Contribution of Geophysical Investigations in the Paleontological Research for the recovery of *Deinotherium giganteum* from Siteia, Crete.

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ABSTRACT

Fossil parts of the *Deinotherium giganteum* were located for the first time in Crete, during the excavations which were conducted by the Natural History Museum of Crete in 2002. A geophysical survey program (August 2004 and May 2005) was conducted by the Laboratory of Geophysical-Remote Sensing and Archaeo-environment in the area where the first fossils have been located by the Natural History Museum of Crete.

The goal of the geophysical survey was to detect possible locations where the larger bones of the *Deinotherium* would be buried under. This geophysical investigation had an additional motivation, as it was the first time in Greece that geophysical techniques were employed in order to locate buried fossil parts of prehistoric animals.

An area of $44m^2$ was surveyed during the first phase of the geophysical investigations employing the ground penetrating radar and the electrical resistivity mapping techniques. Additionally a $13.5x6.5m^2$ rectangular grid, which included the area investigated during the first geophysical phase, was surveyed using the electrical resistivity tomography technique.

The geophysical investigations in the locality of Gela, Aghia Fotia identified a number of geophysical anomalies that are possibly related with parts of *Deinotherium giganteum*. The 2004 excavation program confirmed some of them, indicating the complementary role the geophysical methods can have in the paleontological research.

INTRODUCTION

Geologically the Siteia bay constitutes a neotectonic graben that was formed by the action of two perpendicular fault sets. The Phyllitic-Quartzite nappe comprises the west bedrock of the surrounding area, while the carbonate Tripolitza nappe, which overlies the Phyllitic-Quartzite nappe, forms the south and east part of the area (Fig. 1).

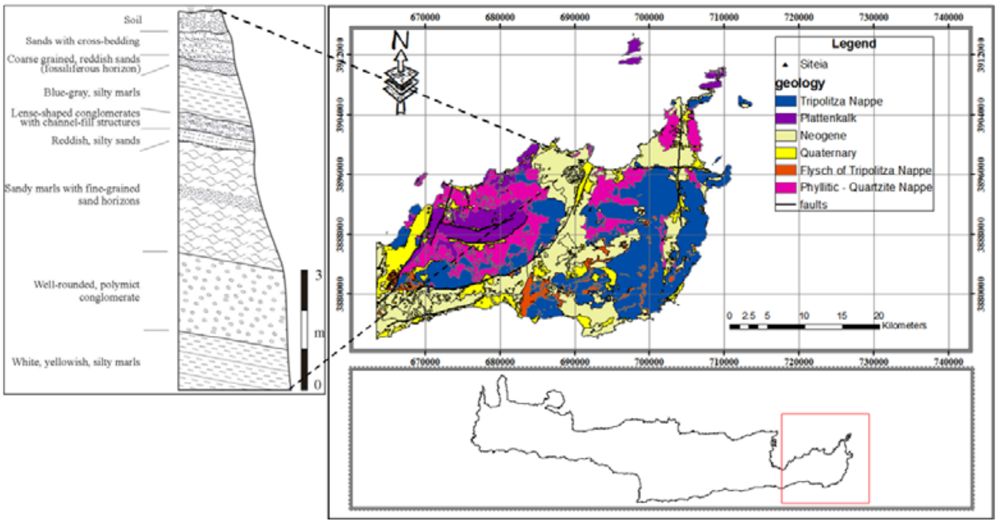

Figure 1. Geological map of east Crete (right) and the ten meters vertical geological sequence at the site of Gela, Aghia Fotia, Siteia region (left).

Several neotectonic basins were formed by a number of Middle Miocene to Pliocene (Fassoulas, 2001; Ring, *et al.*, 2001) multi-directional normal faults (Angelier et al., 1982; Fassoulas, 2001), which mainly have an east-west, north-south and northeast-southwest direction. A sequence of non-marine clastics, fluvio-lacustrine and marine sediments constitute the Neogene sedimentation (ten Veen, 1998). Furthermore a ten meter stratigraphic section of the Neogene sediments from the Gela (two kilometers east of the town of Siteia, eastern Crete) excavation area can be seen in figure 1 (Poulakakis, et al., 2005).

The excavation program that was initiated at Gela site in 2002 by the research team of the Natural History Museum of Crete, brought to light skeletal material which recognized that it belonged to one *Deinotherium giganteum* individual. The finding of *D. gigantium* from Gela exhibits an additional scientific importance, as it represents the first report of this large mammal from the area of Crete and it additionally gives a new overview in the knowledge about the distribution of the animal in Greece and Europe.

Deinotheres belong to the family of Deinotheriidae and became known to the scientific community about 150 years ago. Their main diagnostic characteristics have been described extensively by Markov et al (2001), while at present day there are two valid genera: the *Prodeinotherium* which is smaller and older and the larger and younger *Deinotherium* (Harris, 1973).

