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GEOPHYSICAL INVESTIGATION OF HYDROGEOLOGICAL CONDITIONS AND SALINATION PROCESSES AT THE MARATHON – KATO SOULI BASIN (NE ATTICA, GREECE)

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Abstract

This work presents the results of gravity, TEM and geological surveys conducted in the area of Marathon - Kato Souli Plain, as part of an effort to study its hydrogeological characteristics. The gravity survey offered a rather detailed image of the alpine basement and together with surface geological observations, insight into the post-alpine tectonic processes that have controlled the development of the area. The TEM survey produced detailed three-dimensional images of the aquifer systems and salination conditions. The results have shown that (a) the alpine basement is located much deeper than previously thought and, (b) that the sea water intrusion takes place both near sea level and at depth. The depth and morphology of the alpine basement are believed to have been fashioned by faults that either have not been active during the Quaternary, or are buried under thick terrestrial and alluvial deposits. Sea water intrusion forms at least two distinct salination horizons, presumably as a result of intersecting faulting structures that facilitate horizontal and vertical transportation of sea water between permeable formations. The vertical alternation of permeable-impermeable rock formations may be attributed to (alpine) folding, which results in vertical repetition of the same lithological units, in this case karstified marbles.

1. Introduction

This paper presents the results of gravity, TEM and geological surveys conducted in the area of Kato Souli, Marathon (NE Attica, Greece), as part of a research programme to study its hydrogeological characteristics: given that the aquifers (karstic and unconfined) experience intense salination effects (e.g. Koumantakis et al., 1994), one principal objective of the surveys was to evaluate the depth and morphology of the basement (hence the macroscopic characteristics of the structures hosting the aquifer systems) and to map the geoelectric (salination horizons) and neotectonic structures in an attempt to understand the origin and development of such phenomena. Notably, this would also provide information about reverse pollution effects, i.e. data on the paths through which pollutants due to intense agricultural activity may be transported to the sea and to the nearby natural reserves of Schinias wetland and pine forest. Finally, the results of the surveys may contribute to the understanding of the geology and tectonic evolution of the study area and, to a lesser extent, the regional geology and tectonics.

The Marathon basin has an area of approximately 40km^2 and is shaped like a parallelogram with dimensions 9×4.6 km and NE-SW oriented long axis. In the Marathon and Kato Souli plains the relief is very smooth, almost flat as can be seen in Figures 1 and 4. The plains are bounded to the north by mounts Kotroni, Strati and Terokoryfi, to the west by the Penteliko mountain complex, to the south by Marathon bay and to the east by the Drakonera and Mytika uplands. The transition to the highlands coincides with abrupt topographic changes.

2. Geology

The Plain of Marathon is almost completely covered by alluvial deposits and post-alpine sediments. Until recently, it was generally thought that the maximum thickness of post-alpine sediments was 100m (Kounis, 1985), while a thickness of 50m is mentioned by Tzouka (2003) at the vicinity of Mt. Drakonera, based on interpretations of VES data. Nevertheless, and on the basis of the gravity survey reported herein, the thickness of the post-alpine deposits is considerably larger, approaching 500m at the southernmost margin of the study area (see Section 3). The alluvial deposits are fairly typical and indicate progressive withdrawal of the sea during the last ~6000 years, at a mean rate of 0.4-0.5 cm/a (Maroukian et al., 1993; Pavlopoulos et al., 2006). The flanks of the highland areas to the north (Patima area) and east (Sfakona area) stretches of the Plain are covered by undivided scree and talus cones of low-intermediate cohesiveness.

