The importance of TDEM method lies on the measurement time of the transient response. As already mentioned the induced voltage at Rx loop is measured after the turn-off of Tx. That means that we measure a secondary response in the absence of primary field. This approach produces results less sensitive to errors of Tx/Rx geometry, there is no need for complicated tools in order to separate primary signal and finally the Tx/Rx separation has small effect in exploration depth (in contrary to conventional controlled source methods) [6]. These features produce results with the highest lateral resolution.

The exploration depth is mainly affected by the time interval between subsequent turn-off and next turn-on. In order to explore deeper, a bigger time interval required. Because of skin-effect, at early times, the induced currents are concentrated on upper layers leading to measurements that are sensitive to shallow structures only. As the time interval increases, the current intensity migrates to bigger depths and the measured secondary field will depend more on the properties of deeper layers. In addition the current density in shallow structures decreases relaxing in this way the influence of them in the measured secondary field. This elimination of near-surface resistivity variations is a unique feature of TDEM method resulting to high quality data where other geolectric methods failed.

Consequently, the TDEM method has excellent resolution of conductive layers at depth, whereas the resolution of resistive layers is limited [7]. Advantages of the TEM method are its sensitivity to conductors at great depths and the lightweight equipment compared to VES. Drawbacks of the TEM method are low resolution of resistive layers, relatively low lateral resolution in general, high degree of coupling to manmade conductors [8] and that the method is conceptually advanced.

2.2 Data acquisition and processing

All measurements performed using TEM-FAST 48 instrument [9] mainly due to its precision and rapidity of acquisition. We used single loop setup with square 50m x 50m. The transmitting current was 3.8A and the time window of measurement was varying from 4 to 1024 μs or from 4 to 2048 μs in order to derive the best data set from each location, according to signal-to-noise ratio.

Data processing is based on the solution of inverse problem in time domain electromagnetic sounding using TEM-Researcher proprietary software. Initially, for each sounding, the best apparent resistivity vs. time curve is selected (Fig.1) in order to produce an inverted 1D, horizontal layering, model (Fig.2). Subsequent (i.e. belonging to the same profile) 1D inverted models were correlated (interpolated) in order to obtain the 2D slices along individual profiles. By combining the 2D slices and projected them in different depths we are able to provide 3D imaging.

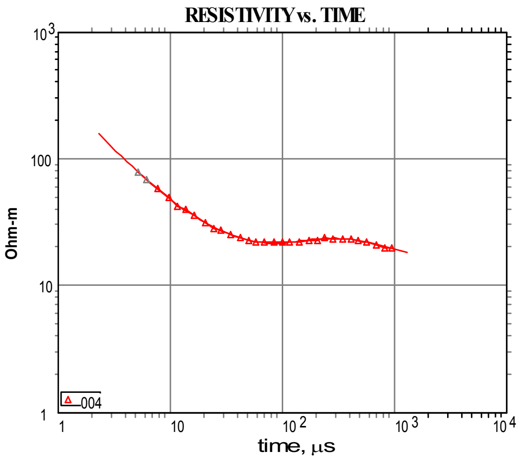

Figure 1. Apparent resistivity curve (sounding over alluvial deposits)

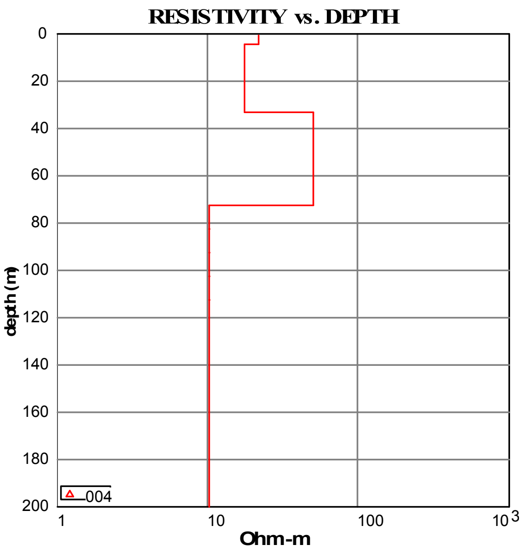

Figure 2. Result of 1D inversion of resistivity curve shown in Fig.1

3 Study area

The Keritis basin is located on the municipality of Chania, at Crete Island and is situated between 35°2450N to 35°3000N and 23°4959E to 23°5800E (Fig.3). The area is $136 km^2$

