Site Effect Assessment in the Mygdonian Basin (EUROSEISTEST area, Northern Greece) using RMT and TEM Soundings

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Abstract

During the project "Euroseistest Volvi-Thessaloniki", a strong-motion test site (EUROSEISTEST) for Engineering Seismology was installed in the Mygdonian Basin between the two lakes Volvi and Lagada ca. 45 km northeast of Thessaloniki (Northern Greece). The basin itself is a neotectonic graben structure (5 km wide) with increased seismic activity along distinct normal fault patterns. Fluvioterrestrial and lacustrien sediments (approximately 350-400 m thick) are overlying the basement consisting of gneiss with schist. To improve the seismic wave propagation model it is vital to know about site effects, e.g. the geotectonic properties of the area such as the top-of-basement, vertical tectonic boundaries (faults and basement fracturation) and the geothermal regime. Therefore, we carried out near surface EM studies to understand the distribution of the active faulting and the top of basement structure of this particular area.

The RMT (Radiomagnetotelluric) and TEM (Transient electromagnetic) measurements were carried out on three profiles and thirty sounding. The inverted RMT and TEM data show generally a four layer model. The layers are indicated as metamorphic and sediment rocks, which are in detail: marly silty sand with gravel (>> 100 Ωm), marly silty sand with clay (50 - 100 Ωm), sandy clay (30 – 50 Ωm) and silty sand (10 - 30 Ωm). Due to the high resistivity of the top layer, the skin depths of the RMT soundings are around 35 m. The TEM data gives detail information of the lower structure down to a depth of 200 m. According to our analysis, a normal fault next to the Euroseistest could be located having a strike direction of N 60 E. The joint interpretation of RMT and TEM data proves to be an effective tool to investigate complex geology structures.

Introduction

This study refers to the Thessaloniki area, which has recently been affected by the 1978 destructive earthquake sequence [Papazachos and Papazachou, 1997]. It has been well established that the strong ground motion of such a seismic event causes irregularly distributed modification to the local geology [Tranos and Mountrakis, 1998], [Raptakis, et. al., 1999]. Different geophysical methods have been applied in this area [Thanassoulas, et.al.,1987], [Raptakis,et.al.,1999], [Savvaidis,et.al.,1999], [Tranos, et.al, 2003], [Gurk, et.al., 2007], however detail information of fault structures has not been verified so far. Ambient noise measurements from the area east of the Euroseistest experiment give strong implication for a complex 3-D tectonic setting. Therefore we carried out near surface EM studies to understand the distribution of the active faulting and the top of basement structure of this particular area.

Joint TEM and RMT inversion has been successfully applied to geological and engineering problems in the past [Tezkan et.al., 1995], [Schwinn, 1999], [Steuer, 2002]. The RMT method has low penetration depth and therefore gives information of the surface layers, whereas the TEM method gives detail information of the lower structure of the investigated area. Hence, a joint interpretation of RMT and TEM data will produce a good resolution of resistivities and thicknesses, in shallow and in deeper parts of the subsurface.

Test Area and Geological Setting

The investigated sites are located between the Lagada and the Volvi Lake in Northern Greece. The area is now covered with alluvial deposits as shown in (Fig.1). The local geological mapping in this area was done by the Geology Institute the University of Cologne [Maith, 2009]. The Mygdonian system corresponds to various types of sediments that were deposited in a quaternary graben structure. Due to its hydrothermal activity, the top was intensively covered with travertine/tufa deposits, now mostly removed by erosion [Jongmans, et.al. 1998]. The local geological map of the area is shown in Fig.1. We find four major units: metamorphic basement formed by schist and gneisses in the deeper depths, lower terrace deposit was deposited on the top of the basement metamorphic, lacustrine and deltaic sediments including conglomerate, gravel and sand. Fans comprise of soil and silt are located between lower terrace deposit and the Holocene deposit is composed of sand, silt and clay which are deposited on the top of these sediments. To obtain detail information of the geology in this area, TEM and RMT data were observed on all various types of the sediments (Fig.1).