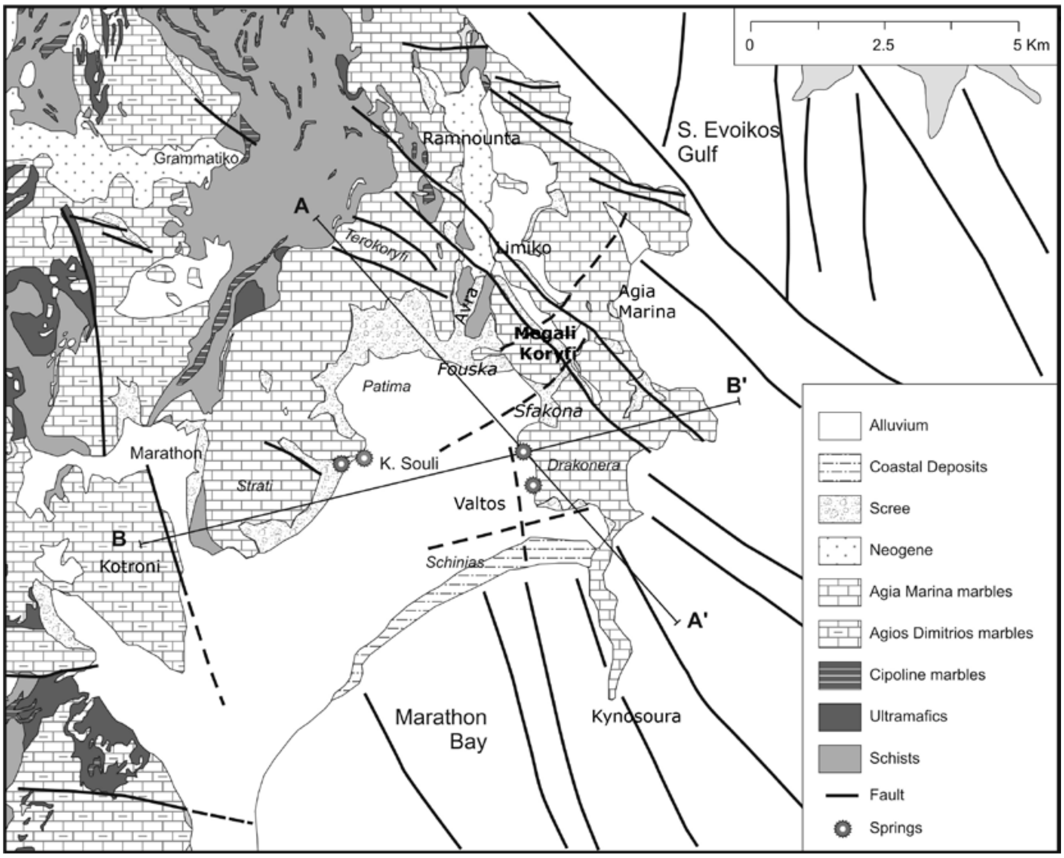

Figure 1- Simplified geological map of the study area (modified from Lozios, 1993 and HCMR, 1989). Toponyms referred to in the text and the traces of the interpretive geological cross sections of Figure 7 are also marked.

The nearest – in terms of geography - outcrop of post-alpine sediments can be observed at the Limikon area, north of the Plain. They are sandy marls and sandstones intercalated with conglomerates, possibly of Pleicone age (Katsikatsos, 1990) and thickness possibly in excess of 50m. Neogene – PleioQuaternary deposits are not observed at the surface, but they may well be buried under the Quaternary sediments of the Plain, especially in areas where the geophysical studies have determined large depths to the alpine basement (see Section 3).

The alpine basement comprises the formations of the autochthonous Attica Unit. Lozios (1993) reports that the base of the stratigraphic column comprises the Ramnounta Schists (highly altered chloritic - feldspathic schists), the thickness of which is estimated by Katsikatsos (1990) to be ~400m. According to Lozios (1993), this formation is homologous to the "Ano Souli – Hagioi Theodoroi schists", or "Marathon schists" reported by Katsikatsos (1990). The schists are overlain by the “Hagia Marina marbles” and the “Hagios Dimitrios – Terokoryfi marbles”, which Lozios, (1993) considers homologous to the upper Cretaceous formations. Katsikatos (1990) refers to these formations as the “Hagia Marina marbles” and “Marathon marbles” respectively. Their thickness is considerable and may even exceed 800m.

3. Gravity Survey

The main target of the gravity survey was to image the alpine basement, to determine the thickness of the post-Alpine sediments and to reveal the covered structure of the Marathon Plain. One hundred and twenty (120) gravity stations were established in the area, distributed in such a way that the mean distance between any two neighbouring stations is approximately 500m. As shown in Figure 2, they are spread throughout the post-alpine formations covering the Marathon and Kato Souli plains, while several stations are located on the metamorphic basement (uplands) to control the inversion and interpretation processes. This distribution is expected to resolve with adequate precision, of the basin margins as well as the depth and morphology of the basement under the post-alpine formations. Details about the measurements, data reduction and interpretation procedures are given in Chailas et al (2007), so that only a brief introduction will be attempted herein.

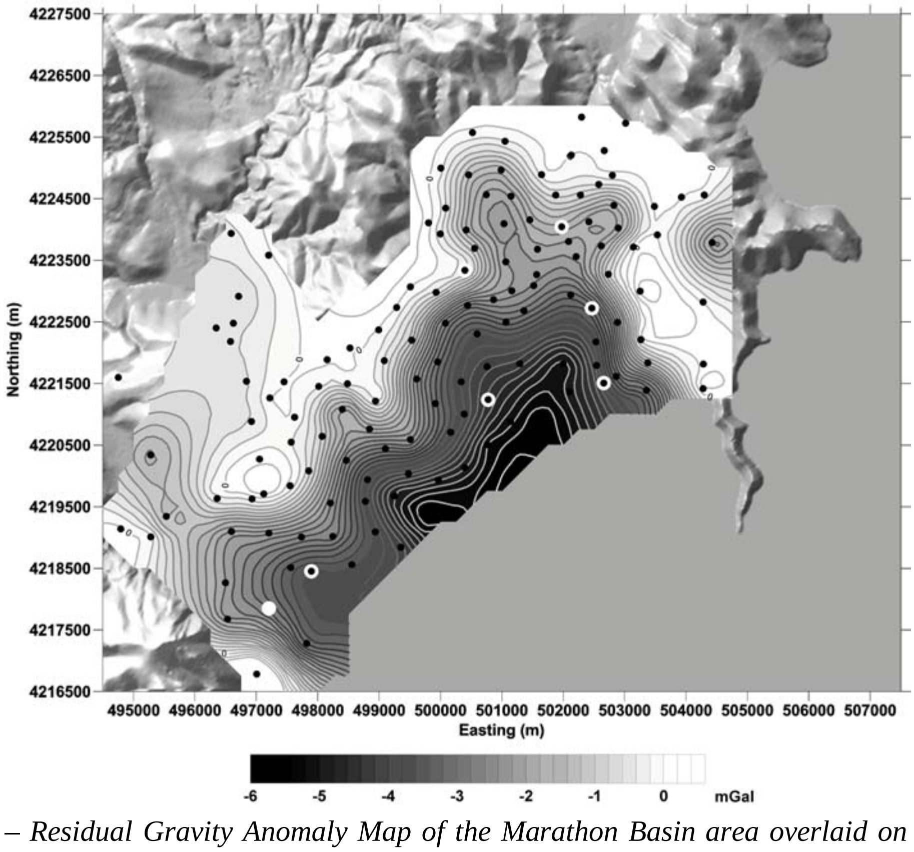

Figure 2 – Residual Gravity Anomaly Map of the Marathon Basin area overlaid on a shaded relief of the DEM prepared for the analysis. Overlaid is the distribution map of the gravity stations. Coordinate axes in metres, EGSA projection system.

