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# Urban archaeological investigations using surface 3D Ground Penetrating Radar and Electrical Resistivity Tomography methods

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**Abstract.** Ongoing and extensive urbanisation, which is frequently accompanied with careless construction works, may threaten important archaeological structures that are still buried in the urban areas. Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) methods are most promising alternatives for resolving buried archaeological structures in urban territories. In this work, three case studies are presented, each of which involves an integrated geophysical survey employing the surface three-dimensional (3D) ERT and GPR techniques, in order to archaeologically characterise the investigated areas.

The test field sites are located at the historical centres of two of the most populated cities of the island of Crete, in Greece. The ERT and GPR data were collected along a dense network of parallel profiles. The subsurface resistivity structure was reconstructed by processing the apparent resistivity data with a 3D inversion algorithm. The GPR sections were processed with a systematic way, applying specific filters to the data in order to enhance their information content. Finally, horizontal depth slices representing the 3D variation of the physical properties were created. The GPR and ERT images significantly contributed in reconstructing the complex subsurface properties in these urban areas. Strong GPR reflections and high-resistivity anomalies were correlated with possible archaeological structures. Subsequent excavations in specific places at both sites verified the geophysical results. The specific case studies demonstrated the applicability of ERT and GPR techniques during the design and construction stages of urban infrastructure works, indicating areas of archaeological significance and guiding archaeological excavations before construction work.

**Key words:** archaeological investigation, ground penetrating radar, 3D resistivity tomography, urban areas.

## Introduction

Ongoing large-scale urbanisation is a feature of developing countries, but it offers a major social problem for developed nations as well. Many urban areas have a long historical background which characterises them, and has accompanied them from ancient to modern times. Visible evidence of this rich historical and archaeological background lies in the large number of archaeological monuments that can be observed in these urban centres. Apart from all these visible monuments, an even larger number of possible archaeological structures are still buried in the urban subsurface, and these, unfortunately, may be threatened by careless design and construction of modern infrastructure works.

Nowadays, geophysical methods are well established techniques for approaching and successfully solving hydrogeological, geological, archaeological, and environmental problems (Dahlin and Owen, 1998; Atzemoglou et al., 2003; Ramirez et al., 1996). Furthermore, such techniques can significantly contribute to understanding the complex changes in the physical environment in urbanised regions. For the above reasons, the relatively new study field called ‘urban geophysics’ has emerged, focusing on the geophysical exploration of cities in order to investigate and characterise the subsurface properties of urbanised environments, and to provide effective solutions to specific problems.

In this work, urban geophysics is used as a tool to explore archaeologically sensitive regions before or during construction works that are carried out within the historical centres of urban areas. Large-scale construction works (roads, bridges, buildings, pipelines) can have a serious impact on archaeological monuments that are still buried in the subsurface of urban regions. The need for early and effective detection of these cultural remains has motivated the use of geophysical techniques in the archaeological exploration of urban areas (Lück et al., 1997).

Traditional geophysical exploration of archaeological sites involves the mapping of the subsurface geophysical properties using soil resistance, magnetic, and electromagnetic methods (Tsokas et al., 1994; Vafidis et al., 2005; Drahor, 2006; Sarris et al., 2007). The compilation of maps that transform the geophysical results into images that resemble the plan view of the buried relics is the ultimate goal of geophysical surveying in archaeological areas (Scollar et al., 1986). This is especially useful when dealing with large archaeological sites in rural environments, the exploration of which requires large human and financial resources.

In contrast to conventional geophysical investigation of archaeological sites, a geophysical survey in an urban area may face some objective difficulties. First, because the archaeological remains are usually located at the upper layers of the ground, the highly heterogeneous nature of these layers in urban areas, due to the

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existence of many man-made objects, may hinder the accurate mapping of archaeological structures. Second, the ambient noise in cities caused by electrical currents and electromagnetic radiation can have an undesirable influence on the geophysical measurements. Finally, the need for a high-resolution geophysical survey conducted in limited time, sometimes combined with restricted site access that requires special regulations or traffic management, imposes additional difficulties. All of the above factors show the necessity of developing innovative research methods in effectively approaching the archaeological exploration of urban sites.

Among the geophysical techniques, Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) appear to be the most suitable techniques for reconstructing the complex subsurface properties in urban areas. The development of new and fully automated GPR and ERT measuring systems, along with advanced and sophisticated processing and interpretation algorithms, have rendered these two techniques very attractive in archaeological site characterisation (Vaughan, 1986; Goodman, 1994; Goodman et al., 1995; Leckebusch, 2003; Conyers, 2006; Xu and Noel, 1993; Griffiths and Barker, 1994; Loke and Barker, 1996; Tsourlos and Ogilvy, 1999; Stummer, 2003; Papadopoulos et al., 2007).

These techniques can provide a rapid, economic, and non-invasive tool in the service of the archaeologists. Several case studies have been reported in the international literature indicating the successful application of these techniques in locating buried antiquities in urban areas. Among them Chávez et al. (2001) used magnetic, GPR, and resistivity methods to characterise the archaeological zone of Teotihuacan in Mexico. Tsokas et al. (2008) used non-destructive ERT to investigate the area around and inside a church. Leucci and Negri (2006) implemented the GPR method to map the subsurface archaeological features in an urban area. More recently, Negri et al. (2008) evaluated the effectiveness of the integration of surface GPR and ERT techniques in researching archaeological items in a geologically complex subsurface. Other methods such as gravity (Sarris et al., 2007) or seismic refraction (Leucci et al., 2007) have not met wide application mainly because of the constraints imposed in collecting such data in the urban territories.

In this work, three case studies are presented, representing the successful results of geophysical investigation employing the GPR and ERT methods, in two different urban regions. The geophysical survey designs employing these techniques, and the various data processing stages, are described. Finally, the geophysical anomalies detected in the ERT and GPR geophysical maps were interpreted in terms of possible buried archaeological features, some of which were verified by subsequent excavations.

## Field methodology and data processing

Figure 1 shows the cities of Heraklion and Rethymno where the case studies presented here were carried out. Heraklion and Rethymno are two of the major cities of Crete, and capitals of the corresponding prefectures. Three different sites were investigated: two of them were located at the centre of the old town of Rethymno and the third was located along the main seaside avenue of the city of Heraklion.

Surface ERT and GPR methods were chosen as most appropriate techniques for the particular test sites after taking into account the surrounding surface features and the complex nature of the subsurface where possible archaeological remains could be buried. An effort to follow a common field strategy in each of the surveyed areas was made, and this was accomplished to a certain degree.

Surface ERT was applied in all three test sites. The data were collected along a dense grid of parallel two-dimensional (2D) sections. This specific survey mode combines effectively the accurate three-dimensional (3D) mapping of possible buried sarchaeological structures and the minimum possible fieldwork time. Bentonite contact electrodes (Athanasiou et al., 2007), illustrated in Figure 2*b*, were used as current electrodes in the Heraklion site. The asphalt surface of the other areas forced the field crew to use metallic electrodes that were inserted through small holes that were opened in the asphalt using a pneumatic drill, as can be seen in Figure 2*a*. A multichannel resistivity instrument (SYSCAL Pro Switch 96) was used to collect the apparent resistivity data.

A similar methodology was followed for the GPR surveys at the three sites. The GPR measurements were collected along parallel transects 0.5 m apart, forming a specific grid. A NOGGIN$^{PLUS}$ unit with 250 MHz and 450 MHz antennas was used for the GPR survey.

A systematic workflow was used to process the collected ERT and GPR data. First, the noisiest apparent resistivity measurements (mainly due to poor ground contact) were removed from all of the individual pseudosections, and a 3D resistivity inversion algorithm (Loke and Barker, 1996) was used to invert the data. The final 3D resistivity inverted models were visualised as horizontal slices at increasing depths. A common strategy was followed to process the GPR sections (first peak estimation, application of automatic gain control, de-wow and DC shift, trace-to-trace averaging filters). Finally, horizontal depth slices at different depth levels were created from the original vertical sections assuming a velocity for the electromagnetic waves of 0.1 m/ns.

Controlled position measurements using a Global Positioning System unit were made, which subsequently were used to overlay the final geophysical maps on the topographic and satellite images of the surveyed areas. The integration of the data was accomplished through a Geographical Information System (GIS) platform and the final processing results were interpreted in terms of possible archaeological structures.

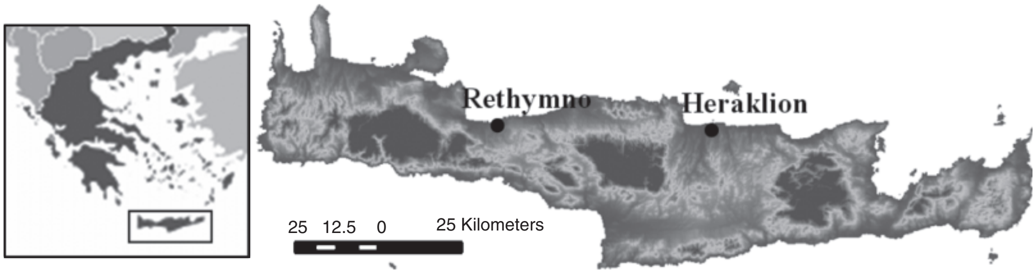


**Fig. 1.** Map of the island of Crete, which is located south of Greece in the area enclosed by the rectangle. The locations of the cities of Heraklion and Rethymno on the north coast of the island are marked.