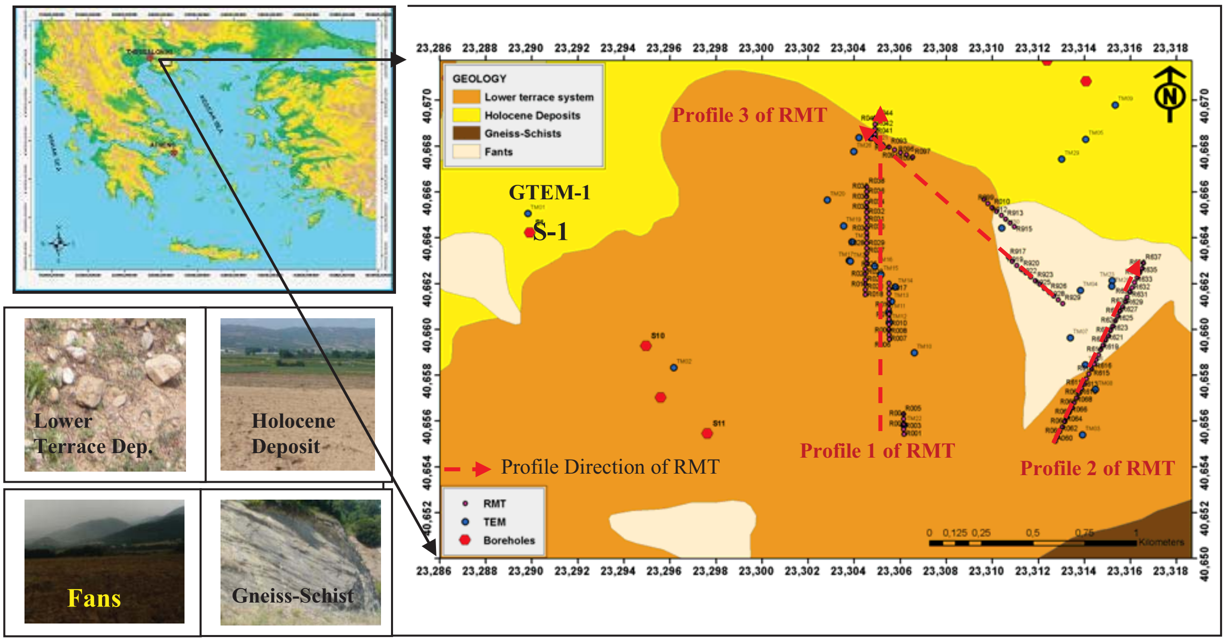

Fig. 1. Site Location, geology of the study area, location of RMT station (•), TEM station (•) and location of boreholes (■) are also displayed in the figure GTEM-1 at the location of TEM-1 sounding.

RMT Measurements and Interpretation

The RMT measurements were carried out on three profiles as indicated in Figure 1. Parameter of the survey design is listed in Table 1. The RMT of profile 1 is along 1600 m with direction N 0 S, whereas the direction of profile 2 is located N60 E, which are parallel with transmitters. The direction of profile 3 in this area is N60W with length of 1400 m, which are perpendicular with transmitter. Due to partial inaccessibility of the area the profiles could not be set up in a straight line. The RMT-F system consists out of two magnetic sensors (induction coils, 30 cm length), a preamplifier for the electrical channels, two electrical antennae and a recorder. It is a four channel instrument (Ex, Ey, Hx, Hy) with the capability of estimating the full impedance tensor [Tezkan and Saraev, 2008].

Table1. Parameter of RMT survey design

RMT Profile	Length [m]	Site distance [m]	Orientation	Transmitter azimuth
Profile 1	1600	25	N0°S	N60°E
Profile 2	1000	25	N60°E	N60°E
Profile 3	1400	25	N60°W	N60°E

A special feature is the way how the electric field is sampled. Instead of grounded dipoles, the device uses symmetrical electrical dipoles (e.g. two arms of 20 m length) that are capacitively coupled to the ground. The system records time series in two bands: D2 band (10-100 kHz) and D4 band (100 kHz—1 MHz). The coherency level is important to prevent signals with high noise level, generally we used for this study a coherency value of 0.8.

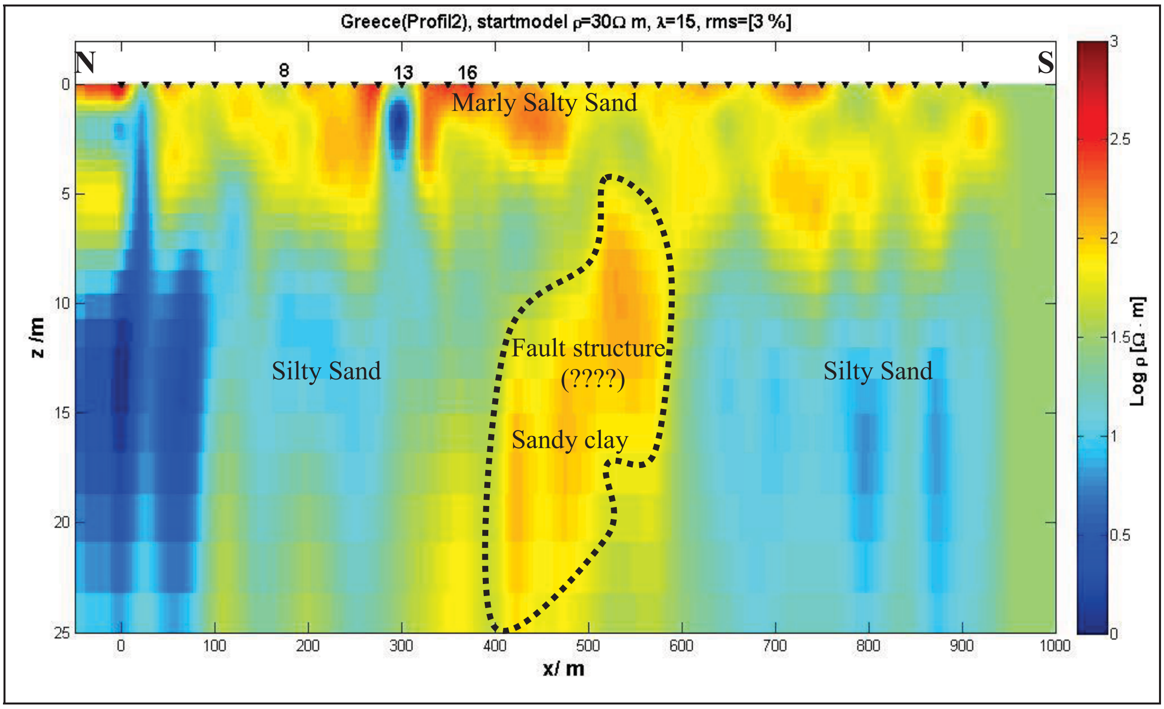

Fig 2. The RMT 2-D inversion model of profile 2 indicates metamorphic rock (marly salty sand) in a depth of 0 -5 m. Stations 1 – 16 and stations 25 – 38 show a very low resistivity (<50 Ωm) zone at depth (5 m – 25 m) which is interpreted as sedimentary (silty sand). Whereas station 17-24 indicate the fault structure (----) as sandy clay.