The coordinates of gravity stations were obtained with differential GPS positioning, which affords an accuracy of a few millimetres in both the horizontal and the vertical coordinates. Gravity measurements were taken with a LaCoste and Romberg Model G gravity meter. Standard observation and reduction/adjustment procedures were followed for both gravity and GPS data. The terrain correction was computed for a radius up to 21 km around each station. The standard Bouguer anomaly (not shown herein) was calculated using a density 2.67 gr/cm^3; with values ranging between 49.5 and 61 mGal, it exhibits a strong westward downhill trend (regional field). To remove the trend, use was made of the gravity data bank available from Lagios et al. (1996): the Marathon gravity data set was spatially extended with data extracted from the data bank and the regional field was calculated by fitting a quadratic surface to the spatially extended data set. The resulting *residual* anomaly map is presented in Figure 2. Values range between 0 and 6 mGal and exhibit a general NW-SE trend with significant fine structure at the area of Kato Souli. The residual anomaly is generally plunging to SE and showing a step-like change in the areas of Kato Souli and Oinois River. It is also apparent that the boundaries of the Basin are quite well defined by the abrupt change of the gradient of the anomalous field along the Alpine – Post Alpine boundary.

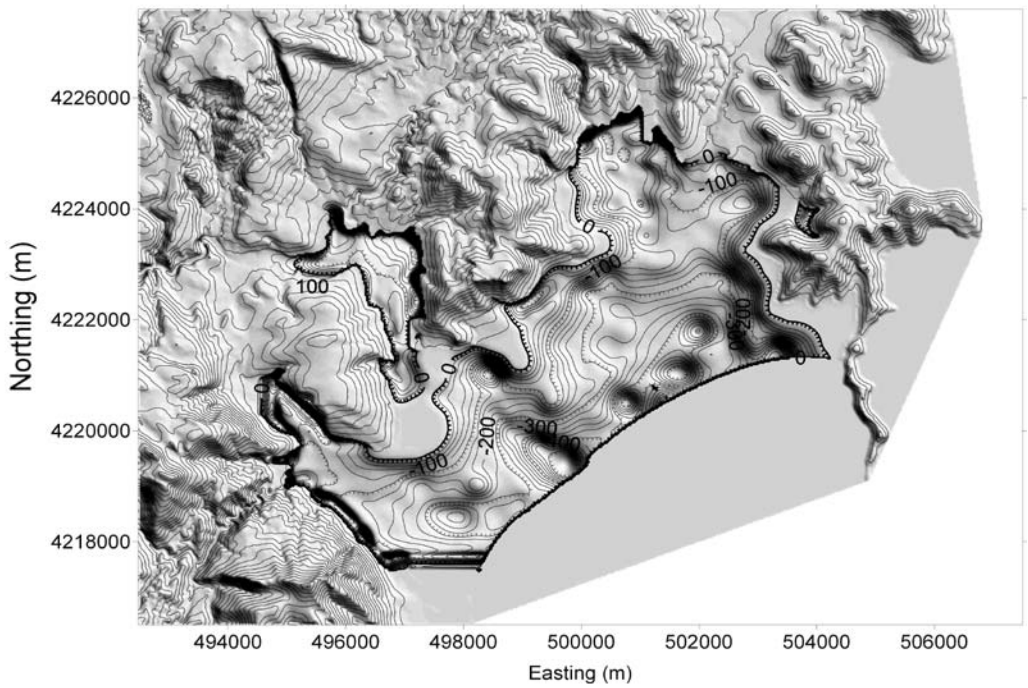

Figure 3 – 3D Model of the Marathon Basin basement relief combined with the detailed shaded relief of the surrounding area topography. EGSA projection system

The residual anomaly was inverted using an unpublished 3-D algorithm developed by S. Chailas and based on the theory of Radhakrishna Murthy et al. (1990). In this approach, any three-dimensional geological object can be modelled with some configuration of adjacent vertical polygonal laminae. Density contrasts between object and host structures are kept constant and the inversion procedure iteratively adjusts the vertical extent of the model until it homes-in to a solution. In this implementation, the post-Alpine formations of the Marathon Basin were considered to be a single object with a density contrast of -0.5gr/cm^3 against the basement rocks. The upper surface of the model (surface topography) was kept constant and the lower surface (Alpine basement) was allowed to vary. The results (topography of the basement) are shown in Figure 3, combined with a digital elevation model of the surrounding area.