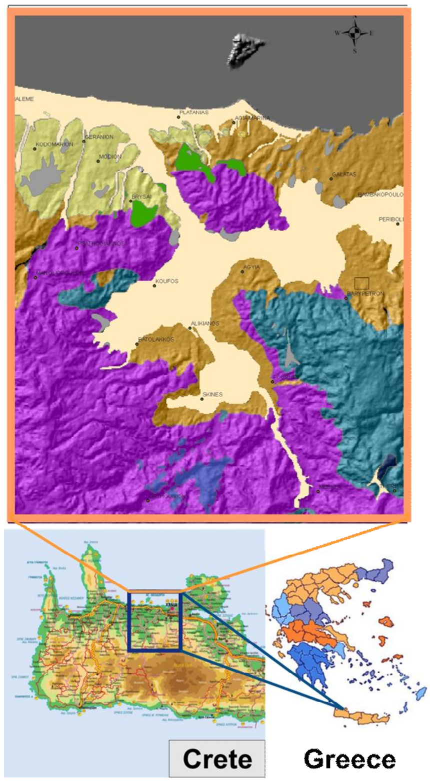

Figure 3: An overview of the study area is presented.

3.1 Geological Settings

The stratification and tectonic units that consists the geological structure of Keritis Basin, from newer to older as shown in Fig.4, are (modified from [10]):

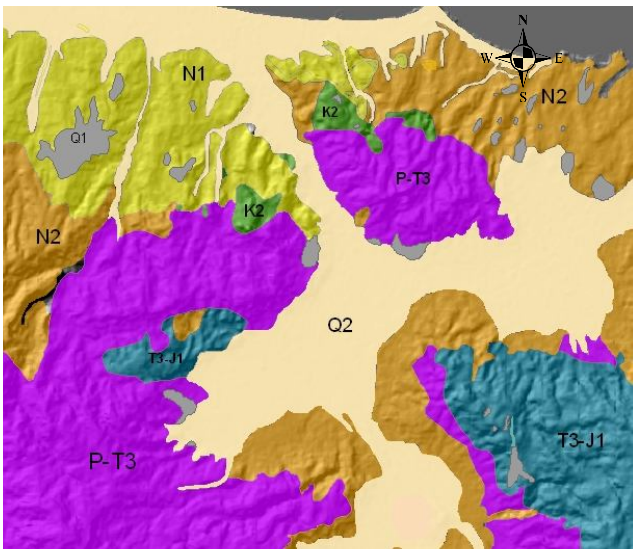

Figure 4: Geological Map of Keritis basin (Q2, Q1: Quaternary Deposits, N2, N1: Neogene Sediments, K2: Tripolis Carbonates, P-T3: Phyllites- Quartzites, T3-J1: Trypalion Carbonates

3.1.1 Post-Alpine Rocks

i. Quaternary deposits (Q2, Q1)

They made up of loose argil-sand materials, clays, breccias, sandstones and materials from alluvium mantle of multiple compositions according to their origination which are from loose to coherent connected. They exist mainly at basins open to sea, at major river beds, at small internal basins as well as side detritus and stream terraces.

ii. Neogene sediments (N2, N1)

The made up from alternating layers yellow-yellow white marls and clastic marly limestones. They are usually biogenic and recent brackish alluvial deposits from coastal areas made which are uniformly distributed layered deposits with thickness from several centimeters to 1-2 meters. Inside these deposits we can meet marls, sandy argyles and conglomerates. The conglomerates and the recent brackish alluvial deposits exist mainly at Chirospili area (southern of Agia) and at Topolia area.

