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*Full Length Research Paper*

# Magnetic and electrical resistivity image survey in a buried Adramytteion ancient city in Western Anatolia, Turkey

**Can Karavul[1], Zehra Dedebali[1], Ayhan Keskinsezer[1], Günay Beyhan[1] and Aşkın Demirkol[2]***

[1]Department of Geophysical Engineering, Engineering Faculty, Sakarya University, 54187 Adapazarı-Sakarya, Turkey.
[2]Department of Electrical and Electronics Engineering, Engineering Faculty, Sakarya University, 54187 Adapazarı-Sakarya, Turkey.

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**This paper examines a buried Adramytteion ancient city in the Balıkesir-Burhaniye-Ören district located in the Western Anatolian region of Turkey. In this research, the some ruins in Adramytteion with the different properties such as magnetic and resistivity is investigated using plausible techniques, which are not experienced before. The attached ruins with the magnetic and resistivity attributes are diagnosed correctly by the use of magnetic and resistivity techniques. In this work, a kiln structure with a high total magnetic field value and a wall with high resistivity values were identified in the same area. The identified archaeological ruins are found in a small part of Adramytteion. However, this leads us to a conclusion that the number of similar parts in Adramytteion are quite high than expected. Hence, both techniques are consistent to bring out a larger part of Adramytteion.**

**Key words:** Adramytteion, magnetic derivatives, analytic signal, Euler deconvolution technique, electric resistivity imaging, two-dimensional modelling.

## INTRODUCTION

An Adramytteion ancient city was founded in the 6th century B.C. at the site of the study area (Pekman, 2005). The Adramytteion ancient city is located in the Burhaniye district southwest of Ören in Western Turkey (Figure 1). Archaeological excavations have been ongoing since 2001 in the area to bring out the ruins belonging to this ancient city. In Adramytteion complex, a church foundation from the 10th century was found in the first archeological studies (Çoruhlu, 2005). Then, two archeological ruins have been identified in the area next to the church remains. Because there are just few ruins belonging to this ancient city, a proper city plan could not be formed as wished. Thus, the research is done for a limited area which covers two archeological ruins such as a kiln and a wall.

The magnetic field observed at the surface is the superposition of the fields resulting from all magnetic objects in the area (Tsokas and Hansen, 2000). Kis and Puszta (2006) used the magnetic method for the detection of Sarmatin graves located in the Hajdúdurog settlement area in Hungary. A method based on the magnetic field changes has been developed to detect the location of these graves. The use of linear transforms, such as the reduction to the pole transform, to remove the bipolar asymmetry by rectifying the magnetic signal (Gunn, 1975; Blakeley, 1995) is well established. The ultimate goal of a magnetic survey is to yield an image that resembles the result that could have been obtained if an excavation had taken place. Thus, the source is mapped and the interference from other sources is suppressed. This study deals with the exploration of the complex attributes of the magnetic signal in order to extract properties of the sources of the anomalous fields.

The electrical resistivity method is widely used in the investigation and detection of shallow-depth targets. The

*Corresponding author. E-mail: askind@sakarya.edu.tr.


**Figure 1.** Balıkesir-Burhaniye region and study area.

method aims to evaluate the variation of the subsurface resistivity by conducting measurement at ground level. The resistivity method has been applied with a great success in solving geological (Çağlar and Duvarcı, 2001; Atzemoglou et al., 2003), engineering (Dahlin et al., 1994) and archaeological problems (Papadopoulos et al., 2006; Drahor et al., 2008; Tsokas et al., 2008). The development of the technology associated with automatically multiplexed electrode arrangements and automatic measuring systems facilitate the acquisition of a large number of measurements in a limited time. Furthermore, the advent of fast computers allowed for the development of automated resistivity sections. Thus, the advanced technology made an estimation of a subsurface resistivity distribution possible from the experimental data (Papadopoulos et al., 2006).