The structure of the basin is well resolved and affords a first and very important observation: It has hitherto been accepted that the basement of the Marathon basin comprises marbles located at a depth of 40-55 m below surface near the margins of the basin and up to 60 m at the central parts (Melissaris and Stavropoulos, 1999; Tzouka, 2003; Margonis, 2006). This understanding was mainly founded on interpretations of geoelectric (Schlumberger) data, particularly those by Melissaris and Stavropoulos (1999). The existence of marbles at such depths has not been verified by drilling; the deepest boreholes in the area do not exceed 20m (e.g. Margonis, 2006). Our work has conclusively shown that the basement is located at definitely greater depths and that its morphology is intricate and tectonically controlled (see below). There's no karstic aquifer at depths of 50 – 60 m below the Marathon Basin and scrutiny will show that the 'shallow' basement assumption was based on misinterpretation of the Schlumberger data.

Instead we probably have to deal with a system of sedimentary aquifers possibly communicating through the intricate tectonic fabric (see Section 5).

4. Transient Electromagnetic (TEM) Survey

The geoelectric structure of the Kato Souli area was investigated with the Transient Electromagnetic (TEM) method, which is very sensitive to conductive formations such as those resulting from sea water intrusion. Information about the TEM method, especially with respect to its application in groundwater research, can be obtained from standard literature, e.g. Fitterman and Stewart (1986), Nabighian and McNae (1991), Christiansen et al. (2006), etc. A total of 36 soundings were conducted at Kato Souli, distributed so that the mean distance between them would be approx. 200m (Figure 4). This affords adequate imaging of laterally extended structures, such as for instance are salination horizons and intermediate depth sedimentary aquifers.

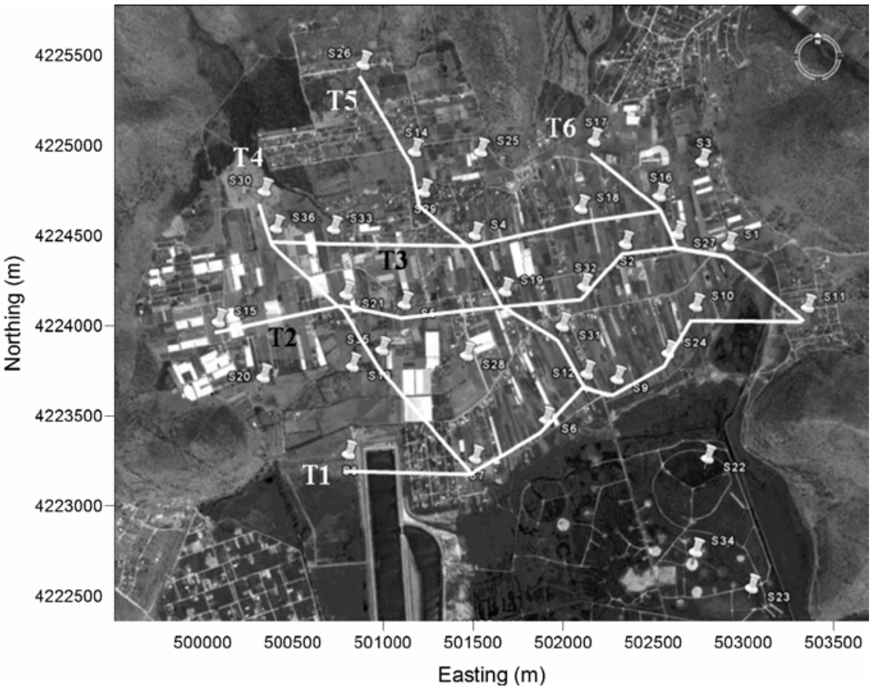

Figure 4 –TEM measurement sites at the area of Kato Souli. T1, T2 and T3 indicate the sections presented in Figure 5 and discussed in the text. EGSA projection system.

Measurements were carried out with the TEM-FAST 48 HPC system (Barsukov et al, 2007). In all cases the single-loop configuration was implemented, with 50×50, 50×70, 70×70 and 100×100 m loops, depending on the available space. Typical examples of TEM data are shown in Figures 5a,b (left). The study area is basically suburban with light industrial activity and analogous noise environment, mainly produced by the emissions of the power distribution grid. This type of noise affects the late times of the transient process. A handful of stations also suffer from galvanic distortions due to nearby grounded metallic conductors (mainly fences), which also affect the late times (e.g. Figure 5b, left). In both cases the healthy (distortion-free) data are shown with black triangles and the distorted data with gray triangles. In general, the noise is significant at times t > 4-5ms, but, depending on the location of the sounding, it may affect anything in the band 1-15ms. As it turned out, this was somewhat fortunate because the depth, depth-extent and layout of the target formations were already resolved by the time that noise began to dominate (see Figure 5). The best quality data were measured at the Valtos area (wetlands) and the worst at the NW areas, where it was emitted by failing groundings of pumping installations.

The interpretation was carried out with approximate inverse imaging after Svetov and Barsukov (1984) and Barsukov et al. (2007) and, mainly, linearized 1-D inversion with Levenberg-

Marquardt stabilization to layered earth models. Distorted data were not used in the inversions. Typical examples are also shown in Figures 5a,b (right). Given the geology of the study area, (aquifers in layered sediments), the models would normally satisfy the observations with a relatively small number of layers, 3-5 as a rule. The resulting simple layered models were subsequently collated (see Figure 4) and interpolated to produce the resistivity pseudosections presented in Figure 6. They were also interpolated in three dimensions to produce the isosurface of 10Ωm, which delimits the zone(s) of intense salination – volume(s) with resistivity lower than 10Ωm – which is shown in Figure 7 together with the gravimetrically determined topography of the alpine basement.