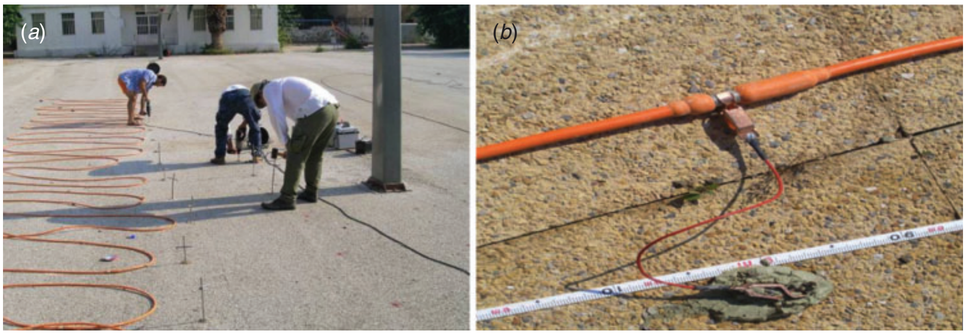


**Fig. 2.** (*a*) Field procedure at the area of Turkish School in Rethymno where a pneumatic drill was used to open small holes in order to insert metal stake electrodes in the ground. (*b*) Bentonite contact electrodes used in the Heraklion investigation.

## Case study 1: Bentenaki, Heraklion

Figure 3*a* shows the Bentenaki area, which is located along the north coast seaside in the central part of Heraklion city. Figure 3*b* is a view of Saint Petros church from the north-east. This church is located in an area that extends to the west between Sof. Venizelou and Mistotaki Avenues. The monument was constructed during Venetian times, and the Catholic part of the monastery was transformed to the mosque of Sultan Ibrahim (Gerolla, 1905). During sidewalk construction work (along the seaside avenue) that was being carried out for better exhibition of the church, a palaeochristian church was found and was partially excavated. This church is believed to have been constructed during early Byzantine times, and constitutes one of the very few surviving monuments of that period. It has frescos and inscription fragments, and seems to comprise part of a more extensive construction complex. The polygon in Figure 3*a* exhibits the location of this palaeochristian church.

In Bentenaki, the geophysical investigations were conducted along Sof. Venizelou Avenue from the 18th English Square at the east to the intersection of Sof. Venizelou and Mitsotaki Avenues at the west, as illustrated in Figures 3*a* and 4*a*, respectively. Due to the urgent construction works that were being carried out in the region to restore the seaside avenue, the area was initially covered using the GPR technique, but ERT measurements were taken only within a section of the site to provide further verification of the GPR results. Sof. Venizelou Avenue is one of the most crowded roads of the Heraklion city. The fieldwork had to be conducted during the night to meet special requirements for traffic management, and was finally completed in 12 h between the afternoon of the 29th until the morning of the 30th May of 2008. The goal of this geophysical campaign was to investigate the area of interest rapidly and efficiently and to provide detailed information about the subsurface. This would guide archaeological excavation work in specific places, and accelerate road restoration work.

## Ground Penetrating Radar (GPR)

The total GPR area of more than 2000 $m^2$ is shown in Figure 4*a*. The area was divided into seven small individual grids (GRID0–GRID6). The individual grids were explored by completing parallel profiles. Similar data collection parameters were used for all the profiles. The inter-line spacing was 0.5 m and the sampling interval along each profile was 0.025 m. The goal was to cover as much of the area as possible, but surface obstacles like ditches, pipelines, and parked cars limited coverage of the area.

Figures 4*b–d* present the processed GPR data for each different grid in the form of horizontal slices at increasing depth. The thickness of each slice is 0.2 m and they were overlaid on the Quickbird satellite image (resolution 60 cm) of the area through a GIS platform. The 'warm' colours indicate the strong subsurface reflectors that are related to buried structures.

The diagrammatic interpretation of the strong subsurface GPR reflections that are more likely to be correlated with buried archaeological structures is shown in Figure 4*e*. The central part of the area, at the west and south of the excavated palaeochristian church (GRID0 and GRID6), is of particular archaeological interest. Strong reflections start to appear from the depth of 0.4 m below the ground surface at the east of the excavation trench. A further continuation of these anomalies

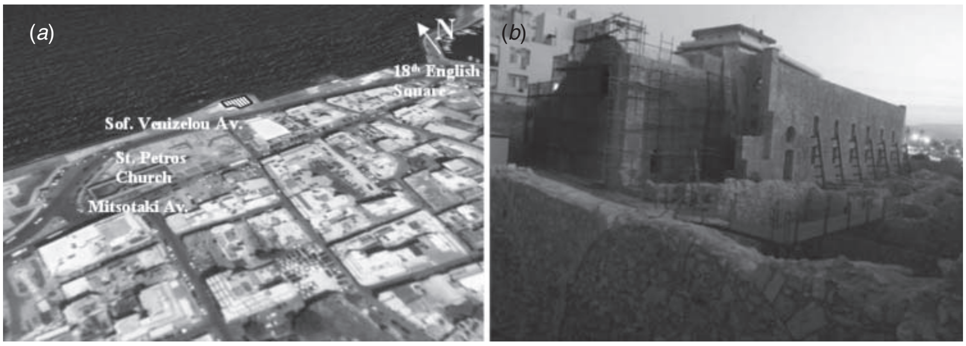


**Fig. 3.** (*a*) Panoramic view of the Bentenaki area at the centre of Heraklion city. The hatched polygon on the coastline shows the position of the excavated palaeochristian church. (*b*) Recent view of Saint Petros church, which is located along the Sof. Venizelou Avenue.

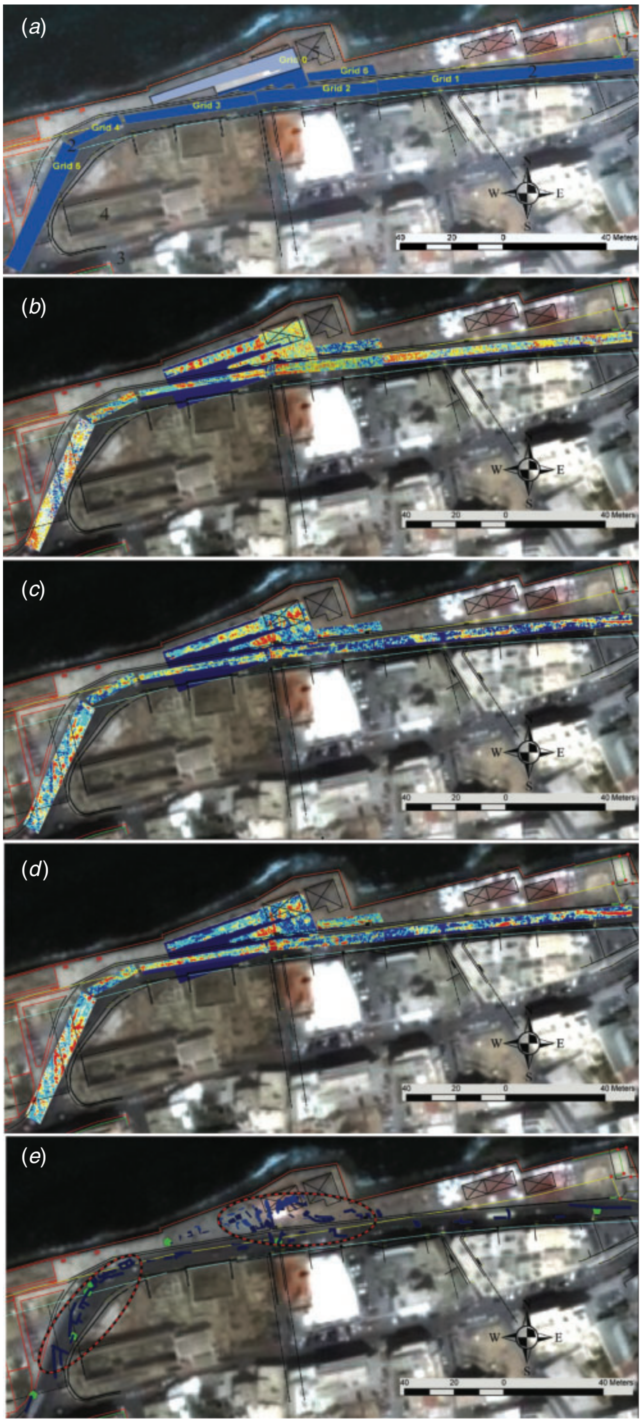


**Fig. 4.** (*a*) Location map for the Ground Penetrating Radar (GPR) grids that were used to cover the area of interest at Bentenaki, Heraklion. The polygon that is overlaid on part of GRID0 shows the area where the Electrical Resistivity Tomography measurements were conducted. (1: 18th English Square, 2: Sof. Venizelou Avenue, 3: Mitsotaki Avenue, 4: Saint Petros church, 5: Palaeochristian church). (*b*) GPR horizontal slice of the depth $Z = 0.4–0.6$ m. (*c*) GPR horizontal slice of the depth $Z = 1.2–1.4$ m. (*d*) GPR horizontal slice of the depth $Z = 1.4–1.6$ m. (*e*) Diagrammatic interpretation of the strong GPR reflections (warm colours). The elliptical areas indicate the regions in which there is higher probability that archaeological structures are located. The horizontal scale is the same for all the images.

to the south of GRID0 to GRID2 and GRID3 can be attributed to architectural structures with a north-south alignment. The semicircular anomalies at the south of the excavated palaeochristian church are probably related to the continuation of this church to the south. Furthermore, the fact that the strong reflections seem to continue to the west of the trench for ~30–35 m, shows that this specific church probably comprises part of an architectural complex extended in that direction.