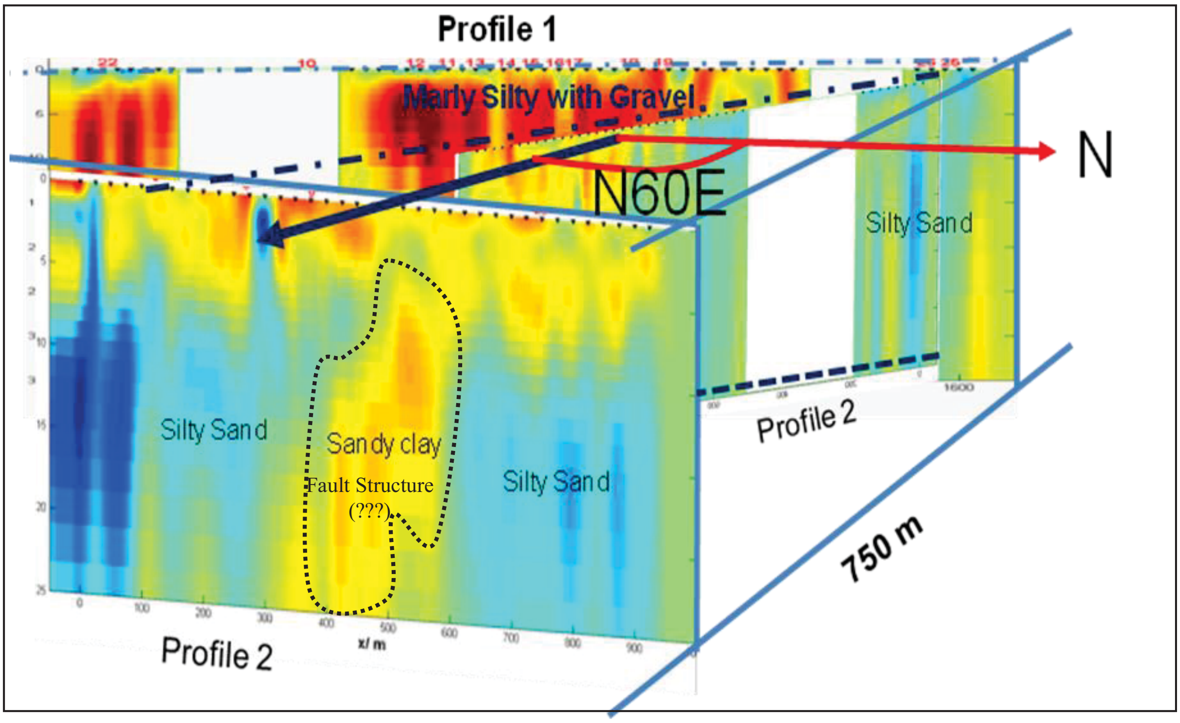

Fig.3. The Fault structure direction (black arrow) derived from 2-D RMT inversions