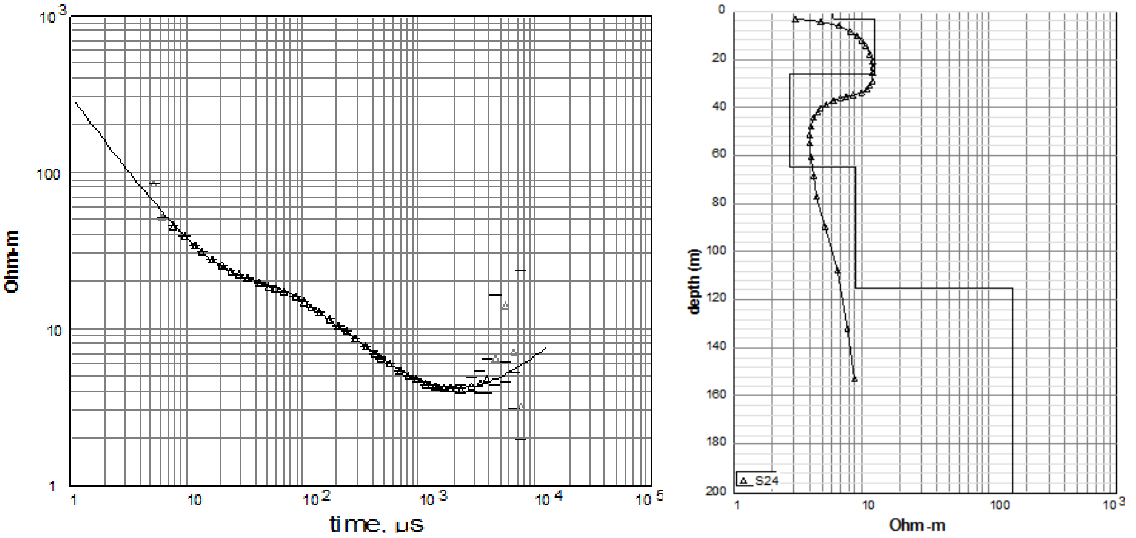

Figure 5a – Typical examples of measured data and their interpretation: Sounding S24. ***Left:*** *The discrete curve (up triangles) represents the late-time apparent resistivity (in Ωm), as a function of time (in μs). The continuous black curve represents the late-time response of the layered 1-D model which interprets the measurements and is depicted in right-hand side graph.* ***Right:*** *The discrete curve (triangles) represents the approximate inverse image of the measurements towards a resistivity vs. depth profile. The continuous line represents the 1-D layered model that optimally interprets the measurement and produces the late-time apparent resistivity response shown in the left-hand side graph.*

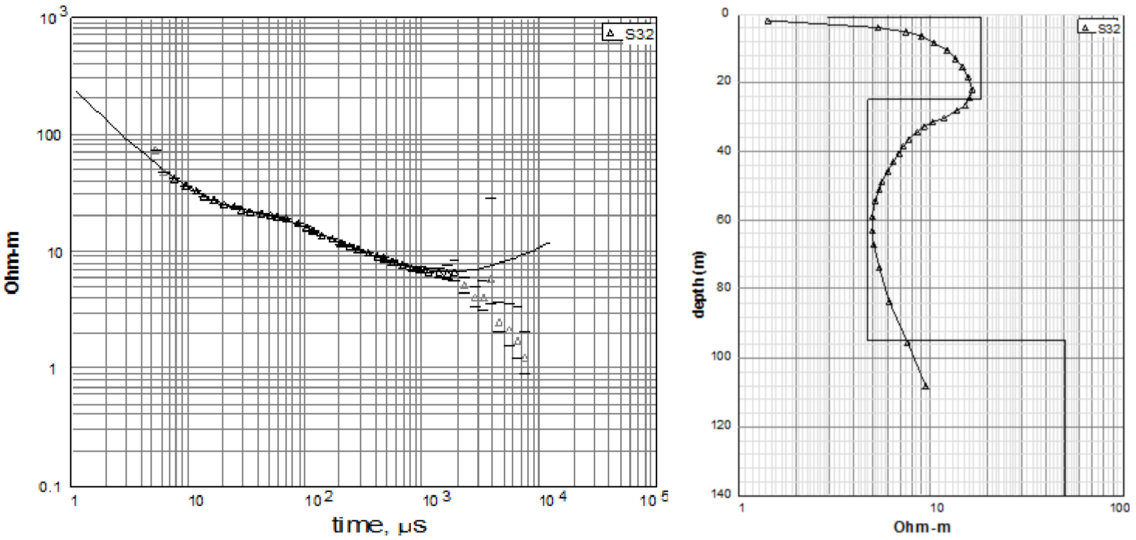

Figure 5b. Typical Examples of measured data and their interpretation: Sounding S32.

