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GEOPHYSICAL PROSPECTION AT THE HAMZA BEY (ALKAZAR) MONUMENT THESSALONIKI, GREECE

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ABSTRACT

A two-phase geophysical survey is presented, whose aim was to investigate parts of the Ottoman Hamza Bey mosque located at Thessaloniki, Greece. Along with ground penetrating radar (GPR), which is a fully non-destructive method, a number of electrical resistivity tomographies (ERTs) were carried out. Bentonite mud electrodes were used instead of metal stakes, in order to comply with the non-destructive character of the whole operation. Our aim was to study the subsurface geological structures at the location of the mosque, and to detect and possibly map any ancient remains concealed under the monument. Both ERT and GPR results indicated a distinct, near surface horizontal discontinuity which was attributed to the presence of an ancient floor at the atrium area of the mosque. This floor was then revealed after a subsequent excavation. Moreover, high resistivity anomalies and distinct GPR signals were observed deeper at the atrium area. They are attributed to possible voids, remains of ancient walls, or other man-made structures concealed under the floor of the monument.

KEYWORDS: Archaeological prospection, geophysical survey, non-destructive testing, ground penetrating radar, electrical resistivity tomography

INTRODUCTION

In this work we present the geophysical survey which was carried out in the Hamza Bey mosque, a significant ottoman monument, situated in the city centre of Thessaloniki (N. Greece). This survey was conducted in the framework for the construction of the new underground Metro line in the city of Thessaloniki, and commenced contemporaneously with an extensive maintenance project of the monument (Fig. 1).

Figure 1. Site location map and the Hamza Bey monument (Raptis and Xanthos, 2010).

Hamza Bey mosque (Fig.1), also known as Alkazar after the cinema that was operating for a long period in the monument, was built in 1467-8 by *Hafsa*, the daughter of the ottoman military commander *Hamza Bey,* as a district muslim house of prayer. The edifice consisted originally of the domed prayer hall that was to become the nucleus of the later architectural complex, with a porch, *revak*, along its northwest façade. In the mid 16th century, a Π shaped ambulatory with a *minaret* was annexed to the *mesçid*, signifying its conversion to a mosque. The edifice was completed during the last decades of the 16th century, when along with the rearrangement of the colonnade and the superstructure of the ambulatory, an asymmetrical three-sided portico was added to the northwest forming a quadrilateral atrium. Repairs and alterations would continue so that the building could be adapted from time to time to the needs of the muslim community, which operated there till 1923 (Raptis, 2012). From 1928 to 2006, when the edifice came to the property of the Ministry of Culture, the monument was used as a market place. The dilapidated state, to which the edifice had come during that period, was treated by an extensive maintenance project, financed by the 3rd Community Support Framework and performed by the 9th Ephoreia of Byzantine Antiquities (Raptis *et al.*, 2007; 2008; Raptis and Xanthos, 2010; 2012). At the same time, the static inadequacy of the monument, farther affected by the cutting of the tunnels of the new Metro line, made necessary the investigation of (a) the building's foundation depth and (b) the underlying anthropogenic layers or pre-existing constructions that could affect the adequacy of the foundation masonries; parameters examined by both conventional excavation methods (Raptis, 2009) and geophysical surveying.

Geophysical surveying for detecting and mapping buried archaeological remains has been very widely used over the past decades (Gaffney, 2008), with electrical resistivity being one of the most popular methods for doing so (Tsokas & Liritzis, 1990; Tsokas *et al.*, 1994; Diamanti *et al.*, 2005, Papadopoulos *et al.*, 2007, Tsokas *et al.*, 2008a; 2009). However, a geophysical application within monuments is a special demanding field which requires a fully non-destructive approach. Given the significance of the monument, a major prerequisite for any geophysical survey is that this should be fully non-destructive. As such the ground penetrating radar (GPR) method is preferable. Several applications of GPR surveys in standing monuments have been reported in literature (Savvaidis *et al.*, 1999; Leckebusch, 2000; Lorenzo *et al.*, 2002; Leucci, 2002; Binda *et al.*, 2003; Piro *et al.*, 2003; Linford, 2004; Nuzzo, 2005; Tsokas *et al.*, 2007).