Two rib bones, an atlas, a radius, a body of vertebra, seven cheek teeth and an incisor from a *Deinotherium giganteum* were revealed from the Middle Miocene sediments in Gela (Poulakakis, et al., 2005). The fossils were found in a relatively close distance between them, so this scatter helped the paleontologists to suspect that the larger bones of the animal, such as the thigh bones, couldn't be very far from the excavated area.

For the above reason, an experimental geophysical survey was conducted in the area of interest aiming towards the shallow depth high resolution mapping of the subsurface. The geophysical methods are well known established techniques which nowadays are routinely used to map the physical properties of the near surface. For the purpose of the above study, electrical resistivity and ground penetrating radar techniques were employed.

The purpose of the electrical method is to determine the subsurface resistivity distribution by conducting measurements at the surface of the earth. To achieve this, electric current is inserted into the ground via two electrodes and the potential difference is measured in two other electrodes. The measured potential difference provides information related to the variation of the current flow through the subsurface. This is an indication of the electrical resistance of the subsurface.

Ground Penetrating Radar (G.P.R.) is similar to the seismic reflection method. A high frequency, small duration electromagnetic pulse is transmitted into the ground which is diffused in the subsurface materials and its direction depends on its properties. A part of the pulse energy is reflected on the surface that separates materials with different properties and is recorded at a receiver on the surface. The remaining pulse energy is diffused at deeper levels. The time between the transmitting and the receiving pulse depends on the velocity along the trace the pulse followed. This time can be measured and if the electromagnetic wave propagation velocity is known, then the depth of the reflector can be determined.

A geophysical campaign using the above geophysical techniques was conducted in the area of interest covering a total area of 88 m^2 in two different phases. The purpose of the geophysical investigations was to indicate specific places where buried fossils of the *D. gigantium* could be found.

The electrical resistance mapping technique was used so as to record the lateral variations of the subsurface resistivity. Electrical resistivity tomography enhanced our knowledge about the resistivity distribution in the vertical and horizontal directions. Furthermore, the GPR method was employed as a verification to the resistivity techniques.

The electrical method has been applied with great success in solving environmental, geotechnical, hydrogeological and archaeological problems, but it is the first time that it was used for paleontological purposes, so as to locate possible places of buried fossils. On the contrary, applications of the GPR method in mapping large bones of dinosaurs (Derek, et al., 2002; Meglich, 2000) and mammoths (Grandjean, et al.) have been reported in the literature.

METHODOLOGY

The geophysical investigations were carried out in two different phases during 2004 and 2005. The geophysical techniques were chosen based on the specific requirements and the nature of the target. According to the information supplied by the paleontologists, the maximum investigation depth of the geophysical methods did not exceed the two meters below the ground surface.

In the 2004 survey, the Geoscan Research RM15 electrical resistance meter, the MPX15 multiplexer and the PA5 frame were appropriately configured so as to measure the subsurface earth resistance from two different depth layers along nine parallel E-W transects with the Twin Probe array (Fig.2). The step interval along both axes was equal to 0.5m. The distance between the mobile probes (one current and one potential electrode) was set equal to 0.5 m and 1 m respectively, while the remote probes (one current and one potential electrode) were placed about 30m away from the surveyed grid.

In addition, a Sensors&Software EKKO 1000 ground penetrating radar with the 225MHz antennas was employed to identify possible subsurface reflections along nine parallel profiles in the E-W direction (Fig.2). The inter-profile spacing was 0.5 m, while the sampling interval along the lines was 10 cm.