GRID1 covered the area from the 18th English Square to the east and extended for 100 m to the west along the Sof. Venizelou Avenue. The interpretation of the measurements was hindered by the superficial deposits, which extended to depths of 0.4–1.2 m. Nevertheless a strong 25 m east–west diagonal reflection was recorded at the depth of 1.4–1.6 m below the surface. Some other minor reflections were located towards the east without having a clear continuation beyond the road borders.

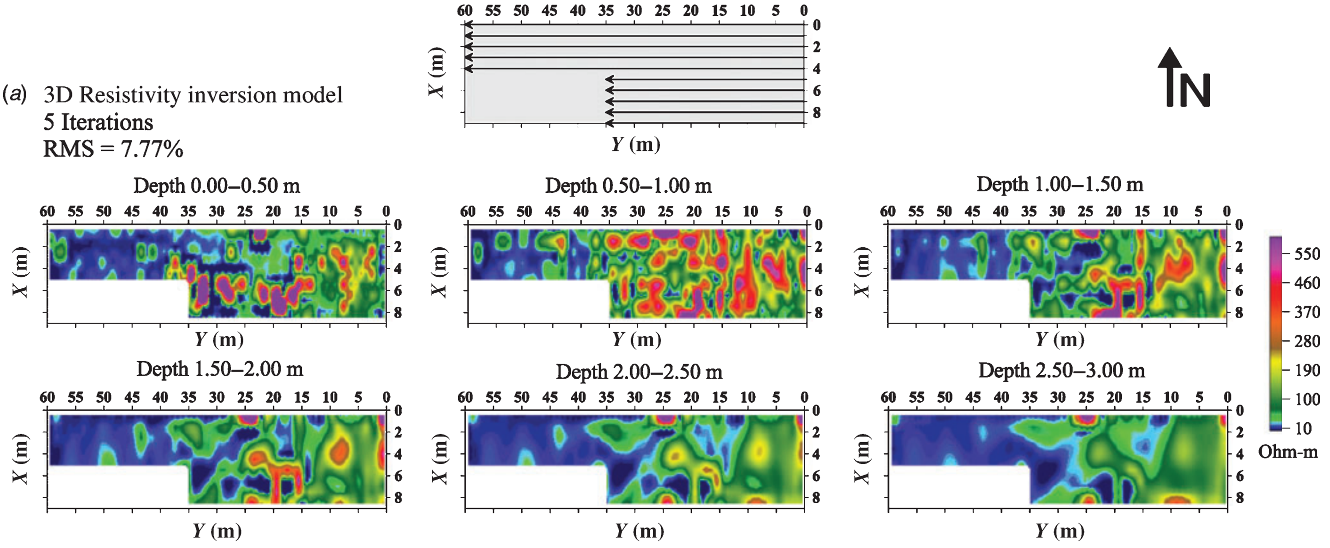
The GRID 2 was laid out along Sof. Venizelou Avenue. It started from the end of GRID1 to the east and extended for ~47 m to the west. The most important anomaly is located at the west edge of this grid. This north–south anomaly is relatively wide and is considered to be an extension of the wall that is located at the east side of the Saint Petros excavation.

The GRIDS 3, 4, and 5 were completed along the seaside avenue, starting from the end of GRID2 at the east and reaching the intersection of Mitsotaki and Sof. Venizelou Avenues at the west. The total length of these grids was ~130 m. The strongest reflections are located within the area of GRID5. These anomalies are of particular interest because they are located at the north and at the west of the west side of Saint Petros church. The reflections located to the NW side of the church have a slight curvature and they extend for ~45 m along the road. However, the anomalies at the west of the church seem to follow a north–south direction for ~13 m. Some linear anomalies in GRID4 and GRID3 are oriented along the east–west direction. Finally a $5 \times 2\ \text{m}^2$ structure, which is probably divided into two different compartments, is located at the east corner of GRID4. In general this area is of equal archaeological interest to the areas covered by GRID0 and GRID6.

## Electrical Resistivity Tomography (ERT)

Figure 4*a* shows the specific area of more than 450 $\text{m}^2$ to the north of Sof. Venizelou Avenue and west of the excavated palaeochristian church that was also investigated with the ERT method. The purpose of the ERT survey was to enhance the information content obtained with the GPR data. The location of the 10 parallel 2D pseudosections that were measured in this area, using a pole-dipole configuration, is presented in Figure 5*a*. Half of the lines were 60 m long, whereas the length of the remaining five lines was 35 m. The distance between the lines and the separation between the electrodes was 1 m, and the measurements were taken with $a = 1$ m and $N_{\text{sep}} = 10a$ ($a$ = electrode spacing, $N_{\text{sep}}$ = maximum separation between the current electrode and the potential dipole). Some extra measurements with different combinations of $a$ and $N_{\text{sep}}$ parameters were also obtained in order to increase the vertical and horizontal area coverage. The infinite current electrode was placed more than 300 m away. Bentonite contact electrodes, like those of Figure 2*b*, were used in as current electrodes.

The 3D apparent resistivity variation at the area at Bentenaki was mapped by more than 10100 measurements. Due to the intersection of three 2D lines with a modern steel-reinforced cement construction, almost 4% of the original data had to be removed because of their unusual high or low values. The inversion algorithm converged to a 3D resistivity model after five iterations, with root mean square error (RMS) = 7.77%. The final inversion model is presented in the form of horizontal depth slices in Figure 5*a*.



(*a*) 3D Resistivity inversion model
5 Iterations
RMS = 7.77%

(*b*) Diagrammatic interpretation

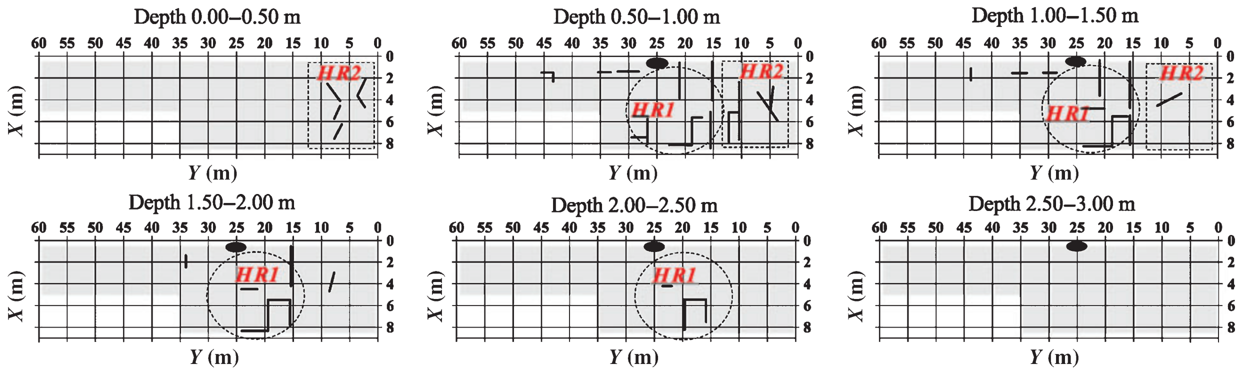


**Fig. 5.** (*a*) Horizontal depth slices at increasing depths, extracted from the 3D resistivity inversion model of the Bentenaki area, Heraklion. (*b*) Diagrammatic interpretation of the strong resistivity anomalies. The layout of the parallel 2D survey lines, conducted to the west of the excavated palaeochristian church, can be seen at the top of the figure.

Although the first depth slice (Z = 0.00–0.50 m) shows areas with strong resistivity variations due to the local inhomogeneity of the upper urban subsurface layers, the remaining depth layers are quite promising with respect to the presence of possible archaeological structures. It is obvious that the east part of the area is of great archaeological interest, as the diagrammatic interpretation map in Figure 5*b* indicates. The promising areas can be divided into two regions. Within the area HR2 that is surrounded by the dashed rectangle, the resistivity anomalies show a rectangular pattern but they do not have a constant directional continuity. However, the high resistivity anomalies within the area HR1 seem to form regular shapes. Considering the fact that these anomalies have a constant direction within all the depth slices down to the depth of 2.5 m below the ground surface, it can be suggested that they are caused by buried architectural remains. Some minor linear features can also be observed at the north-west of the resistivity grid. Finally, the elliptical high resistivity anomaly, which is located at the north centre edge of the grid ($X = 25$ m, $Y = 1$ m) was caused by a local excavated ditch almost 3 m thick. The 3D surface ERT measurements enhanced and verified the data obtained by the GPR survey and both methods suggested that the excavated palaeochristian church comprises part of an architectural complex that extends further to the west.