Despite the development of advanced instrumentation and three-dimensional interpretation techniques, common geophysical practice still relies mainly on two-dimensional approaches (Chambers, 2001). The resistivity technique is very popular in the investigation of archaeological sites for mapping buried antiquities. The success of the method depends on the different resistivity properties between the potential archaeological targets (walls, roads, buildings, graves, ditches, etc.) and the surrounding environment. A number of electrode arrays, such as Wenner and Schlumberger configurations, are used in the resistivity investigation of archaeological sites. The results confirm the high selectivity of the array response to the orientation of the feature, since structures parallel to the array orientation were poorly recognized.

The vertical geoelectrical sounding technique has proved to be very promising for the exploration of buried archaeological targets (Gaber et al., 1999; Chouker, 2001). Furthermore, it gives a strong and clear response over archaeological features for an easy interpretation. The resistivity mapping of specific archaeological areas with this particular array has been used with great success to delineate the plane view of buried archaeological structures in various cases (Sarris, 1992; Tsokas et al., 1994; Sarris et al., 2002; Papadopoulos et al., 2006). The resistivity data acquisition in this work was performed in a two-dimensional manner using the Wenner electrode configuration. All data were processed using the two-dimensional techniques. In addition, the techniques of two dimensional inverted resistivity obtained from the area was displayed in a graphical representation. The overall results revealed that the use of both magnetic solving and resistivity interpretation studies would enhance the diagnostic possibilities of archaeological surveys.

## HISTORY OF ADRAMYTTEION (BURHANIYE-ÖREN)

Adramytthene region was located in a geographically strategic place in Burhaniye-Ören. The region became a settling center having an important maritime trade. Especially in the period of the early bronze age, Adramytthene became popular with the advantages of having a plain and mountainous area extending beyond the coast line as well as mine and forest resources. This area constituted a permanent focal point for different cities of this region mentioned in the literatures of Strabon, Plinius, Stephanos Byzantinos, and other authors. Adramytteion always appeared as an important and great city. The source of information relating to the foundation of Adramytteion is based on Stephanos Byzantinos who lived in the 5th century A.D. The most important archeological finding on the existence of Lydia in the region is a series of rock altars located behind the mountainous zones of the Burhaniye, Havran, Gömeç, and Ayvalık villages (Meineke, 1992; Beksaç, 2001; Pekman, 2005; Çoruhlu, 2005).

It is known that Adramytteion was settled by local people originating from Leleg and Mysia in the classical era. Then, Lydian people and and partially Aeol and Kimmer people came to the region in the following periods. The Kimmer people were defeated by the Lydians in the period of King Alyattes. The Lydian sovereignty ended with the defeat of the last Lydian King (575-546 B.C.) by the Persians (546 B.C.) and the sovereignty passed to the Persians. The first coins related to the region are identified as those particularly minted in the name of Persian Satraps. An archeological finding indicating the existence of Macedonians within the Burhaniye borders was acquired in the surrounding of the Uyuncak Bridge. This finding is a coin composed of four drachmas belonging to Alexander and a tetra drachma belonging to Lysimachos (Wiegand, 1904).

In 323 B.C., the kings of Selevkoslar and Traklar ve Bergama (323 - 236 B.C.) governed the area. After the