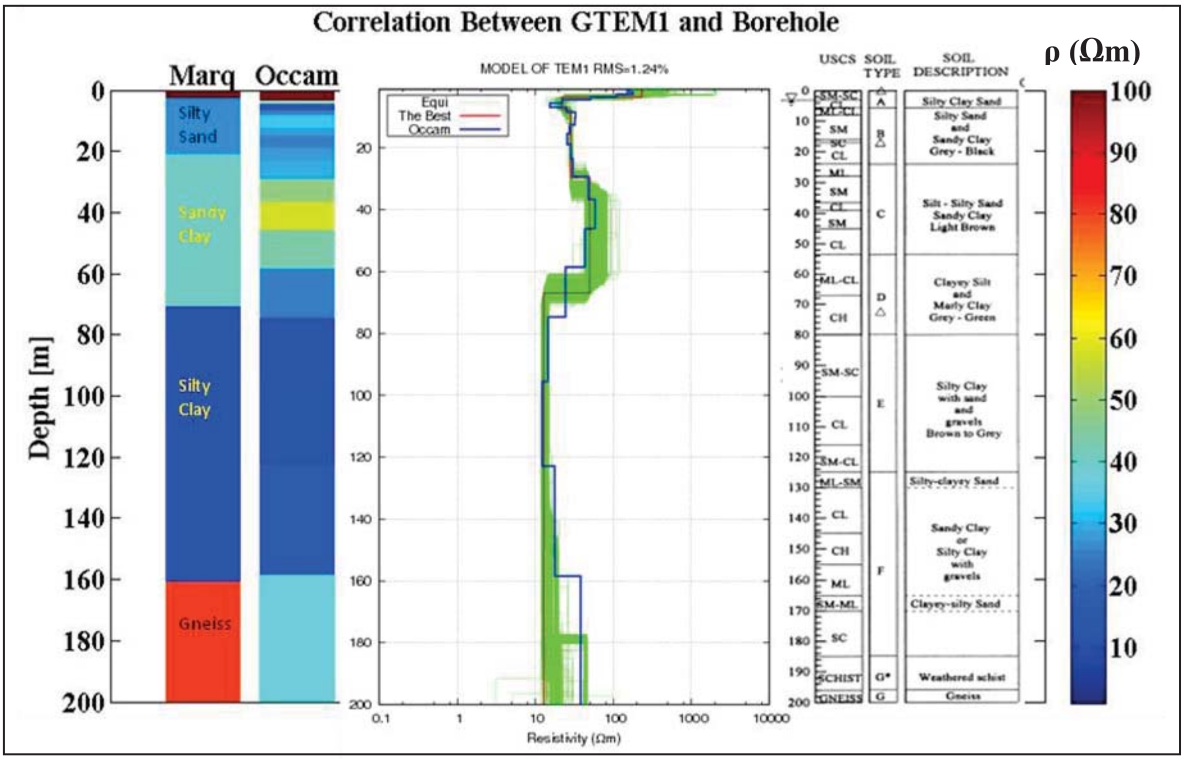

Fig.4. Correlation between the 1-D inversion of the TEM data (GTEM1) at the reference site and borehole S-1 information

In order to calibrate the geophysical measurements with the lithology, TEM data at our reference site was correlated with borehole data in S-1 (Fig.1). This analysis allows identifying characteristic strata based on the electrical conductivity. The modeling of RMT data was done by using 2-D inversion techniques (Fig. 2 and Fig.3). The 2-D inversion was performed with the 2-D Mackie code [Mackie, et.al, 1997], the 1-D inversion was done with the Marquardt [Cerv and Pek, 1979] and Occam algorithm [Constable, 1978]. Prior to any 2-D modeling, the penetration depth have been estimated using the ρ^* (z^*) transformation [Schmucker, 1979]. Penetration depths are found to be around 35 m.

As an example, we explain the RMT model of profile 2 in detail. This model (Fig.2) shows high resistivities on the top layer (more than 100 Ω m) which correlates to the marly silty with clay of the borehole data (Fig.4). For stations 1 -16 and stations 25-38 there is a low resistive structure beneath the surface layer. Between stations 17-24 there is a high resistive structure with the same resistivities as the surface layer. This region is interpreted as a fault structure (Fig.2), which is filled with sedimentary rock (sandy clay).

The data quality and the consistency between ρ_a and φ could be checked in the apparent resistivity curves, which are shown in Fig.5. RMT station 8 on profile 2 show that the resistivity values decrease from highest resistivity (> 80 Ωm) to low resistivity (30 Ωm) with phase values less than 50 °. The sounding curves of station 8 and 13 (figure 5) and station 16 (figure 5) on profile 2 shows that the phases exceeds value more than 45° indicating a low resistive (sediment) structure at larger depths, meanwhile the good conductive metamorphic series is indicated by the phase values lower than 45. Fig. 6 shows a comparison between measured and calculated data at selected frequencies (79 kHz, 387 kHz and 784 kHz). Measured and synthetic data fit well together keeping in mind the geological complexity and inhomogeneous in this survey area, however some misfits which are associated as 3-D effect.

The direction of the fault can be constructed using the 2-D inversion models of profile 1-3 as shown in Fig.3. The direction of the fault structure is found to be N60E.