Another technique that only recently has been used in a fully non-destructive mode is the electrical resistivity tomography (ERT) method. Despite its widespread use in typical field surveys, the application of ERT into standing structures was understandably not very popular due to its destructive nature since typically spike electrodes have to be used to establish galvanic contact. However, relatively new developments suggest that the application of non-spike electrodes to perform ERT surveys in a fully non-destructive manner is possible. Systematic studies of different materials ranging from cooper flat base electrodes (Consentino and Martorana, 2001) to conductive gel or bentonite electrodes (Athanasiou *et al.*, 2007) suggest that they can be a surrogate to spike electrodes and can be used successfully to obtain valid galvanic resistivity measurements in a fully non-destructive manner. As a result they can be used in urban environment and also inside existing monuments or for investigations in the walls of the monuments (Carrara *et al.*, 2001; Tsokas *et al.*, 2008b; Tsourlos and Tsokas, 2011).

The aim of the presented geophysical survey was (a) to study the subsurface geological structures at the location of the mosque and (b) to detect and possibly map buried antiquities under the monument. The case presented here comprises an example of a combined geophysical survey for investigating the area of interest. The geophysical methods employed were: ERT and GPR. Further, it is also an example of indoors surveying.

2. GEOPHYSICAL METHODS

2.1 Electrical Resistivity Tomography (ERT)

Resistivity techniques are established and widely used to solve a variety of geotechnical, geological and environmental subsurface detection problems (Ward, 1989). The goal of resistivity methods is to measure the potential differences on the ground surface due to the current flow within the ground. This measured potential drop reflects the difficulty with which the electrical current flows within the subsurface and hence, it gives an indication of the earth's electrical resistivity. Knowledge of the subsurface material resistivity is used for distinguishing existing underground features, such as layering, voids, man-made structures etc.

ERT can be considered as the development of the standard geoelectrical method. The advent of fully automated measuring instruments with electrode multiplexing ability in combination with the development of advanced interpretation algorithms, allows the collection of a large amount of data and the production of electrical resistivity images of the subsurface. The rapid advanced in computer technology during the last decades, allowed the development of automated algorithms, known as inversion algorithms, which are able to create precise images of subsurface resistivity distribution (Tripp *et al.*, 1984; Li and Oldenburgh, 1992; Tsourlos, 1995). Moreover, the development of automatic measuring systems facilitates acquisition of a large number of measurements in a limited time.

ERT has proved to be a successful method in providing fast and reliable shallow subsurface geoelectrical property images under various field conditions, even in complex geological environments.

2.2 Ground Penetrating Radar (GPR)

GPR is the general term applied to techniques which employ radio waves, typically in the 1 to 1000 MHz frequency range, to map structures and features buried in the ground (or in man-made structures). A GPR unit sends out radio waves that partially reflect back when they meet objects electrically different than their surroundings, and partially propagate in deeper layers. A transmitting antenna emits the radio waves and a receiving antenna records the reflected ones. By recording the time interval between the instant at which the pulse is emitted by the transmitter and is recorded by the receiver, and by knowing its propagation velocity in the subsurface, it is possible to map underground reflectors.

GPR data is typically displayed in two-dimensional (2D) format and those images are called cross-sections. These are the real-time images we obtain when collecting data in the field. We can also create three-dimensional (3D) views of data and also two-dimensional depth slices using appropriate software. These subsurface slices show how GPR signals vary over a grid area at a certain depth and they are very useful for data interpretation because they can reveal patterns that were not easily recognized while analyzing the cross-sections.