3.1.2 Alpine and Pre Alpine Rocks

3.1.2.a Upper Nappes (Allocthonous series)

- Tectonic nappe of Tripolis zone (K2)

The formations of this layer cover a broad area at Chania country. It is usual to find them highly fragmented due to tectonism. The lower layers consist of dolomites-dolomitic limestones, highly tectonized with karstic attributes and cavernous in texture. Their color is form ash to ash-white. The upper layers consist of limestones with colour from black to ash-black

3.1.2.b Lower nappes (Autochthonous series)

- Tectonic nappe of Phyllites-Quartzites (P-T3)

This is the majority at western part of Chania country. The usual formations are carbon limestones, sericitic-chloritic phyllites and quartz meta-bluestones. In these rocks, quartz of significant thickness, interpolates under the form of lodes as well as black crystalline fragmented lime stones of small thickness. Occasionally black thin-bedded and fragmented crystalline limestones are intercalated in these rocks. Their age is between Permian and upper Triassic. In these rocks, quartz of significant thickness, interpolates under the form of lodes as well as black crystalline fragmented lime stones of small thickness.

- Tectonic nappe of Trypallion (T3-J1)

This is the first tectonic layer of Crete. Its basic occurrence is at Omalos area at Lefka Ori. These formations are overlaying on the Plattenkalk limestones. The rocks that exist are marbles, quartz limestones, dolomites and dolomited limestones. The thickness can reach 400 meters and its age is between upper Triassic until Lias.

3.2 Hydrogeological settings

3.2.1 Hydrolithology

The investigated basin can be distinguished in four main categories according to permeability of geological formations (Fig.5):

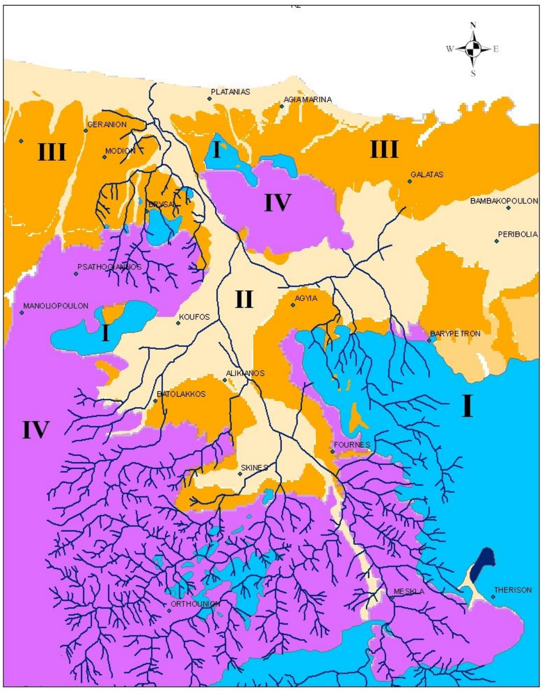

Figure 5. Hydrolithological map of Keritis basin. Blue solid lines denote the drainage network. I, II, III, IV denote categories (details in text)

- High permeability rocks (Category I), inside of which the karstic limestones of Tripolis and Trypalion are comprised.
- Medium permeability rocks (Category II) which include Quaternary sediments belong to Holocene as well as to Pleistocene. These are complex clumps and durable limestones.
- Low permeability rocks (Category III) which include Neogene Sediments belong to Pliocene to middle-upper Miocene age. The upper members consist of marly thick-bedded, organogenic limestones, locally brecciated and the lower members consist of white grey clastic, usually biogenic marls-marly limestones.
- Impermeable rocks (Category IV) consist of phyllites-quartzites.