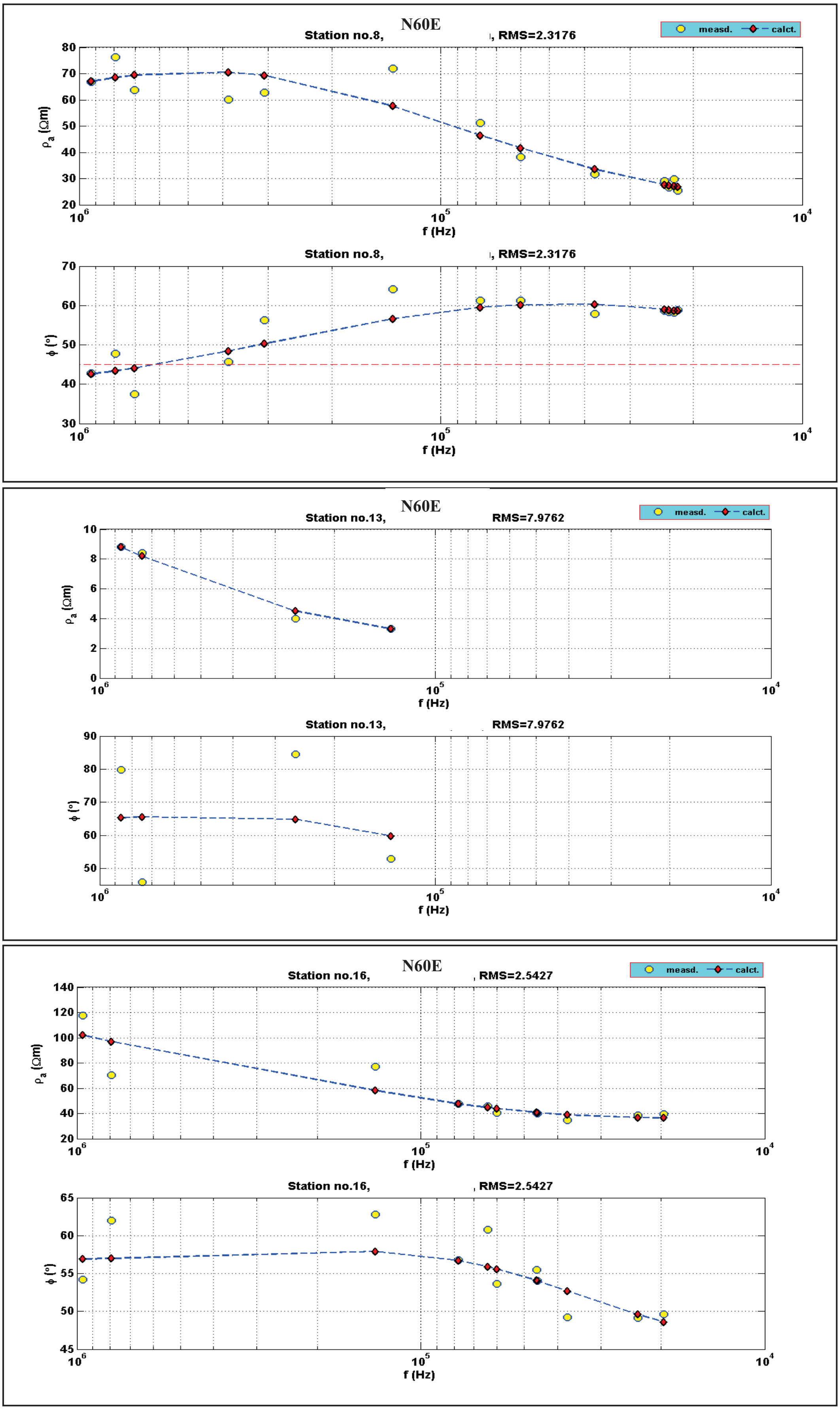

Fig.5. Comparison of measured and calculated RMT data of stations 8, 13 and 16 on profile 2

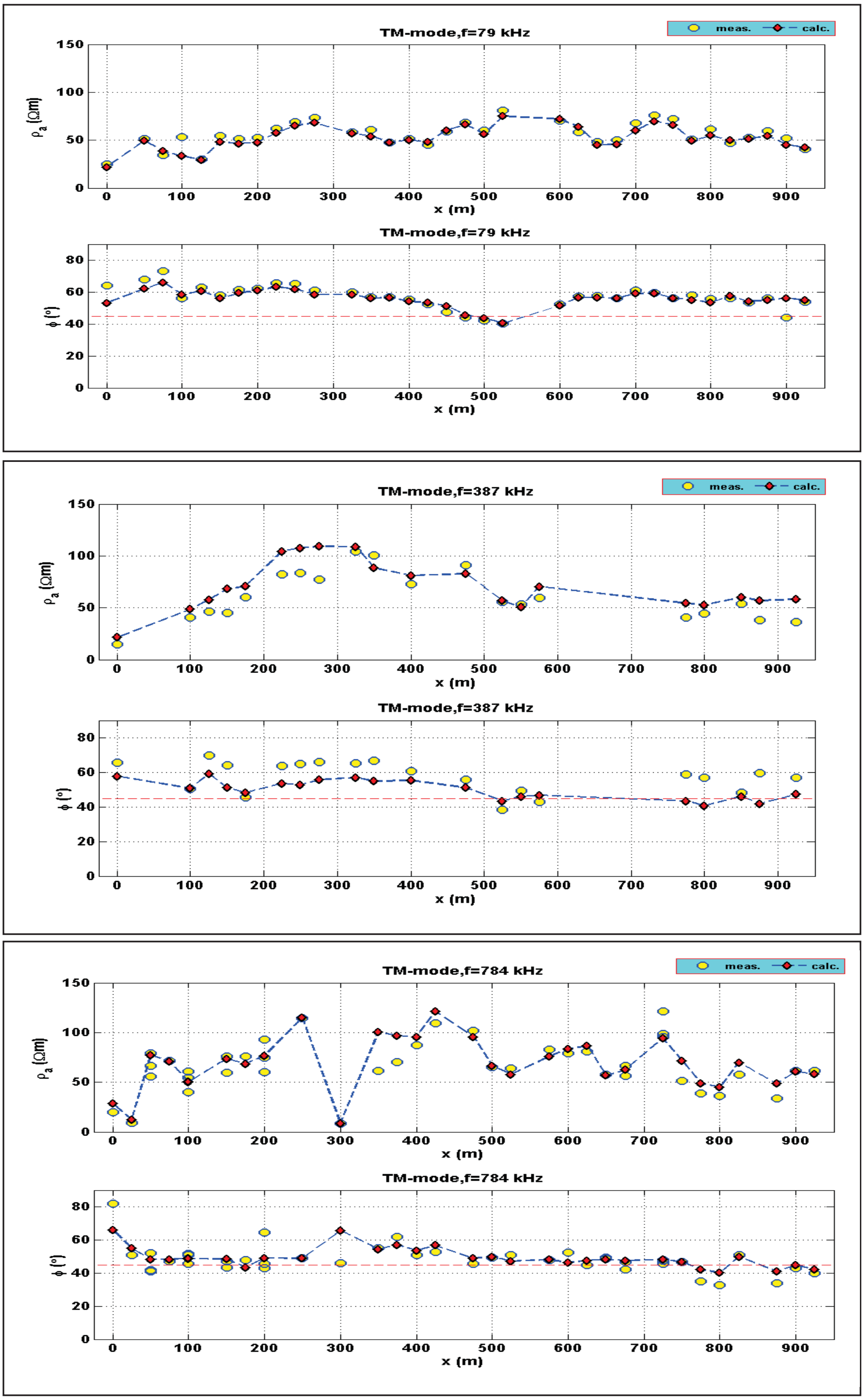

Fig.6. Comparison of measured and calculated RMT data at frequencies 79, 387 and 784 kHz