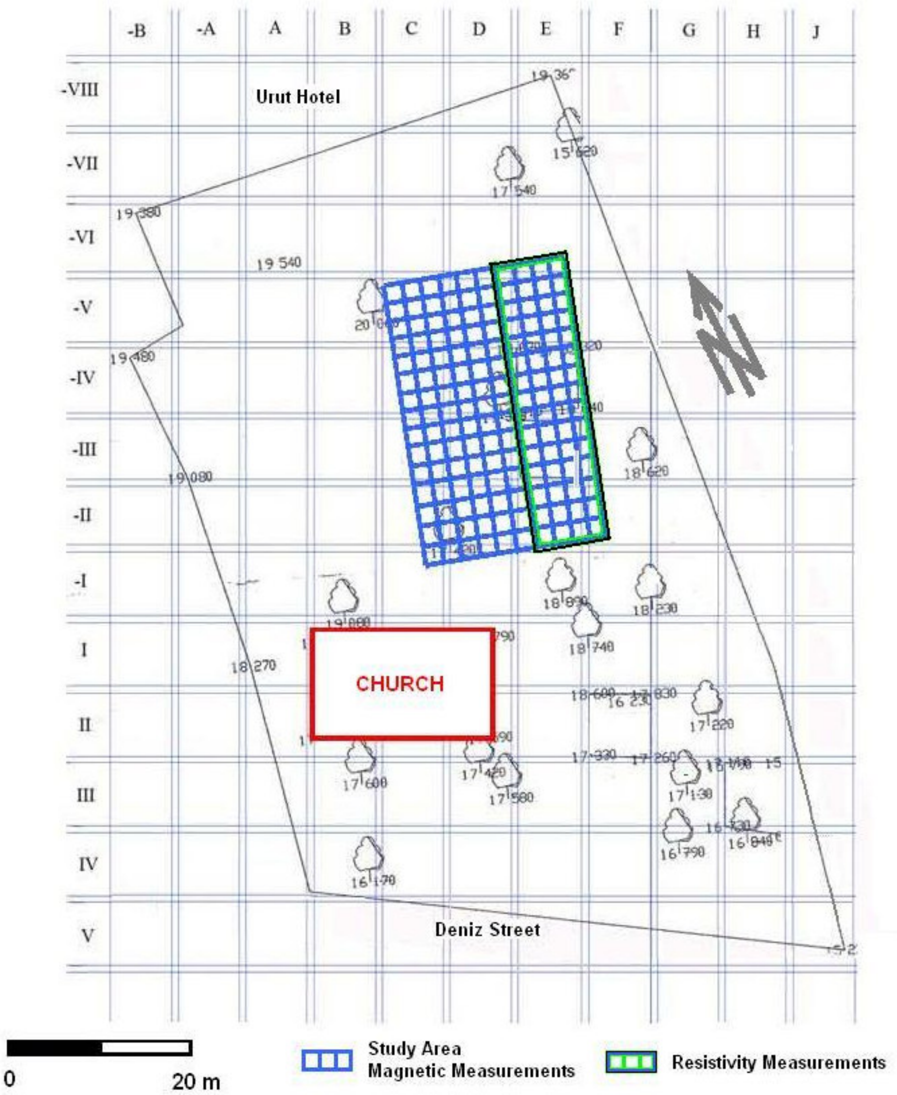


**Figure 2.** Study area layout and measurement points.

Magnesia war in 323 A.D., the control of the area was completely taken by Rome. The existence of an active seismic belt in the area caused destructive earthquakes. It was known that the damages in the area were rebuilt by Rome as Trajanus (98 - 117 A.D.) (Plinus, Naturalis Historia V-122). The Byzantine Empire was the last civilization of the ancient age in the area. Therefore, Adramytteion was the bishopric center of the region (Beksaç, 2001).

## GEOPHYSICAL INVESTIGATIONS

### Study plan

This study was conducted with the aim of detecting the ruins belonging to the ancient Adramytteion city presumed to be buried in the Balıkesir-Burhaniye-Ören district (Çoruhlu, 2005; Beksaç, 2001). Therefore, the archaeogeophysical experimental field was planned by taking into consideration the works in the area and the ruins belonging to the ancient harbor in the area (Çoruhlu, 2005; Beksaç, 2001). According to the plan, the workspace was chosen to be north of the church ruins. Initially, the prospecting was done with a magnetometer to search for structures causing a magnetic anomaly. Magnetic measurements were taken based on a 1 x 1 m grid in a study area that was a 600 $m^2$ rectangle (20 x 30 m).

The magnetic measurement of these points were taken and interpreted by drawing their maps and then the electrical resistivity measurements were taken from the first five profiles of these points from east to west. The work area area map is shown in Figure 2, along with the layout showing the measurement points where the magnetic and resistivity methods were applied.