## Case study 2: Old Turkish School, Rethymno

The location of the old Turkish School, which is located at the centre of the old town of Rethymno, is shown in Figure 6. It is near the Pane Neratze (mosque) and Saint Frangiskos Church as can be seen in Figure 7*a*. Pane Neratze comprises one of the most important sightseeing attractions in the old town of Rethymno. It was constructed in 1657 by Houssein Pasa from the former Santa Maria church and an Augustinian monastery. The Saint Frangiskos church is a one-aisled basilica of the Venetian period. During the field geophysical experiments extensive restoration work was being carried out within the church buildings.

The old Turkish School is located at the west of Saint Frangiskos church. In recent times it has functioned as a primary education institute, and accommodates the 1st elementary school of Rethymno. An inscription at the west entry of the school reports that it was built in 1796, originally as a school for girls. It has 11 teaching rooms and an impressive Turkish style entry.

A room, which is nowadays used as the chemistry laboratory of the elementary school, is attached to the west side of Saint Frangiskos church. It has a series of closed windows with arches that seem to continue to the west. Parts of walls that project from the east entrance of the yard seem to follow the same direction, as indicated by the arrows in Figure 7*b*. The existence of several built-in alcoves in the courtyard wall at the west side of the yard, which are shown in Figure 7*c*, may suggest the continuation of a building to that direction.

A project involving the construction of a new cultural centre at the north side of the Turkish School yard was recently initiated and funded by the municipality of Rethymno. Because of the

**Fig. 6.** Panoramic Quickbird satellite view of Rethymno old town. The locations of the old Turkish School and the Institute for Mediterranean Studies (IMS), where the urban geophysical investigations were conducted, are shown.

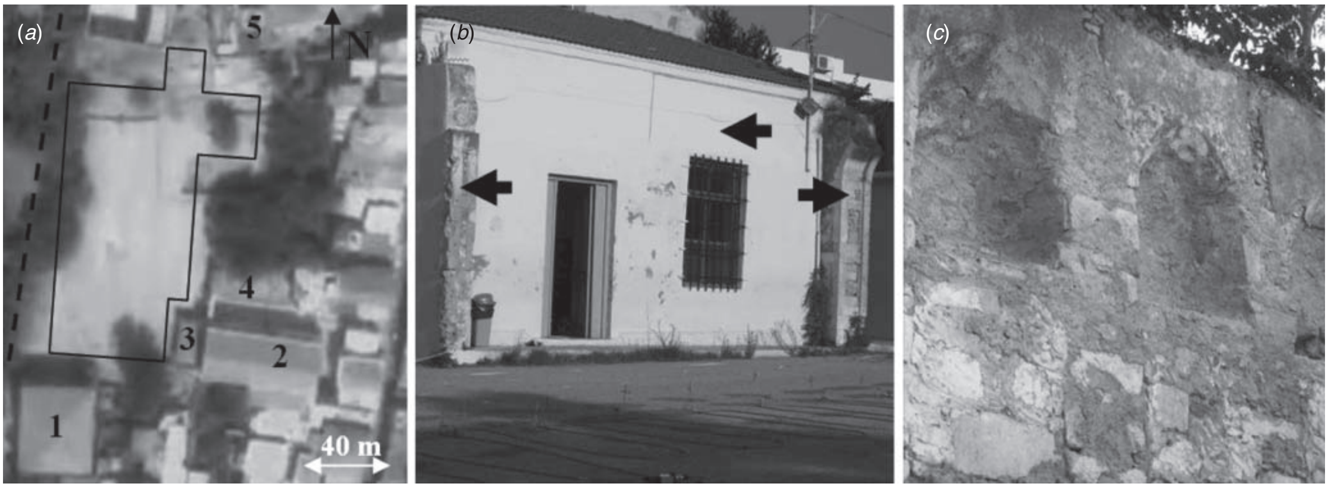


**Fig. 7.** (*a*) The area of the yard of the old Turkish School which was investigated is delineated by the solid polygon. (1) old Turkish School, (2) Saint Fragiskos church, (3) Chemistry laboratory, (4) Hiking Club, (5) Neratze Pane. (*b*) Details of the visible architectural remnants located at the east entrance of the school yard. (*c*) Filled-in alcoves at the courtyard wall (dashed line in *a*) at the west of the yard.

visible historical and archaeological monuments in the area around the yard, geophysical exploration was undertaken to locate possible subsurface continuation of these monuments in the area of the yard. More than 2000 $m^2$ of the Turkish schoolyard at the north of the building facilities shown in Figure 7*a* were investigated with both the GPR and the ERT techniques. The ultimate goal of this geophysical campaign was to reconstruct the archaeological content of the area by detecting, mapping, and visualising the 3D structure of the possible buried archaeological targets, to guide the future excavation activities in selected places and contribute to the construction of the new cultural centre.

## ERT and GPR

The fieldwork at the yard of the old Turkish School was completed in 4 days in August of 2006. Forty-four parallel 2D electrical pseudosections along the south-north direction were measured, using the dipole–dipole configuration. The maximum length of each line varied from 20 to 76 m. The distance between lines, and the electrode spacing along line, was 1 m ($a = 1$). A complete set of apparent resistivity data with $a = 1$ m and maximum separation between the current and potential dipoles $N_{sep} = 6$ m was collected along each line. Some additional data were also gathered with $2a$ and $3a$ distances for the current and potential dipoles in order to maximise the information content and the resolution of the final resistivity model. Unfortunately, it was not possible to use contact electrodes, to minimise the time of data acquisition, because the schoolyard was covered with asphalt. For this reason, metallic electrodes were fixed in the asphalt using a pneumatic drill. In order to ensure good contact of the electrodes with the ground, salty water was poured into each hole and eventually contact resistances of less than 3 K Ohm were attained.

The same area was also covered by GPR data acquisition on a dense grid of parallel lines, spaced 0.5 m apart. In all, 88 lines of data were collected at a sampling interval of 0.05 m. The flat ground of the investigated area contributed to gathering GPR data of high resolution. It has to be noted that due to the almost ideal field conditions at the yard the GPR survey was completed successfully in less than 5 h of fieldwork. This means that in this case the GPR field survey was almost eight times faster than the actual time needed to complete the surface 3D ERT measurements.

The ERT data were processed by following the same general processing steps described earlier. Almost 3% of the more than 33 700 apparent resistivity data that were collected from the yard of the old Turkish School were removed as outliers. The resistivity inversion model shown in Figure 8 consisted of 27 104 parameters and eight layers, and the inversion algorithm converged to this subsurface model after five iterations, with RMS = 9.94%. The GPR data were enhanced through the application of specific filters (see the Data Processing section) and they are presented in Figure 9 in the form of horizontal depth slices every 0.2 m.

The final ERT and GPR maps of Figures 8 and 9, respectively, signify the high quality and spatial resolution of the original