The tectonic regime of the investigated area characterized from faults NW-NE and E-W directions. These tectonics formations characterize the boundaries between the geological and hydrolithogical units as shown in Fig. 6.

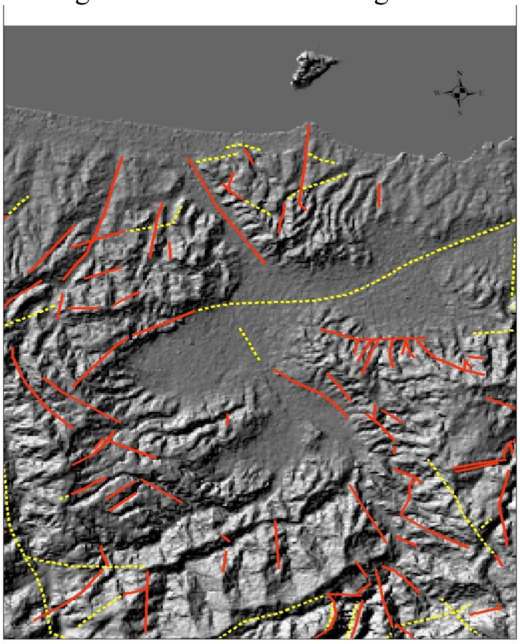

Figure 6. Tectonic map of Keritis basin. Solid red lines denote faults where yellow dashed lines denote concealed faults

4 Results and Discussion

305 TDEM soundings were carried out covering the whole study area. Initially a set of preliminary soundings is taken over four existing wells in order to calibrate crucial parameters for data acquisition and modeling processes. Geological logs for the calibration wells were taken from the Water management authority of Chania Perfecture (Dr. K. Vozinakis). A detailed lithological description can be found in Table 1.

Table 1. Lithological description of calibration wells

Well	*Depth (m)*	*Description*
W1	93	the first layer from 0-27m is Clay, Marly Limestone and conglomerate and the second layer from 27 to 93m is Limestone-Dolomite
W2	100	clayey-sandy and gravel deposits with consecutive layering in loose connection.
W3	110	Limestone-Dolomite
W4	115	alternation clays with gravel from limestone and schist

From each one of 305 soundings a complete set of apparent resistivity and its inverted transformation is derived. The 1D calculated model produced using inversion codes is suitable for local characterization only. In the current study where we primarily interested for the subsurface description and aquifer delineation, only 2D and 3D model projections will be produced.

4.1 2D TDEM modeling

Three geological sections carried out using all the soundings with the following details:

- Section #1 (Fig.7): it is a North South profile which passing the centre of the basin
- Section #2 (Fig.8): a West East profile which is on the western part of the basin, northern area
- Section #3 (Fig.9): a West East profile which is on the western part of the basin, southern area.

The notation of the next three figures is described in Table 2

Table 2: Sections' symbols legend

Symbol	*Description*
Black dashed line	Formation boundary
Black dashed line	Fault
Black dotted line	Sea water intrusion boundary
triangle	Sounding location
arrow	Fault disruption

By correlating the resistivity values with existing formations we can perform the grouping that denoted in Table 3.

Table 3: Sections' letter legend

	Description	*Age*
A	Quaternary Deposits (15 to 80 Ω-m)	Q2 (Holocene), Q1 (Pleistocene)
B	Neogene Sediments (100 to 200Ω-m)	N2 (Pliocene), N1 (Middle-upper Miocene)
C	Phyllites Quartzites (200 to 300Ω-m)	P-T3 (Permian – Upper Triassic)
D	Limestone - Dolomites (500 to 1000Ω-m)	T3-J1 (Upper Triassic – Lias)
X	Sea water intrusion (0.1 to 10 Ω-m)	