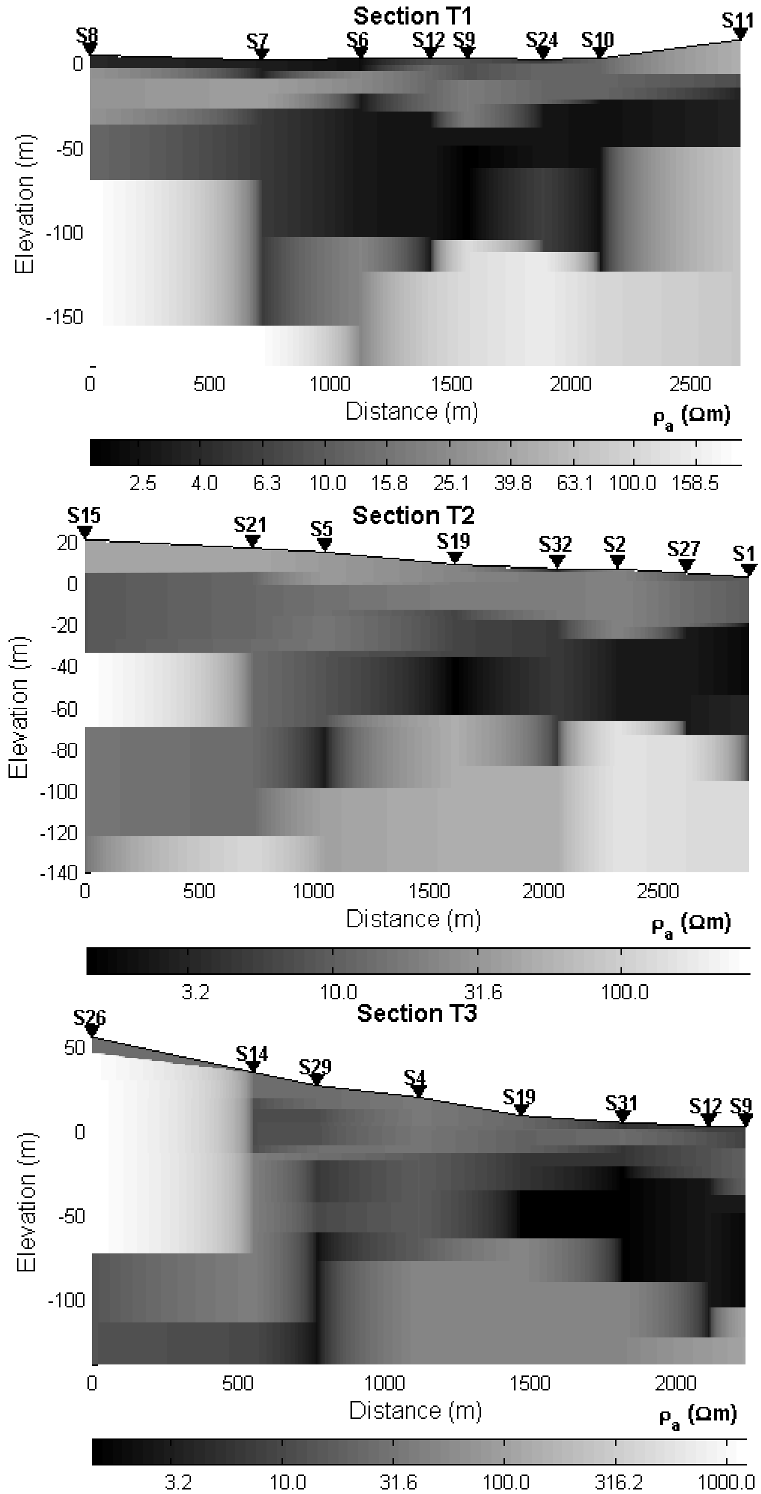

Figure 6 –Resistivity pseudosections constructed by collating 1-D layered interpretations of TEM soundings (also see Figure 4).

Study of the resistivity cross sections T1-T3 (Figure 6) and the combined resistivity - basement topography images (Figure 7) shows that sea water intrusion is both prominent and extensive! In general terms, the salination horizon is thicker at the south and east parts of the surveyed area, with particular reference to the zone defined by the localities of Kato Souli, Patima Fouska, Sfakona and Valtos where it extends from -30m to -80m and at places up to -100m. The saline –

brackish water table is thinner to the N-NE, extending between -30m and -70m, albeit clearly present and detectable up to the northern edge of the studied area.

The relatively high resistivity formations (> 100 Ωm) observable at elevations lower than -80m to -100m in section T1 between sites S8 and S10, section T2 between S21 and S1 and section T3 between S29 and S9 *do not* correspond to the alpine basement, as is also evident from Figures 3 and 7: the basement there is to be found at depths greater than 200m. Given the low density of these resistive domains, it appears possible that they comprise relatively impermeable post-alpine deposits such as marls. Conversely, the alpine basement is detected in section T1 beneath sites S8 and S11, in section T2 at site S15 and in section T3 beneath S26 and S14. In all these cases it is characterized by *very* high resistivity (>300 Ωm and up to 2 kΩm) indicating the presence of compact impermeable rock, possibly schists. The remarkable coincidence in basement depth determinations between the TEM and gravimetric methods is also noteworthy.