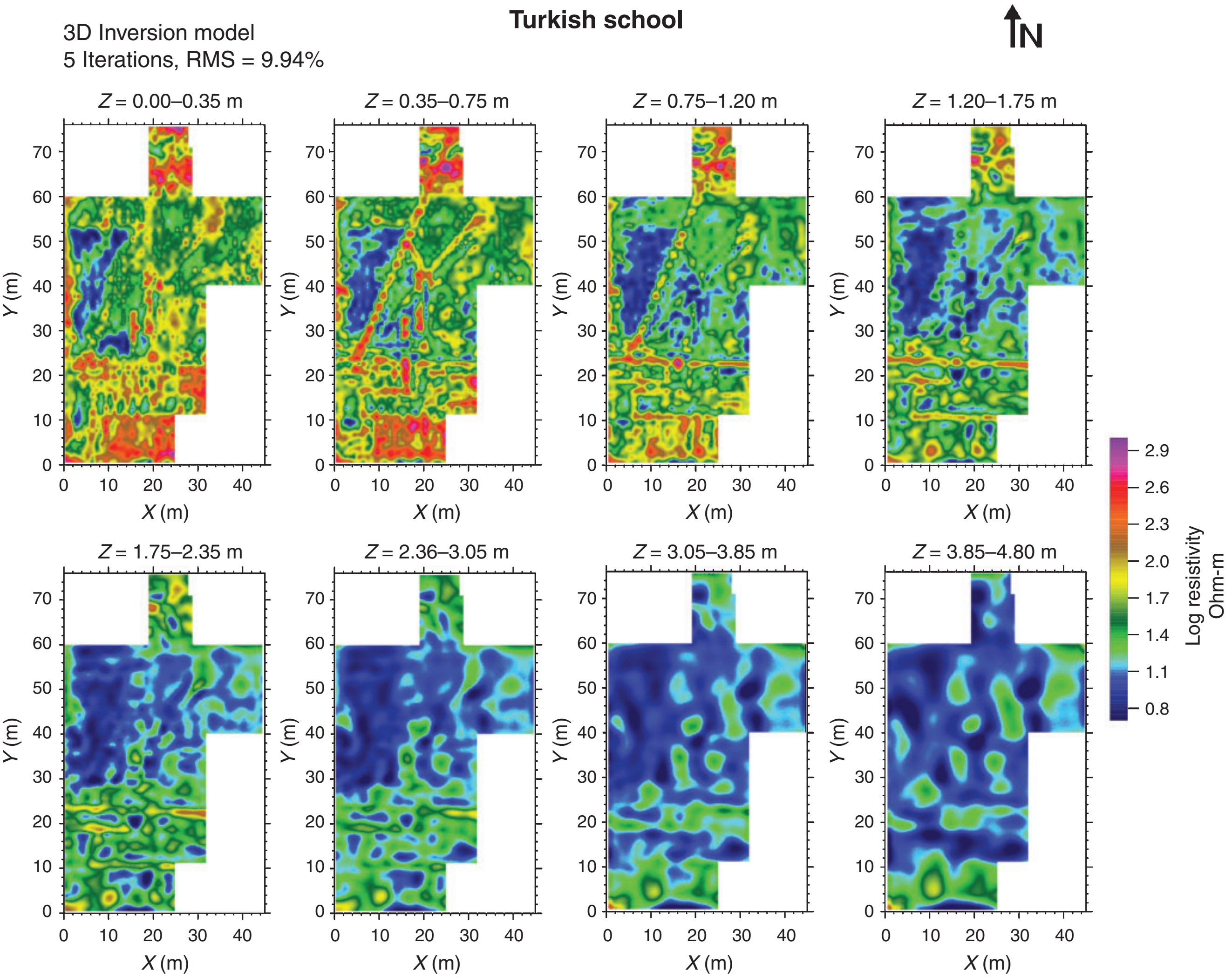


**Fig. 8.** Horizontal depth slices of the 3D resistivity model resulting from the inversion of the apparent resistivity data collected from the yard of the old Turkish School in Rethymno.

collected data. A large number of linear anomalies that are mostly caused by buried archaeological structures can be outlined on both of the maps, and generally a good correlation between the GPR and strong ERT anomalies can be observed. The south part, in particular, and second the north part of the area appear to be the most promising areas as far as the detection of buried architectural remains concerned. Strong GPR reflections seem to be attenuated below the depth of 2.2 m. The ERT data managed to provide extra information concerning the maximum burial extend of the archaeological structures, which seem not to exceed 3.5 m in depth.

The combined diagrammatic interpretation of the strong detected GPR and ERT anomalies is presented in Figure 10. This map resulted from the integration of all the identified anomalies from all the horizontal depth slices from both the GPR and the ERT final results, respectively. The synthesis of the geophysical results was accomplished by geometrical rectification and overlay of the geophysical maps on a Quickbird satellite image of Rethymno city.

At the north of the yard the anomalies T10 and T11 are related to architectural remains that are relatively compact, as the GPR and the ERT maps indicate. These structures have north-south and east-west orientation and are probably related to the facilities of the Augustinian monastery. The excavated archaeological structures that were revealed in the area of the anomaly T10 are shown in Figure 10*b*. This structure was buried at a depth of 0.3 m below the ground surface, which is in agreement with the ERT inversion results. It did not seem to form a regular shape, giving rise to the compact signature that was registered in the geophysical maps. Furthermore part of a buried east-west wall, which was located outside the geophysical grid at the north-west of the anomaly T10, was revealed by the excavation survey and is probably related with the structure T10.

At the south of the investigated area several archaeological remnants (anomalies T12, T13, T14, and T15) were located, which are probably related with the monastery of Saint Frangiskos church. Specifically, the architectural structure T13 extends to the west of Saint Frangiskos church (at the west of the modern chemistry laboratory) and seems to have a similar width to that of the church. At the west extension of the Hiking Club another archaeological structure was identified (anomaly T12), which seems as a projection of the Hiking Club building to the west side of the yard. These buildings are separated into different compartments with internal walls. Finally, anomaly T15 is probably another building related to the built-in alcoves that are located at west wall of the yard, as are some other minor anomalies (T7, T8, and T9) at the centre and at the east of the yard are likely caused by buried walls.

The obvious anomaly T1 crosses the centre of the old Turkish School yard. Subsequent excavations in the area proved that T1

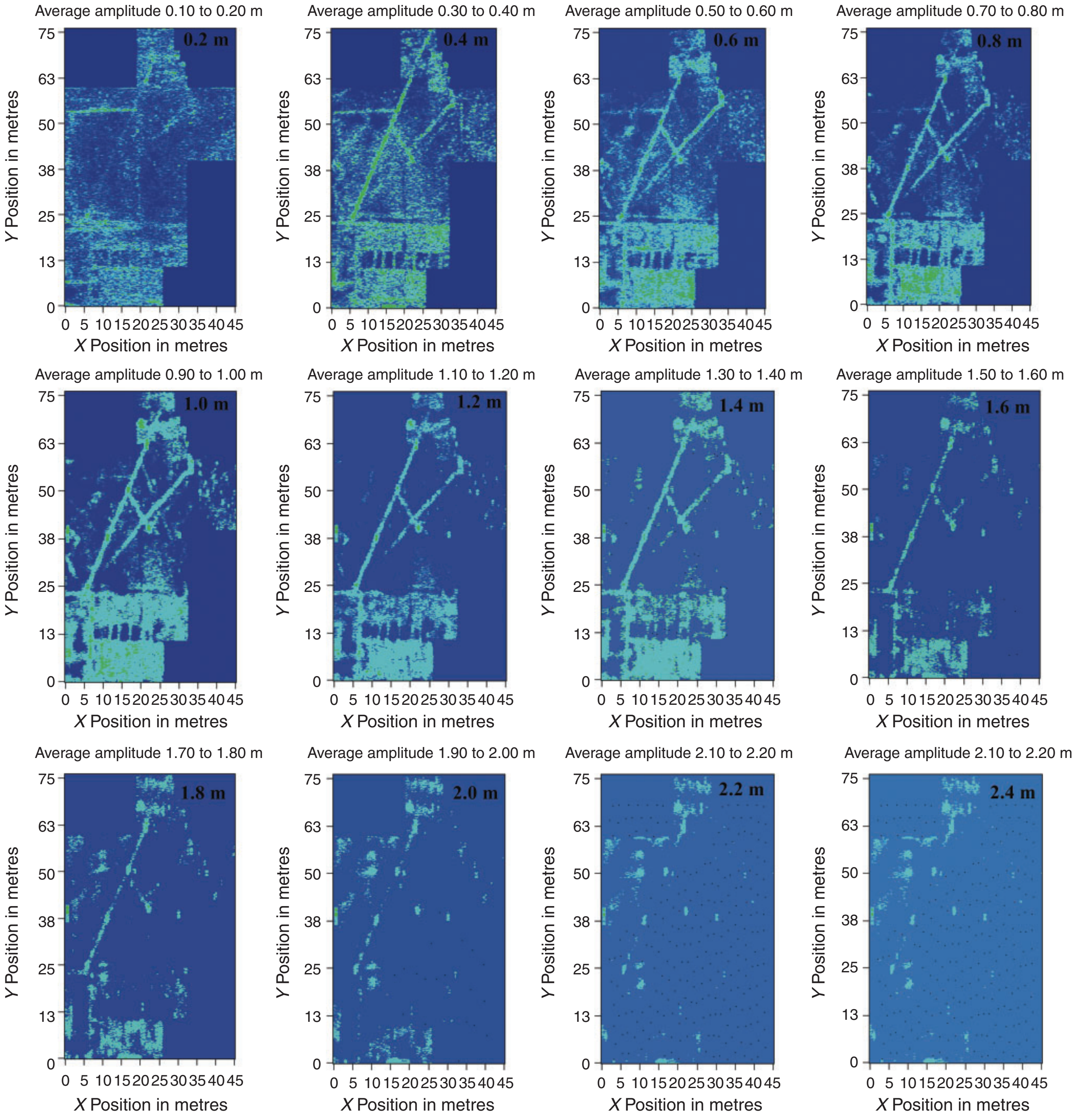


**Fig. 9.** Horizontal depth slices at every 0.2 m, which represent the strong reflections of the electromagnetic waves from the archaeological structures that are buried in the subsurface of the old Turkish School yard.

anomaly is related to a drainage ditch or rainwater channel, as is shown in Figure 10*c*. This channel is superficial, has a NE–SW direction and is probably a modern construction. Anomalies T2, T3, and T4 seem to be related with this specific pipe, and the linear anomalies T5 and T6 are probably related modern drainage structures as well.

## Case study 3: The new building of the Institute for Mediterranean Studies, Rethymno

The Institute for Mediterranean Studies (IMS) is located at the centre of the old town of Rethymno. It is located ~250 m to the north-west of the old Turkish School. IMS belongs to the Foundation for Research and Technology Hellas, one of largest national research institutes in Greece. The IMS has been hosted in a renovated building complex since 1996.

Recently, the building next to the existing IMS facilities was bought in order to cover the increasing needs of the Institute. Because this building is located within the centre of the old town of Rethymno, it is fully protected by Greek archaeological law, and any future restoration work must be approved by the Archaeological Service. The historical importance of this building is significant as two of the ground floor rooms of this building were used as churches in the past. The Archaeological Service decided to carry out excavation work in these rooms in order to recover the possible archaeological structures that were buried beneath these rooms.