Today GPR is being used in many different areas including locating buried utilities, mine site evaluation, forensic investigations, archaeological digs, searching for buried landmines and unexploded ordinances, measuring snow, ice thickness, quality for ski slope management and avalanche prediction (Davis and Annan, 1989; Guy *et al.*, 2000; Saarenketo and Scullion, 2000; Spikes *et al.*, 2004; Solla *et al.*, 2010; Diamanti and Redman, 2012).

3. GEOPHYSICAL SURVEY

The geophysical prospecting using the ERT and GPR methods in an indoors environment was carried out in two phases: initially, we applied the ERT method to the mosque itself and its atrium and collected GPR profiles on the atrium floor. Then, excavation works took place which removed the superficial layer, with mean thickness equal to ~0.6 m, and revealed the ancient flooring at the atrium area. And lastly, after the revelation of the ancient floor, we conducted geoelectrical and GPR measurements again on the atrium floor. This geophysical survey was part of a more extensive campaign of geophysical investigations at the entire area of the monument.

3.1 ERT: Data Acquisition, Processing and Results

For the ERT measurements of both phases we used the Iris Syscal-Pro resistivity meter. It has to be noted that this was a fully non-destructive geophysical survey since for the ERT method we used bentonite electrodes (Athanasiou *et al.*, 2007) instead of spike electrodes which are typically used with this method.

All measured ERT sections were inverted using a program developed by Tsourlos (1995). The two-dimensional inversion scheme performs an iterative optimization based on a two and a half dimensional finite element forward modelling scheme. The algorithm is fully automated and performs iterative smoothness constrained inversion (Constable *et al.*, 1987). All inversions produced a low misfit error between the real and the predicted data (3%) despite the fact that subsurface of the studied area is quite complicated.

During the first stage of the geoelectrical prospecting, we collected seven linear ERTs on the floor of the Mosque and atrium (Fig. 2) in an attempt to obtain indirect information regarding the deeper geometry and lithology of the subsurface at the area under study. We chose the Wenner-Schlumberger array to perform the survey as it has a good signal to noise ratio (Ward, 1989) and adequate vertical resolution. The ERT lines had variable length, ranging from ~17 m to ~28 m, depending on the available space in relation to the desired resolution.

The maximum potential to current electrode separation was n=7 (i.e., seven times the length of the potential measuring dipole). The inter-electrode spacing was set to a=0.9 m for the A1, A2 and A5 ERT sections and equal to a=1 m for the remaining. In this way we achieved a maximum penetration depth without sacrificing the resolution. The non conventional (bentonite) electrodes used, as well as the multi cable are shown in the photograph of Fig. 3. This photograph is actually showing a part of the transect A1.

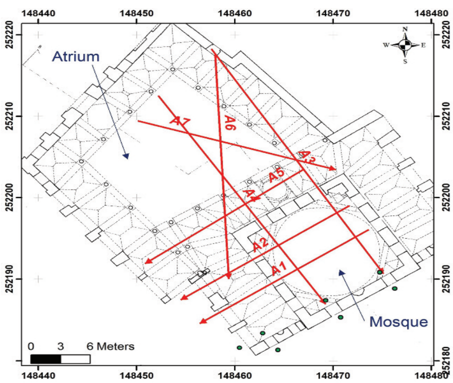

Figure 2. A plan view of the studied area presented in an arbitrary coordinate system. Coordinates are in meters. The solid red lines denote the location and the arrows the direction of the ERTs of the first phase.

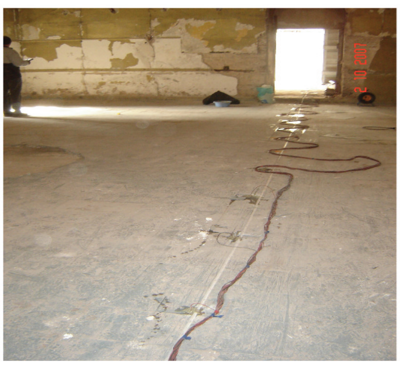

Figure 3. Photograph of the bentonite electrodes and the interconnecting multi cable during data acquisition for tomography A1. Part of the transect in the main praying room is shown.