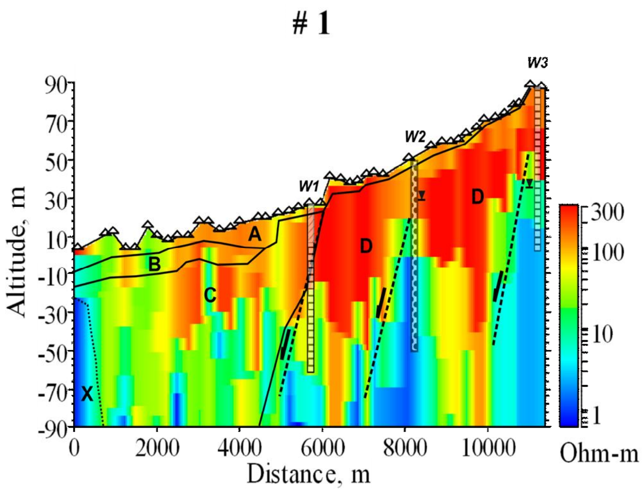

Figure 7. Geoelectrical section #1.

On that profile we recognize the sea water intrusion because on that sounding we were very close to the coastline, so that's why we have that interpretation. Also on this profile we can identify three main faults: at 4200, 7000, 10000m from the beginning of the profile, with directions E-W, NW-SE and E-W.

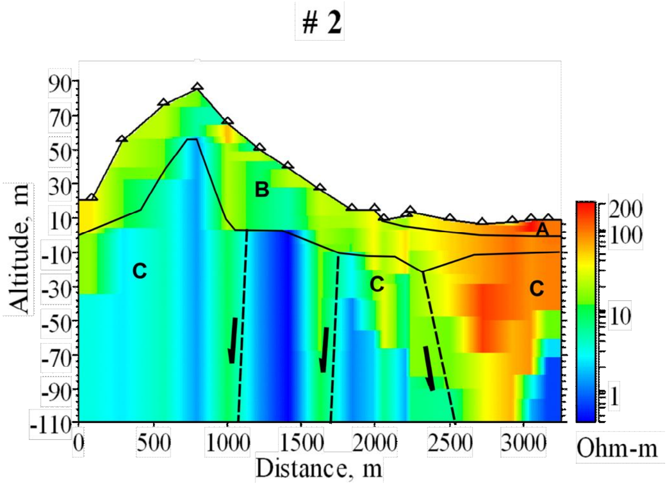

Figure 8. Geoelectrical section #2.

In this section three faults also identified: 1100m from the beginning with direction NNE-SSW and from 1750m with the same direction as well. Also at 2525m we have fault with direction NNW-SSE

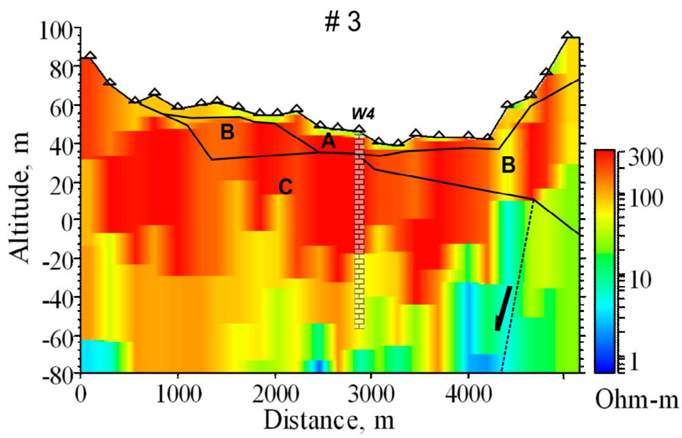

Figure 9. Geoelectrical section #3.

In section #3 one fault identified in 4300m with the direction NNW-SSE.

The filled sketches at Fig.7 and Fig.9 (correspond to logs W1 until W4) show the different geological units based on geological logs and everything is confirmed in the geophysical section.