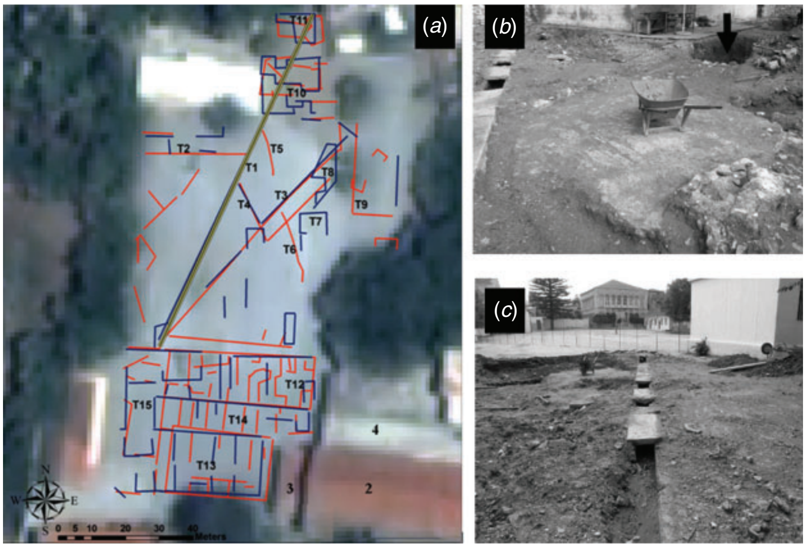


**Fig. 10.** (*a*) Combined representation of the diagrammatic interpretation of the Ground Penetrating Radar (red) and the Electrical Resistivity Tomography (blue) anomalies from the yard of the old Turkish School and code numbers of these anomalies (2) Saint Fragiskos church, (3) Chemistry laboratory, (4) Hiking Club. (*b*) Excavated archaeological structure related to the geophysical anomaly T10 in the north of the school yard. The black arrow indicates an east-west excavated wall, which was outside the geophysical grid. (*c*) Modern drainage ditch or rainwater drain related with the geophysical anomaly T1.

A geophysical survey using the ERT was completed in one of the rooms. The geophysical grid is shown in Figure 11*a*. Unfortunately the second room was not investigated because by the time that the ERT system was available, the excavation work had already begun. No GPR measurements were conducted in the specific area. The ERT method is a non-destructive tool that can satisfy the need of the Archaeological Service to reconstruct the buried archaeological structures in the interior of the building.

## ERT

The dimensions of the room investigated were $5 \times 12\,\mathrm{m}^2$. In all, 11 2D pseudosections were measured, using the dipole–dipole configuration. The lines were oriented from east to west (along the $Y$ axis). The electrodes were placed every 0.5 m along each line and the distance between lines was 0.5 m as well. The results of excavations in the room that was attached at the north and exactly next to the one that was being investigated provided significant information concerning the maximum burial depth of the archeological structures. The maximum burial depth did not exceed 2 m in depth. This information contributed to organising and planning an optimum ERT survey, which was focused on mapping with accuracy and maximum resolution the first 2.5 m of the subsurface. More than 4350 apparent resistivity measurements with basic electrode distance $a = 0.5$, 1.0, 1.5 m, and maximum $N_{\mathrm{sep}} = 8, 7, 5$ respectively, were collected. Although a drill was used in this case to open the holes where the metal stake electrodes were placed, less than 2% of the original data were removed as outliers, showing the high quality of the collected data.

Figure 12*a* shows the resistivity model that the inversion algorithm converged after six iterations with a final RMS = 5.89%. Although the area is small the diagrammatic interpretation of Figure 12*b* is of great interest as far the existence of archaeological structures concerned. The high resistivity anomalies are mainly concentrated at the north-east corner of the grid ($X = 2$–5 m, $Y = 0$–5 m). These anomalies are caused by buried walls that seem to continue towards the second room that is attached to the north. Furthermore, a prominent linear anomaly is observed at the south of the room ($X = 0$–1m, $Y = 3$–8 m), where some vertical parts seem to further continue to the south. Finally, some other minor linear anomalies are located at the west of the investigated area.

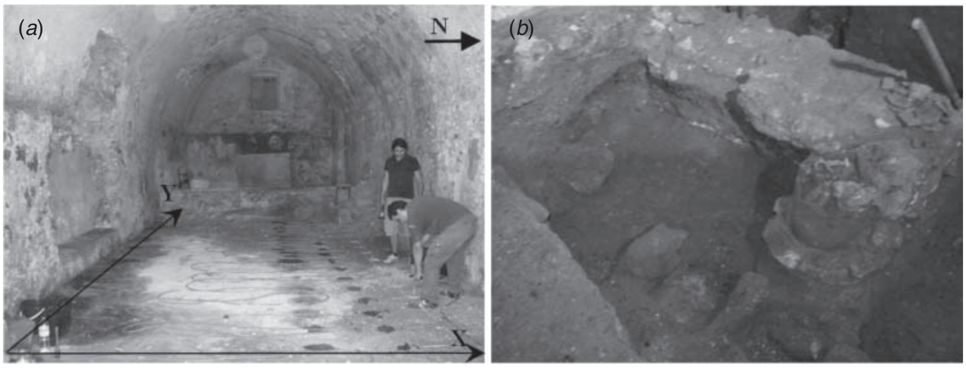


**Fig. 11.** (*a*) Area being investigated inside the room of the new building of the Institute for Mediterranean Studies. The dimensions of the room are $X = 5$ m and $Y = 12$ m. (*b*) Excavated wall close to the entrance of the building.

Subsequent excavations revealed a cooking area belonging to a house of more recent (historical) times, which is shown in Figure 11*b*. This excavated house is located close to the entrance of the building ($X$ = 3–5 m, $Y$ = 0–5 m).

## Conclusions

In this work three case studies are presented which involved the integrated application of the surface GPR and the ERT methods in order to archaeologically characterise specific urban areas. A significant number of strong GPR reflections in the central part of Bentenaki area indicated that the palaeochristian church comprises part of a broader architectural complex. The ERT survey, which overlapped part of the GPR grids, enhanced the information content obtained with the GPR data and provided additional information regarding the depth extent of the archaeological structures. Some very promising GPR anomalies forming regular shapes were also identified at the west side of Saint Petros church.

The ERT and the GPR surveys resulted in subsurface images of comparable accuracy in the case of the geophysical exploration in the yard of the old Turkish School in Rethymno. In the south part of the area several archaeological remnants forming possible buildings, separated in different compartments, were registered in the geophysical maps. To the north, excavation work verified the geophysical results by revealing an archaeological structure that did not form a regular shape. Finally a modern drainage ditch caused the linear anomaly that crosses the yard in a diagonal direction.

Although the new building of the IMS in Rethymno occupied a relatively small area the inversion model contributed in identifying some linear resistivity anomalies that were caused by buried archaeological relics. The subsequent excavation at the entrance of this building revealed a cooking area belonging to a house of more recent times.

Generally these case studies can be regarded as successful as far as the objectives and the final results of all the geophysical surveys concerned. The objectives of these geophysical campaigns were focused on reconstructing the complex urban subsurface, locating with accuracy possible buried structures of archaeological interest, and finally guiding the excavation work in selected places. Although measurements obtained in some areas suffered from increased levels of noise, the final images were of high spatial resolution and revealed clear linear anomalies that could be attributed to buried archaeological structures. The subsequent excavation in the specific sites provided significant proof that verified the geophysical results.