### Geophysical surveys

#### *Magnetic data acquisition and interpretation*

The magnetic method was performed in gridded areas of various sizes using the survey procedures which are standard in

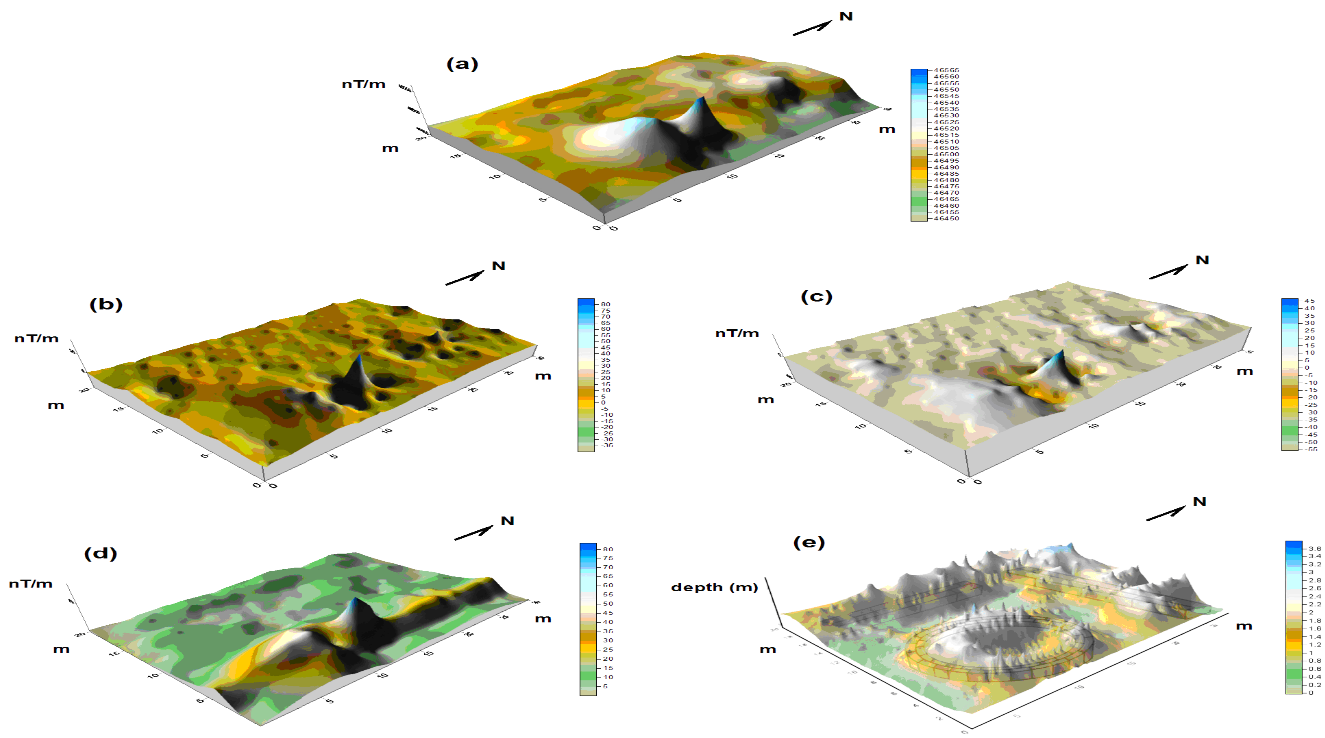


**Figure 3.** (a) Magnetic anomaly map of Adramytteion, (b) Vertical derivative, (c) Horizontal derivative, (d) Analytic signal solutions, and (e) Euler deconvolution depth solutions.

archaeological prospecting. The line and measuring intervals were taken volatility and data were collected using parallel or zigzag measuring techniques. Subsequently, all data from every grid were combined by the survey plan. The dimensions of the whole area were subjected to large-scale magnetic investigation at Adramytteion are 20 x 30 m (Figure 3). The gridding process was carried out using a number of grids measuring 1 x 1 m. During the data acquisition, the total magnetic field data were collected using a Scintrex Proton Magnetometer at a 1 m sampling interval along parallel NS orientated traverses separated by 1 m. The magnetic data taken from the field (55° N) were made by the pole reduction by assuming a declination degree of 5° E and a total magnetic field of 46000 nT. Then, based on the data, information about the geometry and depth of the structure was obtained using derivative calculations, analytic signals and Euler deconvolution techniques.