4.2 3D TDEM modeling

In order to have a clear picture of the aquifer area that we are interested we performed a 3D projection. Electro-stratigrahic horizontal slices obtained by means of the combined interpretation of TDEM surveys and their 3D interpolation. A set of four independent slices is produced according to depths as follows:

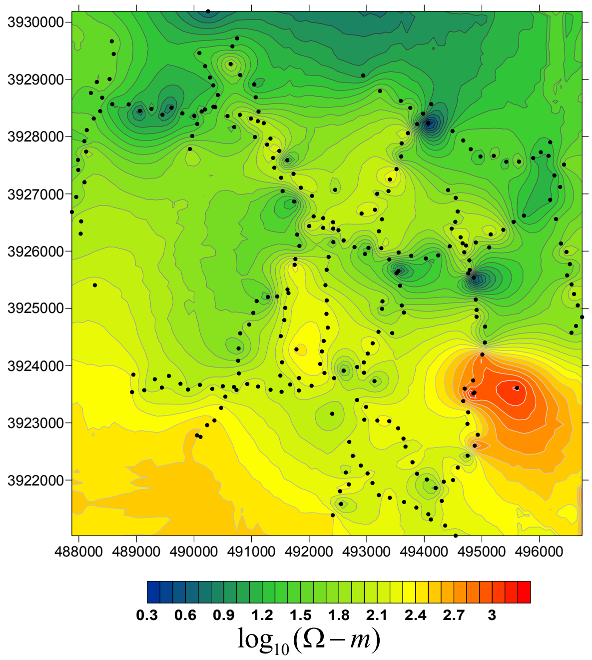

Figure 10. Resistivity of rock at layer 1 (0-25m). Dots denoted sounding positions

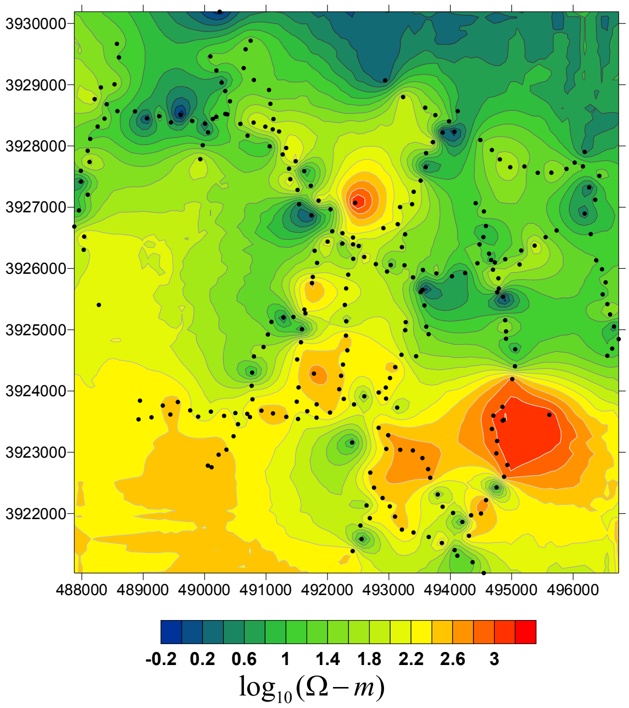

Figure 11. Resistivity of rock at layer 2 (25-50m). Dots denoted sounding positions