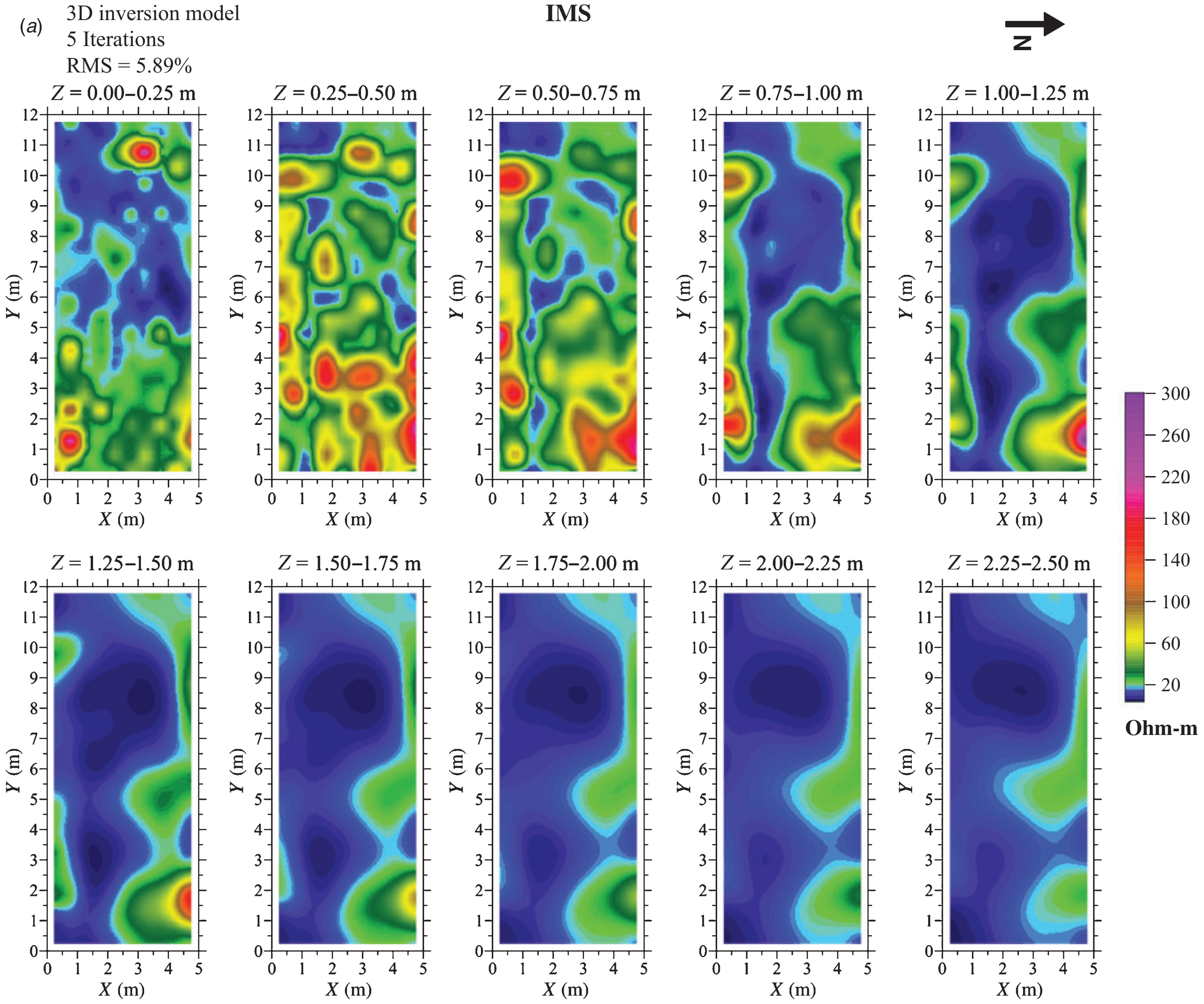


**Fig. 12.** (*a*) 3D resistivity inversion model from the room of the new building of the Institute of Mediterranean Studies (IMS). (*b*) Diagrammatic interpretation of the strong resistivity anomalies.

(*b*) Diagrammatic iterpretation

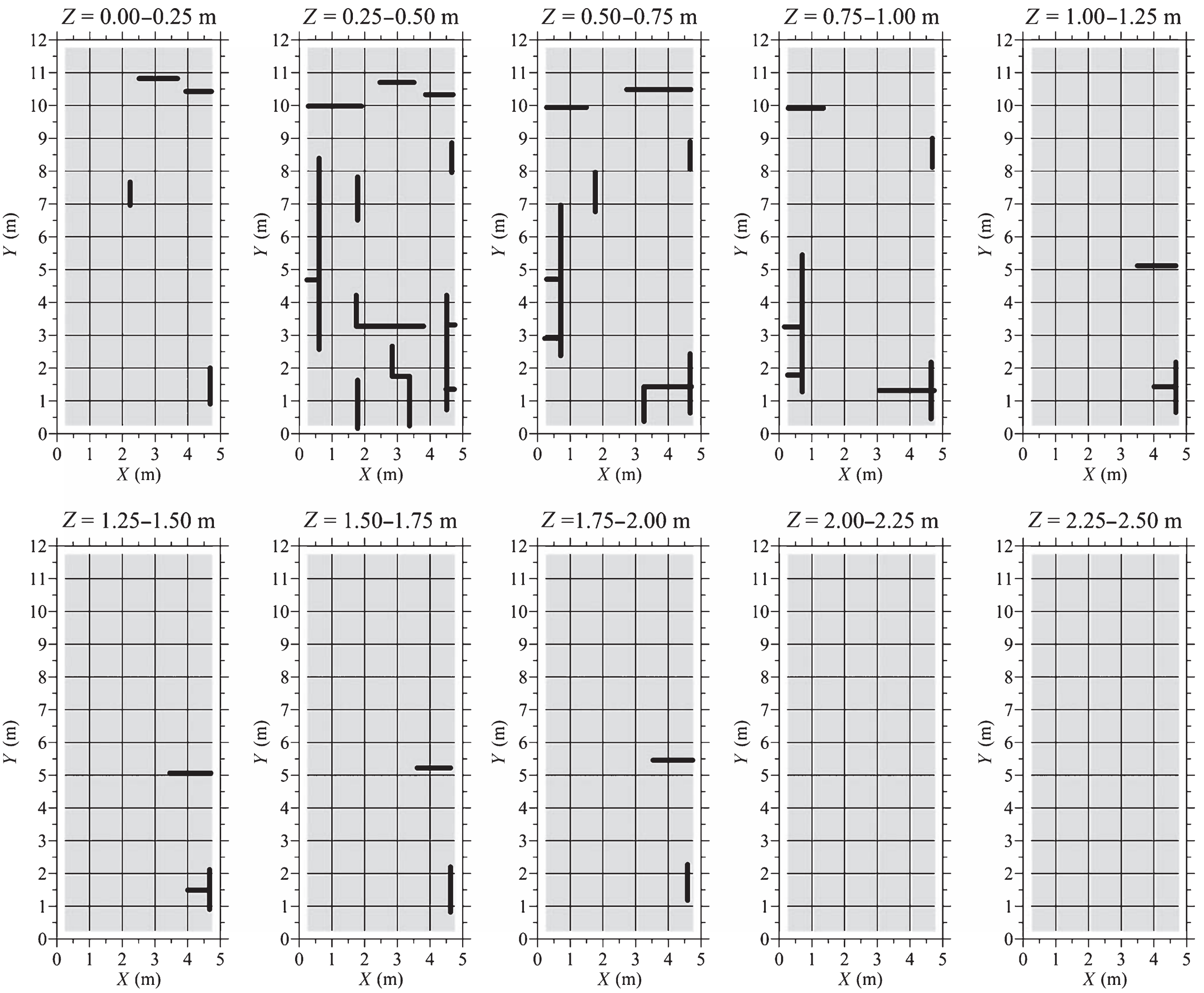


**Fig. 12.** (*continued*)

The contribution of urban geophysical exploration is very significant at the stages of designing and developing modern urban infrastructures. The effective use of geophysical methods can simultaneously help to enable the fast and economical construction of modern infrastructures, and contribute to the preservation of buried cultural monuments. In fact, construction work at all the field sites reported here was actually guided to a certain degree by the geophysical results. Archaeological excavation time was significantly reduced by excavating only the specific parts that were indicated by the geophysical campaigns. This fact obviously contributed to the acceleration of the construction procedures involved in each case.

The surface GPR and ERT methods seem to be the most appropriate and promising techniques to resolve buried architectural structures in urbanised areas accurately, fast, and efficiently. Indeed, the development of modern, mobile, and sophisticated GPR systems renders the GPR method fully automated, and transforms it into a necessary tool in exploring large urbanised areas rapidly and effectively. Similarly, the upgraded multichannel ERT systems, and the use of contact electrodes, can provide additional information about subsurface resistivity anomalies that can be related to archaeological monuments, reducing the survey time and effort required by older versions of ERT systems. Generally speaking the GPR method can provide a high-resolution image of the subsurface quickly and with accuracy, whereas the ERT technique can act as an essential complementary tool in order to verify and enhance the GPR results, and additionally to increase the vertical information content of the subsurface interpretation.

The case studies proved the efficiency of surface ERT and GPR techniques in the archaeological exploration of urban areas. The combined use of these methods and the integration of the final results seem to be adequate to reconstruct the complex subsurface material properties encountered in the urban settings and to guide the archaeological excavation in selected places. The application of geophysical investigation methods can effectively meet the differing needs of construction development and preservation of archaeological monuments. In general urban geophysics provides a valuable tool at the stages of designing and constructing modern infrastructure, by assisting with the protection and preservation of the cultural heritage of an urbanised area.

## Acknowledgments

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## References

Athanasiou, E., Tsourlos, P., Vargemezis, G., Papazachos, C., and Tsokas, G.N., 2007, Non-destructive DC resistivity surveying using flat-base electrodes: *Near Surface Geophysics*, **5**, 263–272.

Atzemoglou, A., Tsourlos, P., and Pavlides, S., 2003, Investigation of the Tectonic Structure of the NW Part of the Amynteon Basin (NW Greece) by means of a Vertical Electrical Sounding (VES) survey: *Journal of the Balkan Geophysical Society*, **4**, 188–201.

Chávez, R. E., Cámara, M. E., Tejero, A., Barba, L., and Manzanilla, L., 2001, Site Characterization by Geophysical Methods in the Archaeological Zone of Teotihuacan, Mexico: *Journal of Archaeological Science*, **28**, 1265–1276. doi: 10.1006/jasc.2000.0627

Conyers, L. B., 2006, Innovative ground-penetrating radar methods for archaeological mapping: *Archaeological Prospection*, **13**, 139–141. doi: 10.1002/arp.282

Dahlin, T., and Owen, R., 1998, Geophysical investigations of alluvial aquifers in Zimbabwe. *Proceedings of the IV Meeting of the Environmental and Engineering Geophysical Society (European Section)*, Sept. 1998, Barcelona, Spain, 151–154.