Fig. 4 shows the inversion results for all the profiles measured at the locations shown in Fig. 2. All the geoelectrical sections are presented in linear and logarithmic rainbow scale. Before attempting any interpretation it must be noted that any buried antiquities under the survey area should be of different resistivity (usually higher) than the surrounding geological formations.

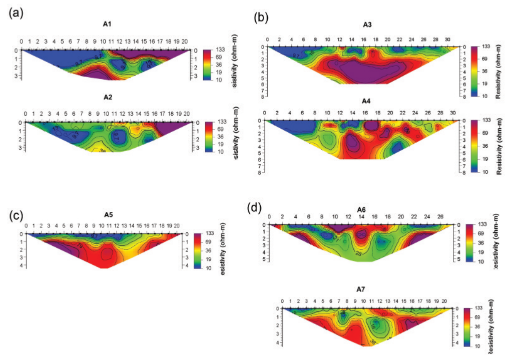

Figure 4. Inverted ERT data for the (a) A1, A2, (b) A3, A4, (c) A5 and (d) A6, A7 profiles carried out at the locations denoted in Fig. 2.

Both A1 and A2 inverted sections (Fig. 4a) present a similar subsurface resistivity picture. They reveal a relatively conductive formation located along the first few metres of the profile, beginning from the surface and extending up to ~2 m. This formation consists mostly of fine grained clayey material, a fact witnessed by the boreholes performed in the area. A resistive formation which underlies this clayey layer is attributed to the presence of a cemented coarse grained material, also verified by drilling. This cemented material seems to disappear abruptly at ~10 m along the sections, whereas the thickness of the fine grained layer increases leading to a lateral discontinuity at the 10-11m of the sections. Moreover, highly resistive anomalies appear close to the surface and towards the end of the profiles. These anomalies are located outside of the main praying hall of the mosque and they overlay the clayey layer. This antistatic formation can be attributed to either the foundation masonries of the monument, or, to older ancient remnants covered by soil when the monument was constructed.

ERT sections A3 and A4 (Fig. 4b) cross the floor of both the Mosque and its atrium (Fig. 2). Similarly to sections A1 and A2, section A3 also reveals a low resistivity formation, extending up to ~2 m in depth, and a higher resistivity formation which is located deeper. Profile A4 reveals a strongly undulating upper limit of the higher resistivity formation. These deeper very resistive anomalies observed at both A3 and A4 sections could be related to the foundations of the monument.

ERT A5 (Fig. 4c) is located parallel to A1 and A2 and it reveals a similar resistivity picture. The upper part of the formation of high resistivity undulates also but it appears shallower, at about 1 m, than it is in the praying room.

Looking at profiles A6 and A7 (Fig. 3d) we see highly resistive features located not only near the surface but also within the conductive formation. A conductive feature between 11 and 14 m along profile A7 surrounded by high resistivities could possibly be a subsurface void filled by clay.

After the excavation at the area of the atrium which revealed the ottoman marble, we went back and carried out three supplementary resistivity tomographies at the locations shown in Fig. 5. This second set of ERT sections was obtained using the dipole–dipole array, while the 24 inter-electrode spacing was set to a=0.5 m. The dipole- dipole array having decreased electrode spacing was preferred in this phase. This is because we intended to image better the lateral changes which had already revealed by the Wenner-Schlumberger tomographies of the first phase. The superior lateral resolution of the particular array is well known (Ward, 1989).