TEM soundings

In order to overcome the resolution problem of TEM soundings for near surface structures, we carried out RMT soundings at each TEM location to use this additional information in the following joint inversion. The distance between the TEM stations is depending on the accessibility of the area. Thirty loop-loop measurements (Tx: 50 m x 50 m and Rx: 10 m x 10 m) were performed during this campaign. TEM data were obtained using the Zonge NT 20 transmitter and the Zonge GDP32 receiver.

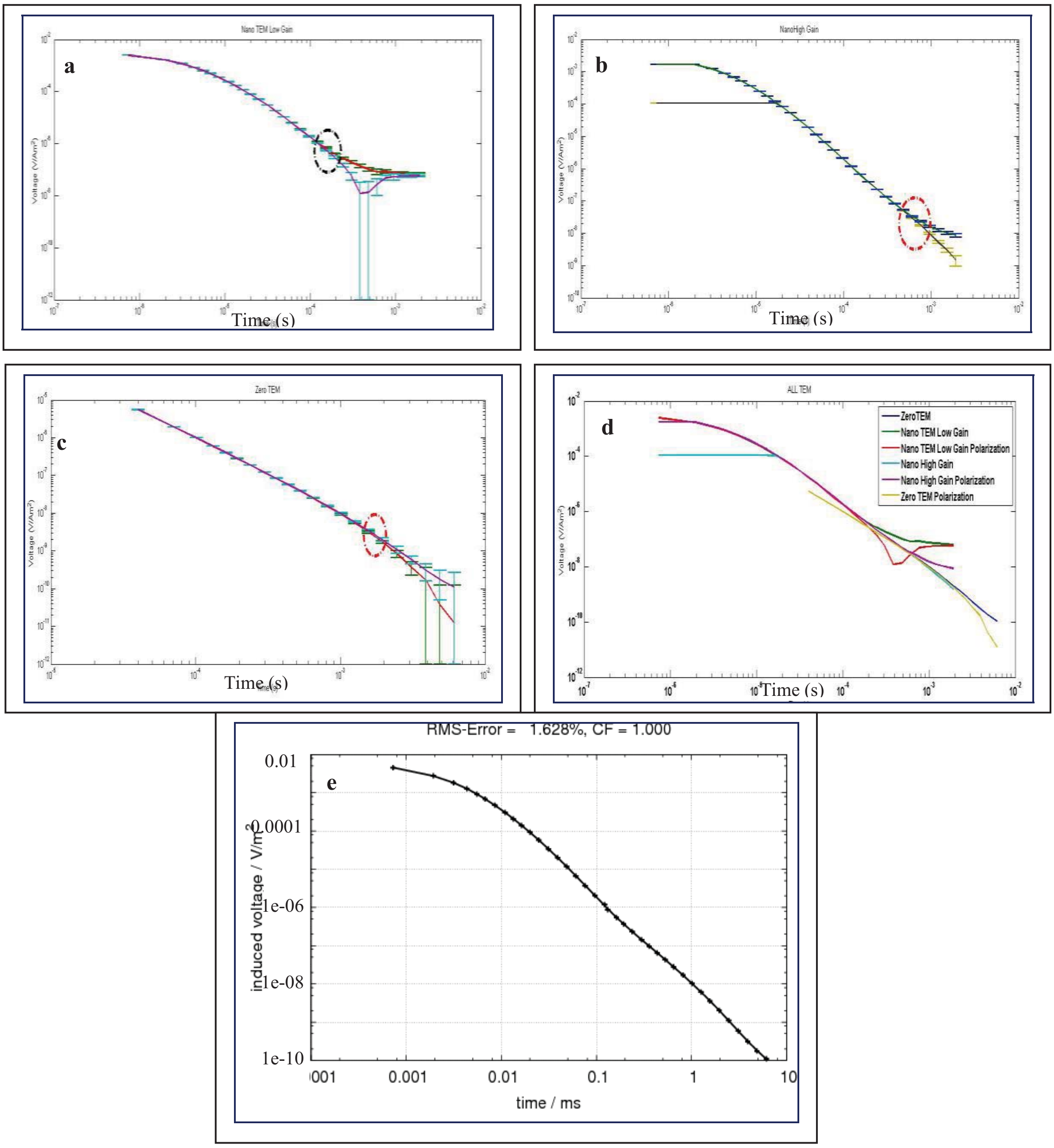

Fig.7. The segmentation recording scheme for the in-loop Zonge manufactured TEM system; low-gain Nano TEM (a), high-gain Nano TEM (b), automatic-gain Zero TEM (c), combination of all-transient (d), TEM sounding of station 1 was processed with deconvulation and inversion (e). The circle indicate unreliable decay curves for very late times that we address to be an A/D conversion problem of the Zonge device.