Drahor, M. G., 2006, Integrated geophysical studies in the upper part of Sardis archaeological site, Turkey: *Journal of Applied Geophysics*, **59**, 205–223. doi: 10.1016/j.jappgeo.2005.10.008

Gerolla, G., 1905, Monumenti Veneti nell' isola di Creta, Venice, 2b, 125–127.

Goodman, D., 1994, Ground-pentrating radar simulation in engineering and archaeology: *Geophysics*, **59**, 224–232. doi: 10.1190/1.1443584

Goodman, D., Nishimura, Y., and Rogers, J. D., 1995, GPR time slices in archaeological prospection: *Archaeological Prospection*, **2**, 85–89.

Griffiths, D. H., and Barker, R. D., 1994, Electrical Imaging in Archaeology: *Journal of Archaeological Science*, **21**, 153–158. doi: 10.1006/jasc.1994.1017

Leckebusch, J., 2003, Ground-Penetrating Radar: A Modern Three-Dimensional Prospection Method: *Archaeological Prospection*, **10**, 213–240. doi: 10.1002/arp.211

Loke, M. H., and Barker, R. D., 1996, Practical Techniques for 3D Resistivity Surveys and Data Inversion: *Geophysical Prospecting*, **44**, 499–523. doi: 10.1111/j.1365-2478.1996.tb00162.x

Lück, E., Eisenreich, M., Spangenberg, U., and Christl, G., 1997, A Note on Geophysical Prospection of Archaeological Structures in Urban Contexts in Potsdam (Germany): *Archaeological Prospection*, **4**, 231–238. doi: 10.1002/(SICI)1099-0763(199712)4 : 4<231::AID-ARP87>3.0.CO;2-6

Leucci, G., Greco, F., Giorgi, L. D., and Mauceri, R., 2007, Three-dimensional of seismic refraction tomography and electrical resistivity tomography survey in the castle of Occhiola (Sicily, Italy): *Journal of Archaeological Science*, **34**, 233–242. doi: 10.1016/j.jas.2006.04.010

Leucci, G., and Negri, S., 2006, Use of ground penetrating radar to map subsurface archaeological features in an urban area: *Journal of Archaeological Science*, **33**, 502–512. doi: 10.1016/j.jas.2005.09.006

Negri, S., Leucci, G., and Mazzone, F., 2008, High resolution 3D ERT to help GPR data interpretation for researching archaeological items in a geologically complex subsurface: *Journal of Applied Geophysics*, **65**, 111–120. doi: 10.1016/j.jappgeo.2008.06.004

Papadopoulos, N.G., Tsourlos, P., Tsokas, G.N., and Sarris, A., 2007, Efficient ERT Measuring and Inversion Strategies for 3D Imaging of Buried Antiquities: *Near Surface Geophysics*, **6**, 349–362.

Ramirez, A., Daily, W., Binley, A., and Labrecque, D., 1996, Tank leak detection using electrical resistance methods. S*ymposium on the application of geophysics to engineering and environment*, Keystone CO, April 28–May 1, 1996.

Sarris, A., Dunn, R. K., Rife, J. L., Papadopoulos, N., Kokkinou, E., and Mundigler, C., 2007, Geological and geophysical investigations in the Roman cemetery at Kenchreai (Korinthia), Greece: *Archaeological Prospection*, **14**, 1–23. doi: 10.1002/arp.280

Scollar, I., Weinder, B., and Segeth, K., 1986, Display of archaeological magnetic data: *Geophysics*, **51**, 623–633. doi: 10.1190/1.1442116

Stummer, P., 2003, New Developments in Electrical Resistivity Imaging. *Dissertation* submitted to the Swiss Federal of Institute of Technology, Zurich.

Tsokas, G.N., Giannopoulos, A., Tsourlos, P., Vargemezis, G., Tealby, J.M., Sarris, A., Papazachos, C.B., and Savopoulou, T., 1994, A Large Scale Geophysical Survey in the Archaeological Site of Europos (northern Greece): *Journal of Applied Geophysics*, **32**, 85–98. doi: 10.1016/0926-9851(94)90011-6

Tsokas, G. N., Tsourlos, P. I., Vargemezis, G., and Novack, M., 2008, Non-destructive Electrical Resistivity Tomography for Indoor Investigation: the Case of Kapnikarea Church in Athens: *Archaeological Prospection*, **15**, 47–61. doi: 10.1002/arp.321

Tsourlos, P., and Ogilvy, R., 1999, An algorithm for the 3-D Inversion of Tomographic Resistivity and Induced Polarization data: Preliminary Results: *Journal of the Balkan Geophysical Society*, **2**, 30–45.

Vafidis, A., Economou, N., Ganiatsos, Y., Manakou, M., Poulioudis, G., Sourlas, G., Vrontaki, E., Sarris, A., Guy, M., and Kalpaxis, Th., 2005, Integrated archaeological studies at ancient Itanos (Greece): *Archaeological Science*, **32**, 1023–1036. doi: 10.1016/j.jas.2005.02.007

Vaughan, C. J., 1986, Ground-penetrating radar surveys in archaeological investigations: *Geophysics*, **51**, 595–604. doi: 10.1190/1.1442114

Xu, B., and Noel, M., 1993, On the Completeness of Data Sets with Multielectrode Systems for Electrical Resistivity Survey: *Geophysical Prospecting*, **41**, 791–801. doi: 10.1111/j.1365-2478.1993.tb00885.x

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# 3 차원 지표레이다와 전기비저항 탐사를 이용한 도심지 유적 조사

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**요 약 :** 현재 진행되고 있는 광범위한 도시화는 종종 무분별한 토목건설을 수반하게 되며, 이는 도심지에 묻혀있는 고고학적 가치가 있는 중요한 역사적 유구들을 위협하기도 한다. 도심지 지역에 묻혀있는 고고학적 유구들을 파악하는 데에는 지표레이다와 전기비저항 탐사가 매우 유력한 방법이며, 이 논문에서는 3차원 전기비저항 탐사와 3차원 지표레이다 탐사에 의한 고고학적 조사를 위한 복합물리탐사의 3가지 사례를 설명한다. 조사지역은 그리스 크레타섬 내 가장 번화한 두 도시의 역사적 도심지에 위치해 있다. 이 지역에서 평행한 측선들로 이루어진 격자망의 측선을 따라 고밀도의 3차원 전기비저항과 3차원 지표레이다 탐사자료의 획득이 이루어졌다. 먼저, 전기비저항 탐사자료의 3차원 역산을 통하여 하부 전기비저항 구조를 획득하였으며, 지표레이다 탐사자료는 탐사자료로부터 최대한의 정보를 도출하기 위하여 특정 필터를 적용하는 등 체계적인 자료처리 과정을 거쳤다. 이로부터 최종적으로 지하하부 물성의 3차원적인 변화를 나타내는 수평 절개 단면 영상을 획득하였으며, 이와 같이 획득한 3차원 지표레이다와 전기비저항 영상들은 도심지 지역의 복잡한 하부 물성을 영상화하는데 매우 중요한 역할을 담당하였다. 즉, 강한 레이다 반사파와 고비저항 이상을 나타내는 부분은 고고학적 유구로서 해석되었으며, 탐사 후에 수행한 일부 지역에서의 발굴결과와 매우 잘 일치하였다. 이와 같은 사례는 도심지 지역에서의 기반시설물의 설계 및 건설 단계에서 고고학적으로 의미가 있는 중요한 영역의 도출 및 건설공사 수행 이전에 고고학적 발굴에 대한 가이드라인을 제공하는 등 도심지역 고고학적 물리탐사에서 전기비저항 탐사와 지표레이다 탐사가 매우 높은 적용성이 있음을 잘 보여주고 있다.

**주요어 :** 도심지, 고고학적 조사, 3 차원 전기비저항, 지표레이다

# 地中レーダおよび電気探査による都市域の3次元遺跡調査

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**要 旨 :** 都市域の拡大に伴い不注意な建設工事の施工件数が増加し，地下の貴重な遺跡構造物が擾乱を受ける頻度の増加が懸念される。地中レーダおよび電気探査は、都市域に埋没している遺跡構造物の破壊防止手法として期待が高い。本研究では3つの調査事例を紹介する。調査地域の考古学的な解明のため、各調査事例では3次元電気探査および地中レーダ探査による複合物理探査を施行した。

試験調査地はギリシャのクレタ島の歴史的に有名な2地域に設けた。複数の平行測線を設定し、電気探査および地中レーダ探査の高密度記録を取得した。浅層比抵抗構造は見掛比抵抗を元に3次元インバージョンにより求めた。地中レーダ断面は含有情報を強調するために特定のフィルタを適用し、系統的な処理を施した。最後に、物性値の3次元変化の理解が容易となるように水平深度スライス断面を作成した。地中レーダと電気探査の探査断面は都市域の複雑な浅層遺跡構造の再現に大変貢献した。地中レーダの強反射領域と高比抵抗異常を示す領域は考古学的構造物の存在可能性を示している。探査後に両地域の一部の地点において掘削が行われ、本探査結果が検証された。本実証試験により、電気探査と地中レーダ技術が、工事施工前に考古学的に重要な場所を特定し、遺跡掘削の指針を与えることがわかり、都市域のインフラ整備の設計および工事の際の適用有効性が示された。

**キーワード : 遺跡調査，地中レーダ，3次元電気探査，都市域**