A number of techniques can be applied in an automatic mode to yield the spatial distribution of parameters that describe the source. Even within magnetic prospecting for the depth of a structural target, a number of automatic techniques can be used. For example, a three-dimensional Euler deconvolution (Reid et al., 1990) and the three-dimensional analytic signal technique (Roest et al., 1992) are advanced for automatic interpretation figures. They may be used to solve specific problems such as determining the burial depth (Tsokas and Hansen, 1995). The use of the analytic signal amplitude (Nabighian, 1972, 1974) poses some attractive features for any type of magnetic prospecting. In terms of geophysical property, it is advantageous that it peaks exactly over the edge of the buried dipping contact that causes the magnetic anomaly (Nabighian, 1972). In addition, its amplitude is independent of inclination, declination, remnant magnetization and dip if the sources are two-dimensional (Blakeley, 1995; Thurston and Smith, 1997). With respect to archaeological geophysics, as a disadvantage, the analytic signal anomalies are relatively much broader than the lateral extent of the buried target.

The goal is to delineate the edges of the buried bodies, to estimate their susceptibility contrasts, and to produce burial depth estimates all at once. Since the magnetic field is a potential field and the fact that, because of the two-dimensionality of the contact model already introduced, it is two-dimensional. This implies that the vertical and horizontal derivatives of the field form a Hilbert transform pairs. Derivatives, in general, play a role in magnetic interpretation because they isolate contacts over which the field can be expected to change rapidly and therefore have large values for its derivatives. More specifically, in this case the analysis that yields the contact parameters involves both the vertical and the horizontal derivatives (Thurston and Smith, 1997).

In this work, the data processing was implemented taking advantage of the anomaly map of Adramytteion in Figure 3a. In light of the computations, some processes were prepared such as the vertical derivative in Figure 3b, the horizontal derivative in Figure 3c, the analytic signal solutions in Figure 3d and the Euler deconvolution depth solution maps in Figure 3e were prepared. Finally, the magnetic data were processed using signal and image processing techniques, allowing the magnetic data to be rendered as an image. High quality images were gained from the surveyed area in a short time and archaeological structures were mapped correctly.

When the vertical and horizontal derivative maps in Figure 3(a) are considered, two different anomalies with a maximum of 80 nT/m for the vertical and 45 nT/m for horizontal are noted. It is highly possible that the high-valued anomaly points to geometrical objects with contents, which differ from their environment. When the analytic signal map in Figure 3(c), calculated by the derivatives, is examined, the existence of the underground structures is obvious. In the conclusion of this study, the Euler deconvolution technique is applied for determining the depths of the structures whose approximate geometry, which reveals its image under the ground. The depth map in Figure 3(e) is obtained via this technique. From the map, many structures with various geometries are determined at different depths from approximately 2 m.

***Electrical resistivity data acquisition***

The electrical resistivity technique is very popular in the investigation of archaeological sites for mapping buried antiquities. The success of the method depends on the different resistivity properties between the potential archaeological targets (walls, roads, ruins, ditches, etc.) and the surrounding environment.

The effects of the changes arising from the local geological and climatic soil conditions lead to the detectability of archaeological structures in resistivity prospecting. Anomalies caused by archaeological features may easily be masked by these conditions. In addition, the type of electrode configuration used during the investigation is also important for determining the resistivity value of the medium. The aim of electrical resistivity survey is the repeated survey of the subsurface along the survey line by an expandable electrode configuration (e.g. Wenner or Schlumberger). Using an automatic electronic system, the measuring lines are scanned rapidly to obtain the apparent resistivity pseudo-section of the subsoil from the first electrode to the last electrode. This survey technique is performed in a two-dimensional manner and involves a series of measuring lines with different electrode separations increasing with each successive level (Griffiths and Barker, 1993; Dahlin, 2001). In 2006, multi-electrode resistivity imaging techniques using the Wenner electrode array were applied for mapping an area of Adramytteion in order to obtain a two-dimensional view of the subsurface. Resistivity data were collected from five different profiles oriented NW–SE (Figure 2), using two-dimensional imaging surveys by the Wenner electrode configuration.