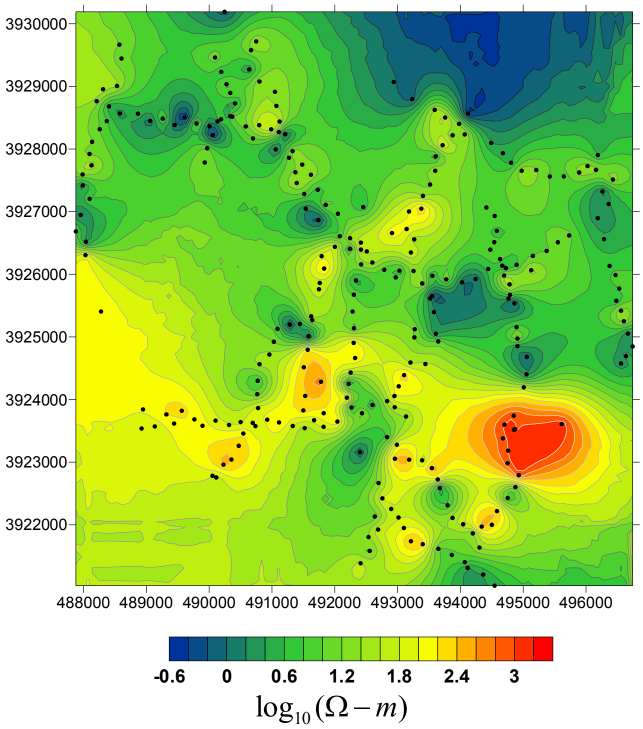

Figure 12. Resistivity of rock at layer 3 (50-100m). Dots denoted sounding positions

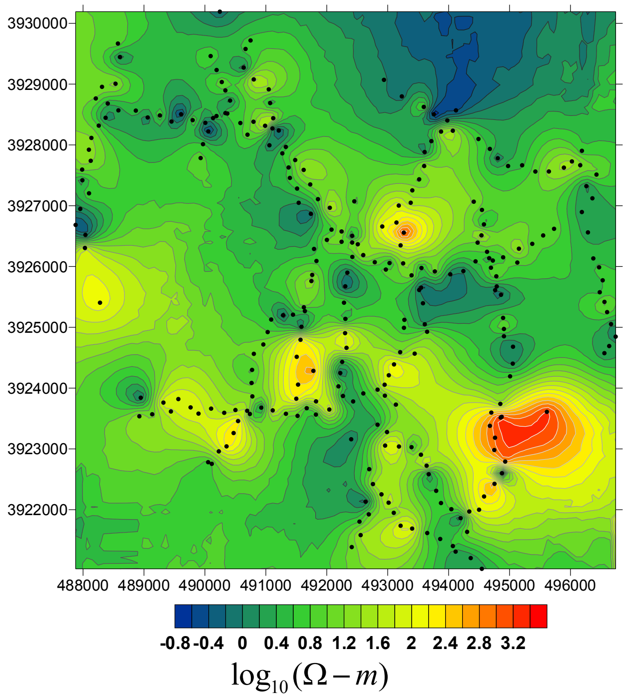

Figure 13. Resistivity of rock at layer 4 (100-150). Dots denoted sounding positions

At the first layers we can see the highly resistive zone on the SE and SW of the investigated area. These high values on the SE directions occurred because of the Tripoli nappe, especially the limestone-dolomite. In addition we can also identify high resistance values on the SW part because of the Phyllites-Quartzites. In the upper zone from North due to alluvial deposits and Neogene sediments low resistivities were identified

By going deeper one can clearly identify a conductive zone on the northern part of the basin and in some areas on the central of the Basin. The conductive area on the northern part is due to small sea water intrusion from of NE side since the coastline is a few hundred meters away. The independent conductive zones at the central areas are evidences of fresh water. As the depth increases the conductive central zones increased in size.

5 Conclusions

TDEM is a rapid and cost effective method for identifying subsurface geometry. When combined and calibrated with existing data (wells, previous studies) is capable of provide high quality reconstruction of the subsurface. The combined use of wells data and TDEM soundings in the Keritis basin provides important information about the geometry and delineation of the aquifer boundaries as well as the tectonic regime. In the examined area two main zones are depicted: one is identified as a sea water intrusion zone while the other identified as fresh water reservoirs.

The results of this study clearly demonstrate that resistivity imaging could be an important tool for defining the thickness of groundwater aquifers and bedrock mapping in areas with shallow depth. This interpretation can indicate the better locations for irrigation as well as serve as a valid tool for preliminary characterization of aquifers in order to indicate the optimum locations for test and/or productive hydrowells.

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