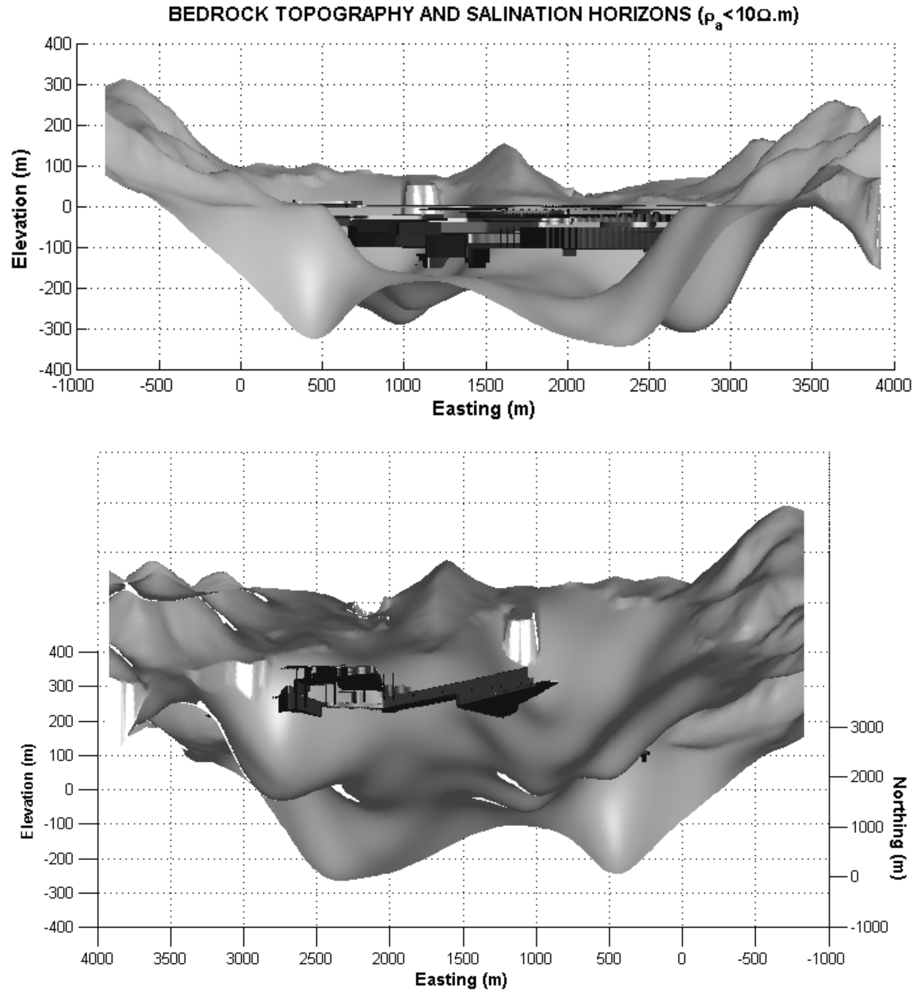

Figure 7 – Three dimensional representation of the 10Ωm isosurface which delimits the zone of intense salination, together with the gravimetrically determined topography of the alpine basement. Top panel is a head-on view, bottom panel is from N and below.

The data of Figures 6 and 7 clearly show that the salination horizon (and all aquiferous formations indeed), are located almost exclusively within the sediments and at depths considerably shallower than those of the alpine bedrock. However, it is important to point out that at the north and north-east of the surveyed area, the salination horizon intrudes into the basement and apparently is to be found farther along, possibly unto the coast. Inasmuch as it is presumed that the permeable rock in the alpine basement comprises karstified marbles, this indicates a transition from sedimentary to karstic aquifer conditions and provides an additional hint about the process

transporting sea water into the sediments of the Marathon – Kato Souli Plain.
Finally, as evident in sections T2 and T3 (Figure 6) and in Figure 7, a *second* saline – brackish water layer has been detected at the N and NW parts of the surveyed area, also within the alpine basement and at elevations lower than -120m. This is attributed to a second (deeper) karstic aquifer, again presuming that the permeable rock formations comprise karstified marbles.

5. Tectonics

The alpine basement comprises exclusively metamorphic rocks, which have undergone two phases of plastic (folding) and one phase of brittle deformation (Lozios, 1993). At large scales one observes isoclinal, as well as open folds with NE-SW and NW-SE axes respectively. As a result, in the immediate area of interest and specifically northward of the Fouska area of Kato Souli, the Ramnounta schist formations appear on top of the Hagia Marina marbles, at the core of an anticline with a general NNE-SSW orientation at the Avra crest, between Mts Agrilia and Megali Koryfi. This is the only outcrop of Ramnounta schists within the surveyed area.
The younger brittle deformation phase is expressed with WNW-ESE to NW-SE faults. Onshore, structures of such orientations are located to the NE of the Plain (Megali Koryfi and Misovardia faults). These are traceable for at least 8km consecutive and quite probably extend into the sea, where the NW-SE fault system dominates. Scrutiny has also shown the existence of neotectonic faults with NE-SW and NNW-SSE to N-S orientations respectively, which are no longer considered to be active.
The older fault generation may exert a very significant influence on the hydrogeological conditions of the study area, because the network of discontinuities it is associated with still comprises a preferential water transportation pathway. This hypothesis is based on the examination of the morphology of the alpine basement, which exhibits local rises and depressions that can hardly be attributed to exclusively exogenous factors like erosion. It appears that the post-alpine sediments have covered a palaeo-terrain that had been tectonically controlled. In consequence, it is suggested that there exist buried tectonic structures (faults and fault zones), whose geometry and kinematics is difficult to determine even at the outcropping alpine formations due to the conspicuous absence of characteristic stratigraphic markers (horizons).
Locations with strong indication for the existence of inactive faults are the Fouska and Sfakona areas at Kato Souli. There, the alpine basement exhibits increased slopes and approaches the elevation of -300m, with morphology characterized by an elongate depression of approximately ENE-WSW orientation just northward of Kato Souli. The S-SE boundary of the depression is flanked by a rise of the same orientation, while further southwards (Valtos area) the basement drops to elevations as low as -500m. Such anomalies can hardly by attributed to non-tectonic causes, hence the suggested existence of inactive faults with approximate ENE-WSW orientation, passing just south of Megali Koryfi and continuing a westward course under the post-alpine sediments of the Plain.
The gravimetric determination of alpine basement morphology also shows that at the eastern margin of the Plain (Mt. Drakonera), the basement exhibits steep slope (35-40°) and plunges to the elevation of -300m. There is no surface indication for the existence of a fault zone at the area. However, examination of the neotectonic map of the S. Evoikos gulf (Hellenic Centre of Marine Research, 1989), reveals the existence of NNW-SSE oriented faults at Marathon bay; the northward continuation of one of these faults *identifies* with the eastern boundary of the Plain and the flank of Mt. Drakonera.
In concluding, it appears that tectonic activity may exercise a twofold influence on the hydrogeological conditions of the study area. First, the alpine folding deformation phases have created inversions of the original stratigraphic column and/or repetition of formations, thus producing alternation of permeable and impermeable rocks. Second, the brittle neotectonic deformation (both older and younger faulting phases) have configured the morphology of the alpine basement and have created preferential water transportation pathways that facilitate the vertical communication between permeable alpine formations.