The interval between profiles was taken as 1 m. This was found to be the most appropriate method for resolving the archaeological problem under consideration at the site. The measurements were carried out using the northern portion of the church ruins as a reference point (Figure 2).

## DIMENSIONAL (2D) INVERSION ANALYSIS AND INTERPRETATION

The measured variable quantity, apparent resistivity, is used to calculate the true resistivity via different calculation methods, one of which is the inversion method. These data can be inverted automatically to create an image of the true resistivity. As a result of this electrical survey, we can create more realistic images correlated with the true resistivity and depth information for subterranean archaeological structures. The pseudo-section forms the input for the inversion techniques, which produce a two-dimensional subsurface model (Loke and Barker, 1996). The two-dimensional resistivity data collected in 2002 and 2003 were evaluated using a two-dimensional robust inversion technique via the Res2dinv software (Geotomo, 2002; Dogan and Papamarinopoulos, 2003). This is a package program prepared with the aim of conducting two- dimensional inversion analyses of measurements taken for many arrays and was used in this study. In the inversion analysis of the Wenner data values, which were obtained from five profiles in the work area, the smoothness-constrained least squares method was used and the inversion model sections of the resistivity data were obtained using Res2dinv software. The inversions of the data depict the root mean square (RMS) errors of 2 - 6.5% from 6 - 10 iterations (Figure 4).

We observed that there are many resistivity anomalies in the investigation area. The traces of the dislocated EW directional resistivity anomaly can be seen in all lines sections. The pseudo-sections along lines 2, 3, 4, and 5 indicate a quite clear picture of this resistivity anomaly (Figure 4). The high resistivity areas near the surface of the pseudo-sections correspond to the part of the buried EW directional resistivity anomaly. On those lines, the resistivity anomaly produces very high resistivity values (550 - 600 ohm-m) and the resistivity distribution changes depending on the thickness and concentration of stones in the burial field. In line 2, the existence of a buried construction with 400 ohm-m resistivity about 14 - 17 m aperture is seen.

When the resistivity section of all lines (1-5) in Figure 5 are considered, the E-W directional resistivity anomalies (Figure 4) most probably arise from the wall as well as stone blocks belonged to the settlement inside Adramytteion city. The high resistivity values (450 - 600-ohm-m) and the resistivity distribution change depending on the thickness and concentration of stones in the burial field. The high resistivity area close to the surface might be a terrace build made of stone and soil.

## Conclusion

The top of the archaeological buildings had been buried in the soil strata. The kiln, pythos, and walls were surrounded by clay near the surface and soil farther down. In both cases, the surroundings comprise a relatively low resistivity material. In the light of the geophysical works, archaeologists started new dig sites in the area. Specifically, two 7x7 m trenches and three 3.5x3.5 m archeological sounding excavations were conducted. Based on the findings derived from the trenches, the following remarks can be made.

The mean archaeological buildings are at depths of about approximately 2 m from the surface. The position of the particular walls in the Adramytteion ancient city are now known, and a picture of the structure is given in Figure 5. The high resistivity region A (kiln) in Figure 5 was found at a depth of 2 m. The NS directional wall (region B) nearest the kiln is at about 1 m in depth. There was the pythos (region C) and an EW directional wall (region D) between the kiln and approximately 6 m north of the kiln.

It was determined that the ruin with the circular form found in region A is a ceramic cooking kiln. Since the trench depth was 2 m, the base of the ceramic cooking kiln could not be brought out of the earth. For this reason, the trench depth ought to be increased in this region in the upcoming years. A dense field of ceramic