In Fig. 6, we present the inversion results for the three geoelectrical profiles in a rainbow scale. All three inverted sections present a similar picture. In all of them there is a superficial highly resistive layer, extending from the ground surface down to about 0.5 m depth, which could be attributed to the marble flooring slabs. Then, there is a conductive layer, extending from ~0.5 to ~1.0-1.5 m depth, which is associated with a clayey-sand formation present at the area, a fact that was confirmed by borehole data. The highly resistivity anomalies located deeper in all three sections could be related to the foundations of the monument, which were later found with archaeological excavation at about 2.0 m in this area (Raptis 2009; 2012). Alternatively, they might comprise the expression of ruins of older phases, or perhaps other man-made structures

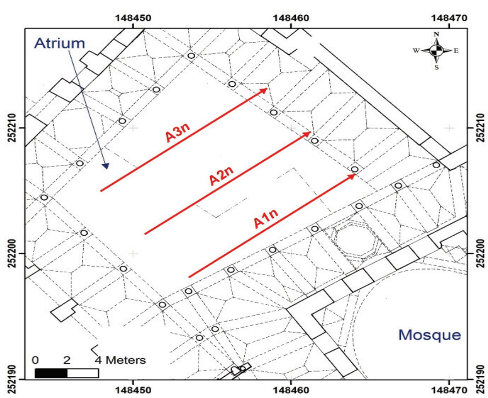

Figure 5. Geoelectrical survey at the atrium. The solid red lines denote the location and the arrows the direction of the ERT sections of the second phase.

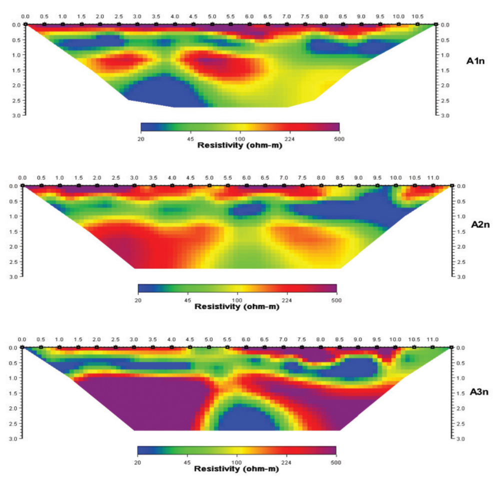

Figure 6. Result of the inversion of the ERT data collected at the locations denoted in Fig. 5.

concealed under the atrium of the mosque
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3.2 GPR: Data Acquisition, Processing and Results

We collected GPR profiles on the atrium floor, each being 0.25 m apart from the other, using a cart-based 250 MHz GPR system produced by Mala (Fig. 7). The trace sampling interval was 0.05 m. We acquired GPR data in two phases: forty-three profiles were collected in October 2007 (Fig. 8), prior to excavation, and forty-five profiles were collected during March 2009 at the same location with the first ones, after the first phase of the excavation works which revealed the marble floor of the atrium (Raptis et al., 2008).

Figure 7. Cart-based Mala system with a 250 MHz GPR in the atrium of the mosque. The instrument is on the ancient floor which was revealed after the excavation. The presence of this floor causes the clear reflection seen in all GPR transects of the first data acquisition phase.

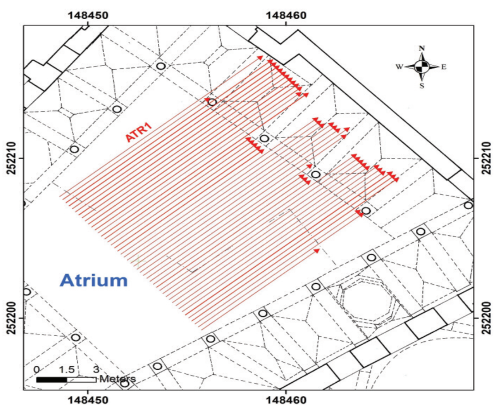

Figure 8. A plan view of the prospected atrium area using GPR (arbitrary coordinate system). The red lines with arrows denote the location and direction of the GPR profiles.