The system allows to measure TEM data in two distinct modes, according to different investigation depths: Nano TEM with low and high gain and Zero TEM measurements (Fig.7). Both modes give unreliable decay curves for very late times that we address to be an A/D conversion problem of the Zonge device. To cope with this problem we simply changed polarity of the receiver loop. Consequently a time consuming data acquisition procedure was required.

The first measurement for shallow investigation was done in NANO TEM low gain mode. This mode uses low currents (about 0.3 A) which is switched of quickly. Moreover, the ramp time were taken from 0.3 µs to 2.5 ms with manual low-gain settings. Whereas, Nano TEM high-gain uses a higher transmitter current (about 3 A), which gives a higher penetration depth with a saturation for earlier time. Nano TEM low-gain and high-gain uses 12 Volt power supply. To obtain higher penetration depths, Zero TEM measurements were carried out from 31 µs to 6 ms time window with accompanying automatic-gain settings. It uses a relatively high transmitter current (10 A) at 24 Volts and 50-55 µs turn-off ramp time.

The penetration depth of TEM methods depends on the time after the transmitters current is switched off [Parasnis, 1986]. The diffusion process of the transient electromagnetic induction field can be visualized using the smoke ring concept [Nabighian, 1979]. Due to the low conductivity (metamorphic rock), the maximal penetration depth (δ_T) of TEM sounding is approximately 200-300 meter. The next step is a deconvolution of the data that was done by the EADEC algorithm (Lange, 2002) followed by a 1-D inversion with EMUPLUS (e.g. Scholl, 2005) (Fig.7 (e)). The 1-D interpretation of the TEM data also shows the lateral boundary of the fault structure at stations 12- 17 on profile 1 (Fig.8).

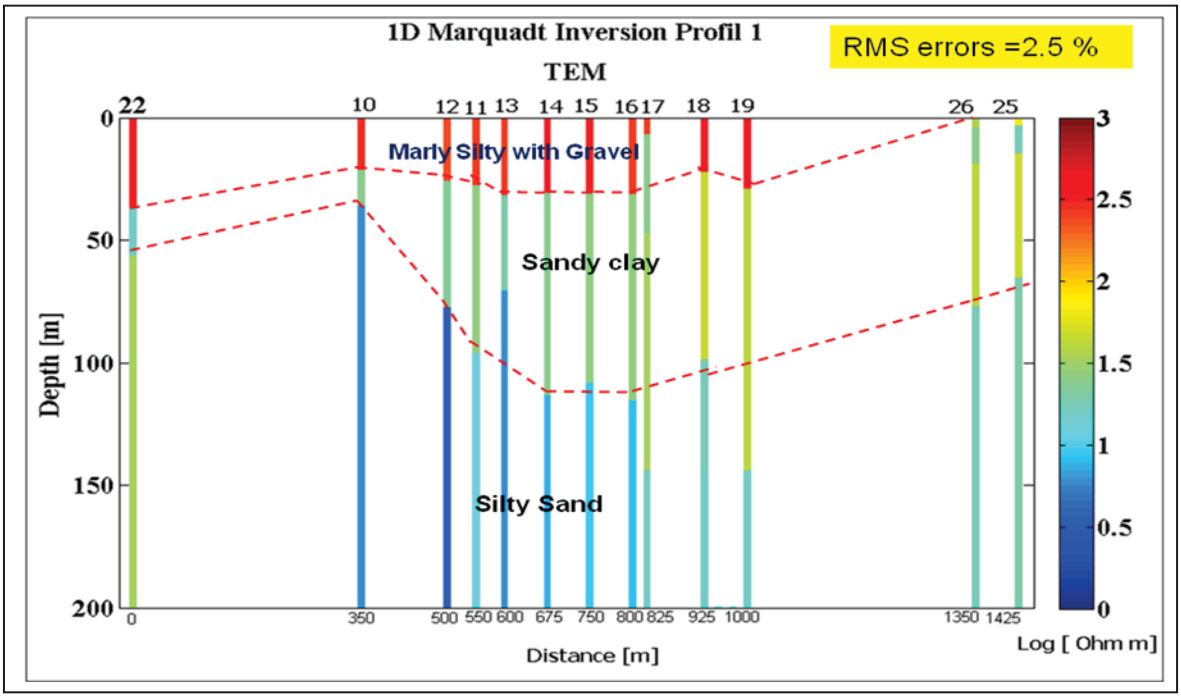

Fig.8. One-dimensional TEM model on profile 1

Joint Interpretation of RMT and TEM data

A joint interpretation can be used to get a better resolution of the model parameter and this will enhance the possibility to detect the active fault structure. Generally we conducted RMT soundings at each TEM site location so that we can estimate a jointly inverted model at each TEM location (Fig.9).