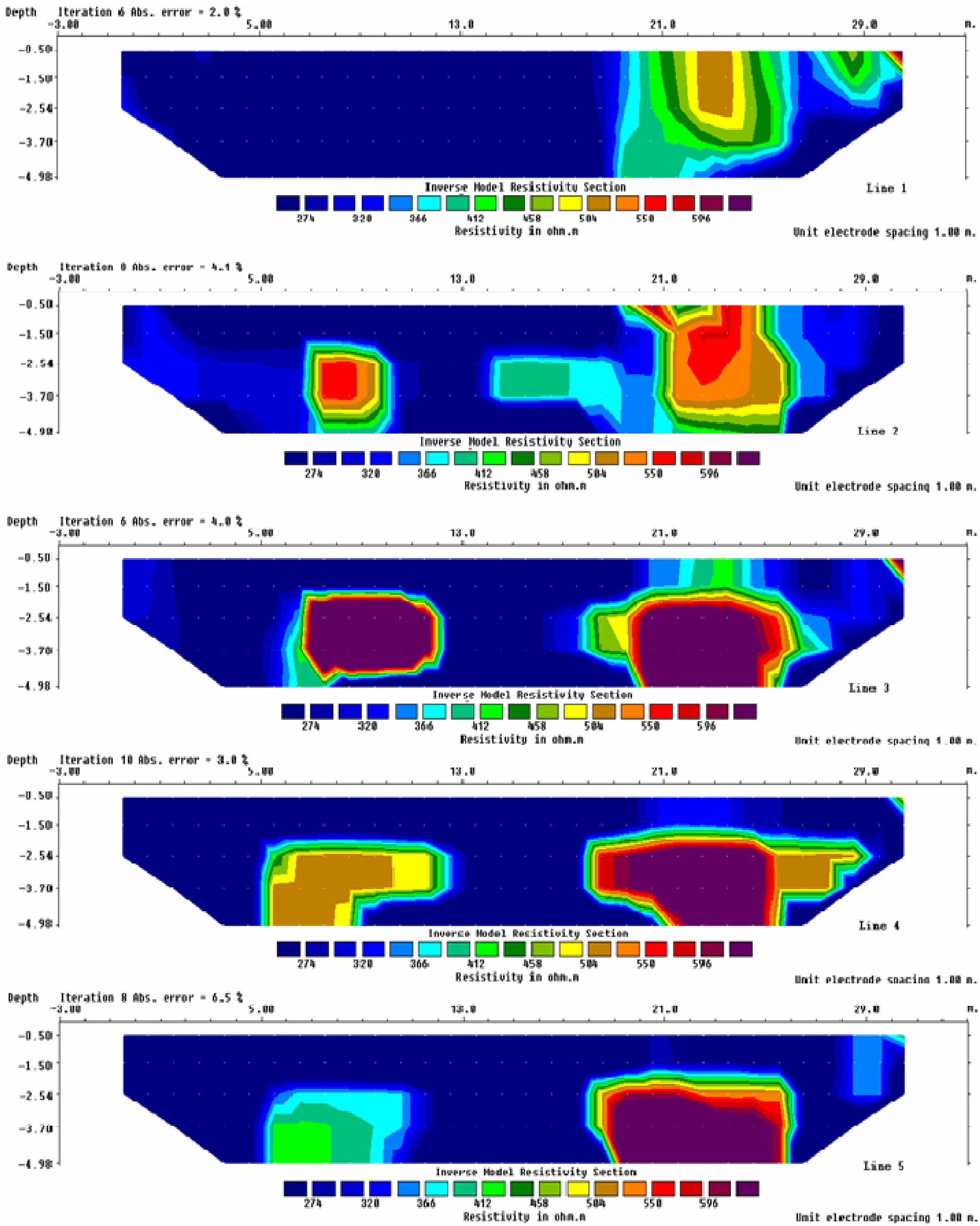


**Figure 4.** Inversion analysis sections of resistivity measurements taken with the Wenner array.

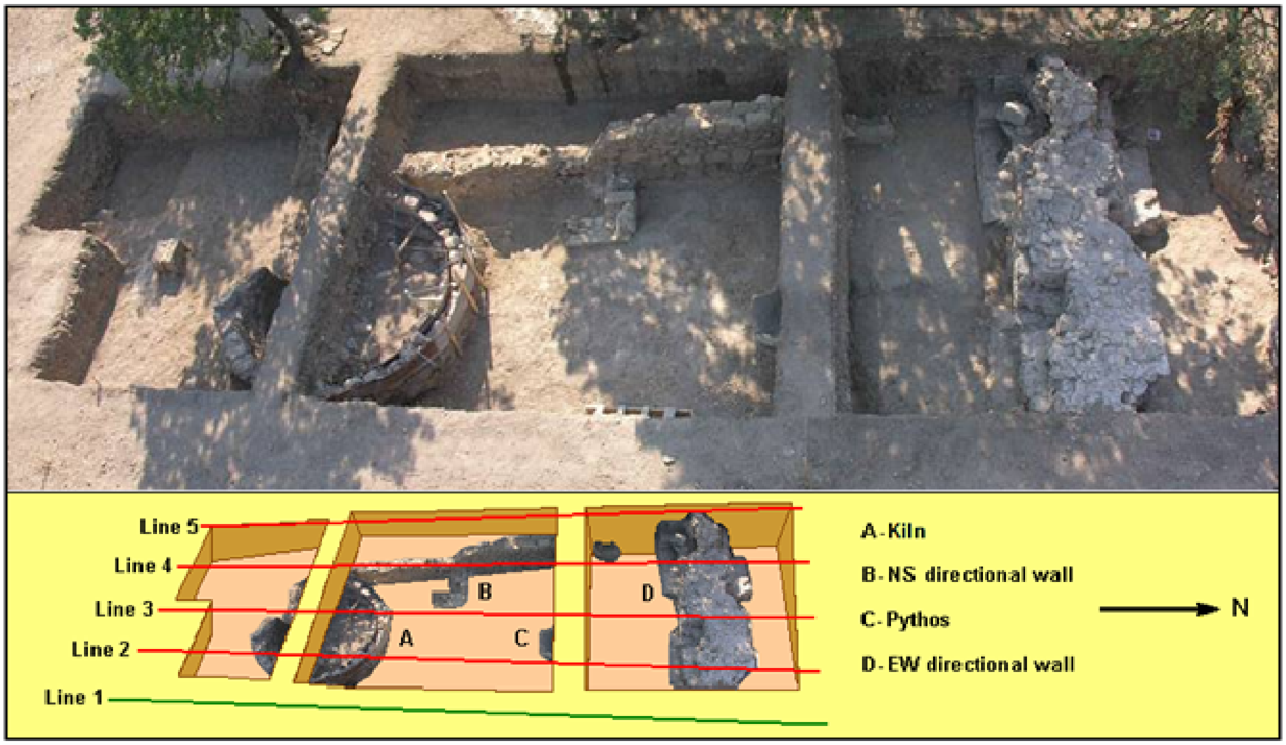


**Figure 5.** Archeological sounding excavations in the study area according to the geophysical survey results.

remnants was found in an area with a nearly 2 m diameter near the north border of the kiln. The bottom half of a pythos with a 0.60 m diameter and 0.15 m wall thickness were found in the dividing wall of the trenches at the same level as, but 4.10 m north of the kiln. A wall extending in the NW direction with a length of 7 m and a thickness of 0.65 m were also found 0.45 m west of the kiln.

In light of the data obtained from the geophysical methods, the wall remnant considered in region D with a high resistivity value was brought out through the trench. A 7 m portion of the wall in the EW direction including trench borders is clearly seen. The thickness of this stone wall was 1.85 m. This wall discovered by the trenches in region D, was evidence of the existence of the building ruin seen in the magnetic map. The total length of this wall (7 m of which was seen in the trench borders, together with its below ground portion) was 14 m. The length of wall B intersecting wall D vertically in the EW direction is 10.5 m. It is thought that the building ruin composed of those walls covers an area of 110 $m^2$. This building ruin should be brought out of the earth by creating new trenches in the future.

It was seen that the ancient ruins brought out of the earth through the archeological trenches and soundings match perfectly with the models generated based on the geophysical data. The depth of the archeological trenches held in the study area was 2 m. The base depth of the kiln and wall found in regions A and B using magnetic and resistivity methods was about 4 m. The depth of the archeological trenches should reach up to 4 m in order to completely unearth these ruins. It is considered that the all reached archeological ruins belonged to the Byzantium age.

In conclusion, new techniques such as magnetic and resistivity were applied first successfully in Adramytteion to reveal its two special items. We believe that the techniques are capable of bringing out the remaining parts of the ancient city.

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