We present our GPR data in the standard cross-sectional format. Position is plotted on the horizontal axis, and depth and time on the vertical axes. To convert the time axis into depth, we assumed a constant signal velocity which. This velocity was set equal to 0.07 m/ns and it was determined by using excavation information regarding the location of subsurface features and from drill data when available. Moreover, we present our data as plan view maps (i.e., depth slices).

All GPR data were processed using Sensors & Software Inc. software. We applied the same processing to all GPR sections and we purposely used a uniform signal velocity for comparisons between them. We applied a standard dewow filter to remove very low frequency components from the field data. Since GPR signals are very rapidly attenuated as they propagate into the ground, we applied a time dependent gain function to the data to compensate for this decrease in GPR signals from greater depths. This is typically referred to as "time gain". We have applied a spherical exponential compensation (SEC) gain to enhance features in the GPR data. We have also applied temporal filtering to the data to remove unwanted frequencies from our signals and to improve data quality and assist interpretation. For the plan view maps, we have also used background subtraction and migration algorithms to process our data. The background subtraction process is used to remove horizontal reflectors in the cross-section data and it is usually applied when we want to enhance the presence of dipping reflectors and geometrical features in the subsurface. Migration is a process that focuses the energy spread over the hyperbolic shape response of targets back to their true positions and therefore, produces a GPR image which is a better representation of the ground (Fisher *et al.*, 1992).

It should be noted here that all indications of targets presented in GPR data are true anomalies even though they may not be the desired targets. Similarly to all geophysical methods, GPR is incapable of giving a false positive reading, which is where experience in reading the records can help the investigator.

Fig. 9 presents four cross-sections acquired at the atrium area prior to excavation. In all forty-three profiles collected in this area, we observe three major flat lying reflections; one at ~0.6, one at ~1.0 m and one at ~2.3 m (Fig. 9, doted lines). The continuous reflection at ~0.6 m is attributed to the top of the ottoman flooring which was revealed after excavation while the reflection at ~1.0 m could be possibly caused by the ceiling of the clayey layer or some artificial layer. Below this second strong reflection and up until ~2.3 m, there seems to be a relatively homogeneous layer. Taking into account the available borehole information, as well as the ERT results we suggest that this layer could be a clayey formation. The strong reflection at ~2.3 m is interpreted as the boundary between this clayey layer and an electrically much different, inhomogeneous formation. This is an anthropogenic formation that can be attributed to either the foundations of the monument, or, to older remnants and layering. This third strong reflection appears at different depths in many GPR profiles, which makes the clayey layer thickness variant. We interpret the flat lying but subtle reflection events within the clayey layer as argillaceous interfaces.

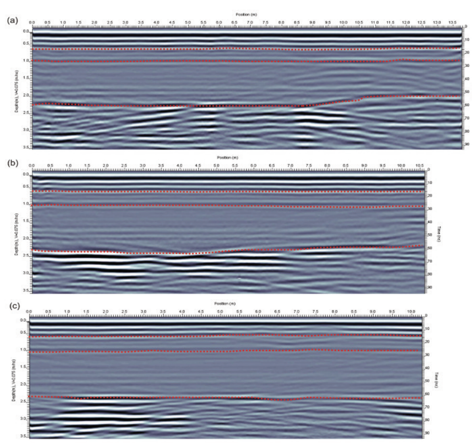

Figure 9. GPR cross-sections acquired on the atrium floor during the first phase of GPR data acquisition. The doted lines denote reflections from targets (boundaries of subsurface bedding) described in the text.