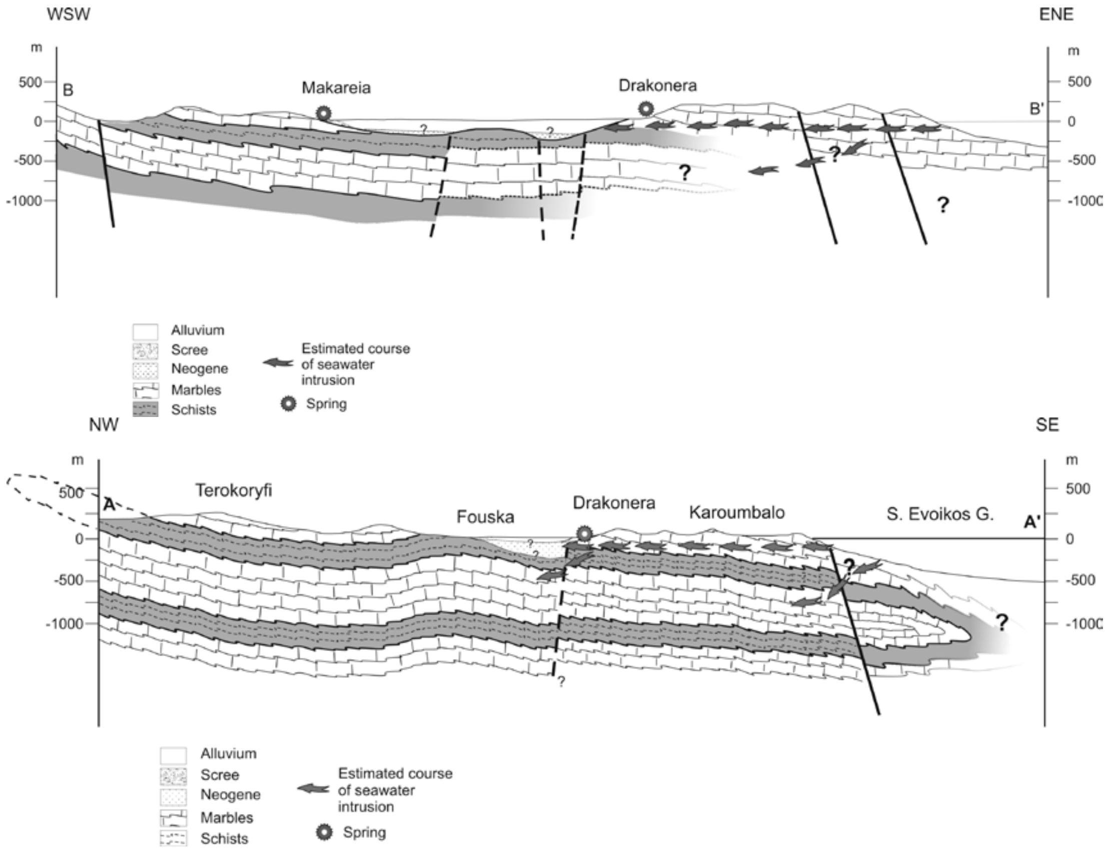

Figure 8 – Interpretive geological cross sections (see Figure 1).

6. Conclusions

The hydrogeological conditions of the study area heavily depended on the litho-stratigraphic configuration and (past) tectonic deformation, as well as on the proximity of the sea, groundwater use (withdrawal rates) and natural or anthropogenic pollution of the groundwater tables. The geophysical investigations have shown that (a) the alpine basement is located much deeper than had previously been estimated and, (b) that the sea water intrusion takes place both at near sea level and at depth. The geological appraisal of these results, in terms of the litho-stratigraphy and the tectonics of the area, facilitates an interpretation of the geophysical observations.

The gravimetrically determined depth and morphology of the alpine basement are believed to have been fashioned by fault tectonics and, specifically, by faults that either have not been active during the Quaternary, or are buried under thick terrestrial and alluvial deposits. At least two distinct groundwater horizons have been detected at different elevations, both of which appear to suffer from sea water intrusion. This may be attributed to the network of discontinuities formed by older and younger faults and fault zones, which facilitates the horizontal and vertical transportation of sea water between permeable geological formations (marbles) at different levels. The vertical alternation of permeable-impermeable rock formations may be attributed to (alpine age) folding, which results in the repetition of the same permeable lithological units along the vertical direction, in this case karstified marbles (Figure 8).

Acknowledgments

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