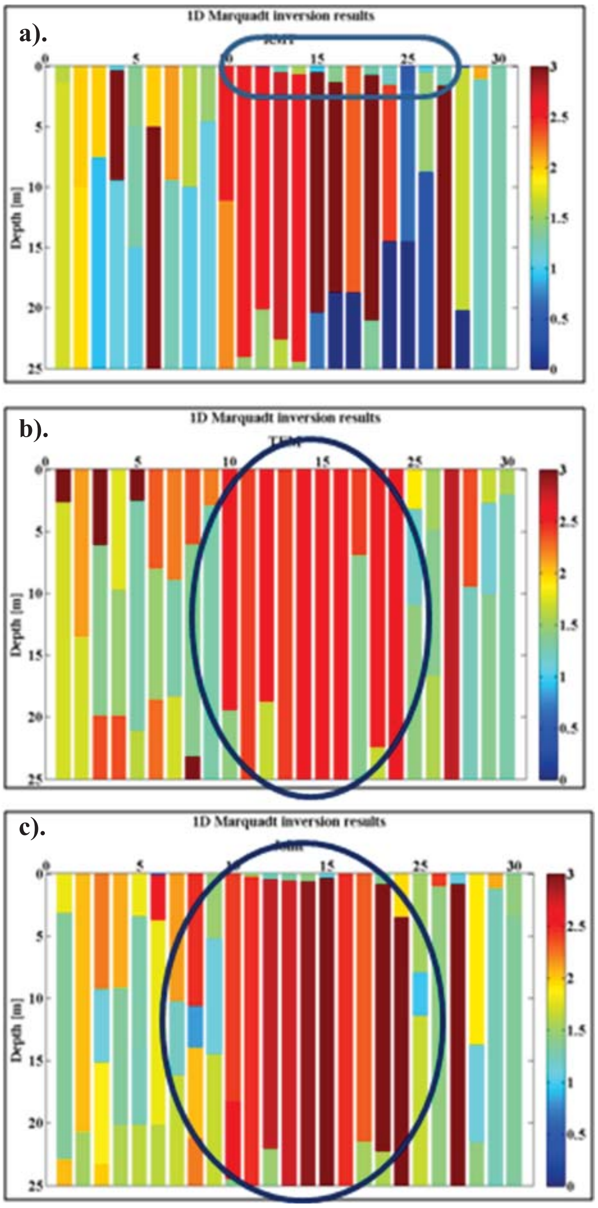

Table2. The importance parameter of station 10

	RMT	Imp	TEM	Imp	Joint	Imp
ρ1[Ωm]	322.46	0.99	367.98	0.57	247.99	0.99
ρ2[Ωm]	158.17	0.99	367.98	0.88	344.23	0.27
h1[m]	5.56	0.97	9.75	0.97	9.15	0.84
RMS[%]	4.90		3.10		3.20	

Table 3. Model resistivies obtained from the RMT and TEM data for the selected stations

Station	RMT	TEM	Joint
10	322.46	367.98	344.23
11	332.20	273.45	303.06
12	450.73	372.20	616.36
13	562.36	271.88	531.33
14	363.93	420.46	865.49
17	199.91	260.49	208.14
26	4.47	23.48	26.93
25	28.71	15.83	32.98

Fig. 9. (a) One-dimensional model section derived by RMT data (b). One-dimensional model section of TEM data (c) Joint interpretation of TEM and RMT data. The comparison between TEM, RMT and Joint on station 10, 11,12,14,17 and 25 are shown with ellipses.

The 2-D model of the RMT data (Fig.2) gives information about the top structure of this area, but the deeper structures and the fault system cannot be resolved in detail solely based on RMT soundings. On the other hand, TEM shows a good resolution of deeper structure. The joint interpretation/inversion process was done using the Marquardt algorithm. The interpretation of the 1-D RMT model between station 13 – 25 resolves of the top layer (Fig 9 (a)) and the TEM 1-D model (Fig.9b) shows the bottom of boundary layers of fault structure (Fig.8) in this area more distinctly, however the top layers of TEM stations 13-25 could not be resolved well because the top layer has high resistivity value (> 80 Ω m) addressed as metamorphic rock from our reference borehole.

Joint inversion can increase the number of model parameter that includes some of which the methods cannot resolve separately (Fig.9c). The importance parameters were calculated for the model resistivities and thickness [Jupp and Vozoff, 1975] [Tezkan et.al., 1995], [Schwinn, 1999], which are plotted in Table 2. It shows the parameter (ρ_1, ρ_2, h_1) as a result of the individual single/joint inversions. Values between 0 (unimportant) and 1 (important) are calculated. From this analysis we conclude that the resistivity values and thicknesses of the fault structure (Fig.9) is well resolved at station 10, 11,12,14,17 and 25; however, at station 13, it is hardly resolved (importance 0.65). The resistivity value at station 26 is weakly resolved with importance parameter 0.12. The model resistivities of the second layer (between 5-20 m) obtained from 1-D models of TEM and RMT data are in good agreement with the joint inversion models (Table 3).

Conclusion

The Inversion of RMT and TEM data indicates a normal fault structure with a strike direction of approximately N 60 E. The RMT and TEM models generally show four layers that can be separated according to their resistivity values. We address them as to be metamorphic and sediment rocks, which are marly silty sand with gravel (>> 100 Ω m), marly silty sand with clay (50 - 100 Ω m), sandy clay (30 – 50 Ω m) and silty sand (10-30 Ω m). The RMT data was interpreted using 2-D inversions technique that results in a good fitting between observed and calculated data. Due to the high resistivity of the top layer, the skin depths of the RMT soundings are around 35 m. The TEM data gives detail information of the lower structure down to a depth of 200 m.

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