Fig. 10 presents depth slices produced by the GPR data acquired on the atrium floor prior to excavation. These slices could be very helpful in revealing subsurface patterns that were not easily seen while looking at the cross-sections. We do not present the shallower slices as they do not display any geometrical features of interest. The plan view map at about 2.0 m starts to show linear reflections, which become more pronounced as we move deeper, and start to disappear at about 2.5 m and deeper. These prominent reflections could be associated to the foundations of the

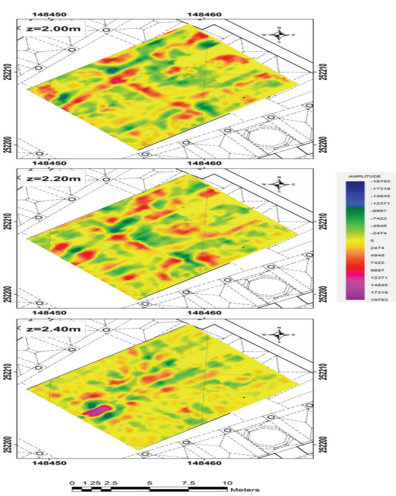

Figure 10. GPR depth slices, at various depths z, obtained from the GPR survey that took place prior to excavation.

monument or other ancient remains located under the atrium of the mosque.

During the excavation works the superficial layer, having a mean thickness of ~0.6 m, was removed and the ottoman marble flooring was revealed. In Fig. 11, we present three GPR sections acquired on this ottoman marble floor, during the second phase of measurements, at the same locations with the ones of Fig. 9. In all three GPR sections there is a strong reflection at ~0.5 m (Fig. 10, doted line) which is attributed to the bottom of the ancient floor. In the clayey medium located below this strong reflection, there is extensive layering. The boundary between the clayey layer and the underlying formation, as well as the reflections from within this deeper medium do not appear as distinct as they did at the GPR sections of Fig. 9 (doted lines at ~1.8 m). A possible explanation for that could be the difference in level of the water table and the different degree of water saturation in this deeper medium at the time of the two stages of data acquisition.

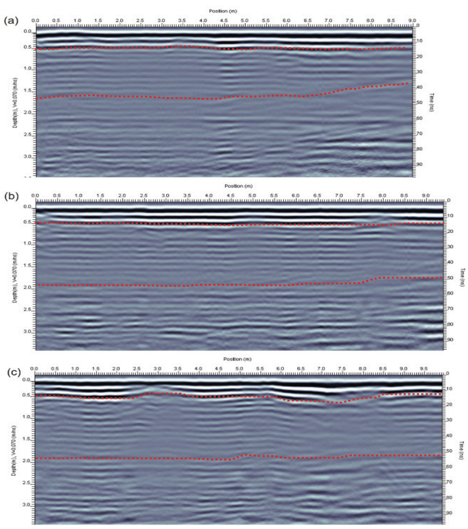

Figure 11. GPR cross-sections acquired on the atrium floor during the second phase of GPR data acquisition. The doted lines denote reflections from targets described in the text.

4. DISCUSSION & CONCLUSIONS

A fully non-destructive, two phase, geophysical survey was performed at the atrium of the Hamza Bey mosque at Thessaloniki, Greece. This survey was part of a more extensive campaign of geophysical investigations which were carried out in the framework of the construction of the new underground Metro line in the city of Thessaloniki, in Greece. We used both the ERT technique and the GPR method. The ERT imaging was performed by using non-conventional bentonite electrodes, which substituted spike electrodes.

After the completion of the geophysical investigations of the first stage, we were able to map and indicate the location of the original floor which was buried at a mean depth of about 0.6 m below the modern one. Moreover, we identified features located deeper which comprise possible anthropogenic structures that could be related to the foundations of the monument or to pre-existing remains buried below the atrium of the mosque. During the second stage of measurements we could identify the same subsurface layering as at the first phase of investigations. The ERT method mapped highly resistivity anomalies, located deeper, that could be attributed to foundation masonries or archaeological remains in the area. The GPR of this second phase however, did not provide as clear subsurface images for the deeper layers as it did during the first phase. Differences in the subsurface dielectric properties (e.g., moisture, water table level) at the time of the two stages of data acquisition could be a possible explanation for this.

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