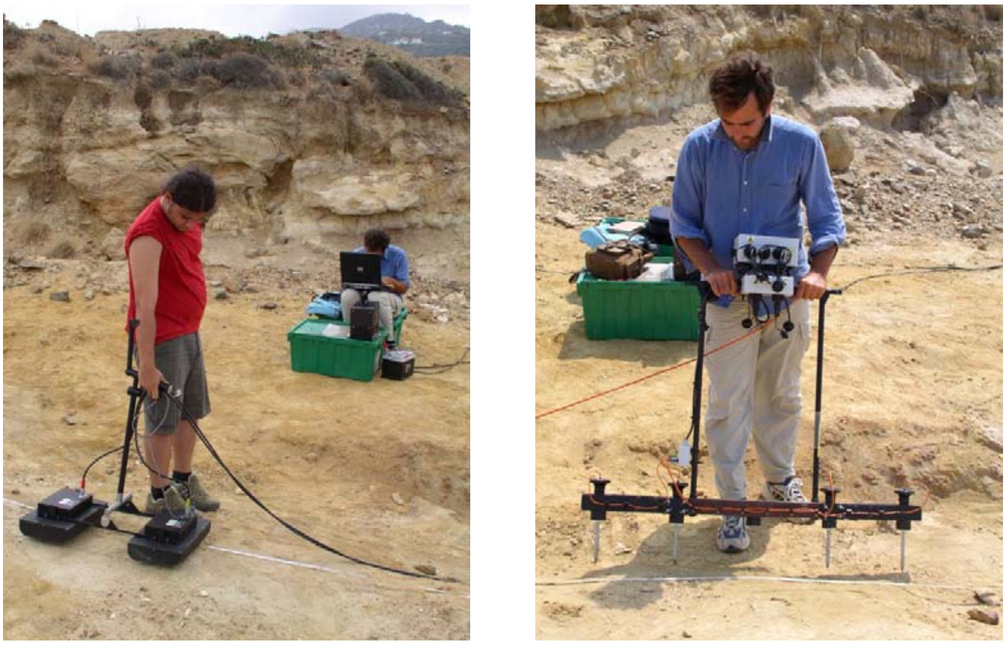

Figure 2. The EKKO1000 ground penetrating radar (left) and the Geoscan Research RM15 resistivity meter were employed in the geophysical investigations of the site of Gela.

In May 2005, the geophysical campaign was dedicated to the use of the electrical resistivity tomography method so as to study the horizontal and the vertical variation of the subsurface resistivity. The Sting R1 resistivity meter, the Swift switching unit and a multiclone cable were used to measure fourteen parallel resistivity tomographies (Y00 to Y65) in an automatic mode employing the dipole-dipole configuration (Fig. 3). Twenty eight electrodes were laid out along each line with a 0.5m inter-electrode spacing. The inter-line spacing was 0.5 m and an area of 13.5x6.5m^2 was investigated, which included the region surveyed in 2004. Figure 4 shows the layout of the parallel lines surveyed with the three different geophysical techniques.

DATA PROCESSING

The RM15 resistance measurements were statistically processed in order to enhance the signal and limit the background noise. A despiking filter was applied to the data in order to remove the extreme high and the low resistivity values. The above process was followed by a y-axis line equalization technique, which is mainly used to smooth the original values and reduce the data to an average level (mean resistance value). Kriging interpolation was used for gridding the data and finally greyscale and colour images were created.

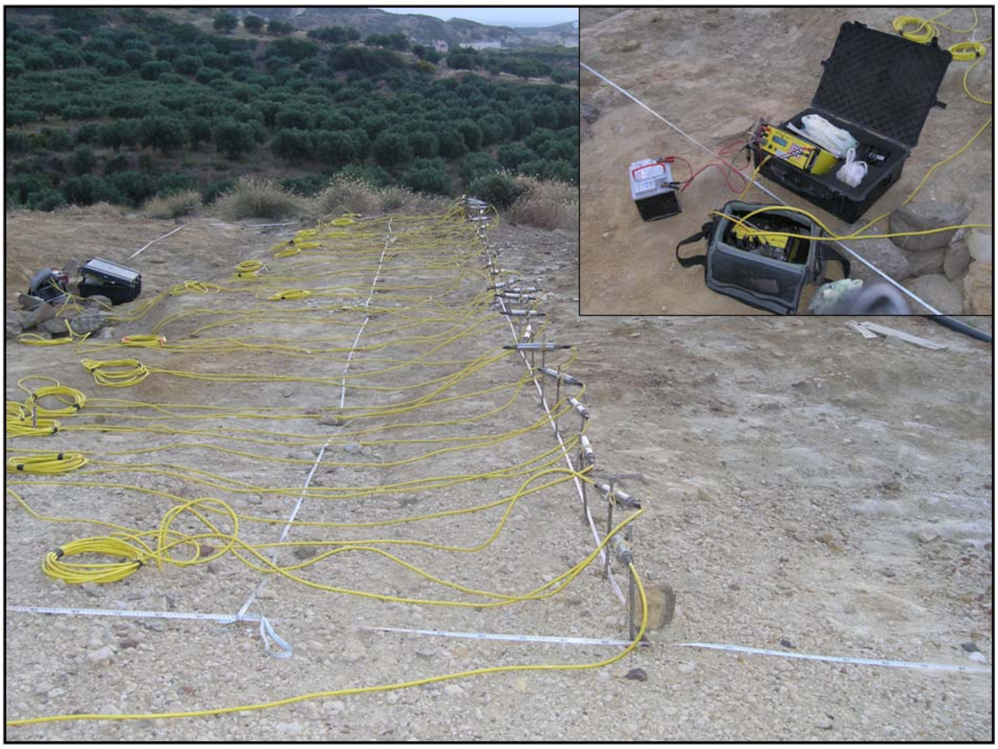

Figure 3. The Sting Advanced Resistivity Tomography package and the layout of the electrodes for measuring the electrical resistance of the soil through the dipole-dipole configuration.

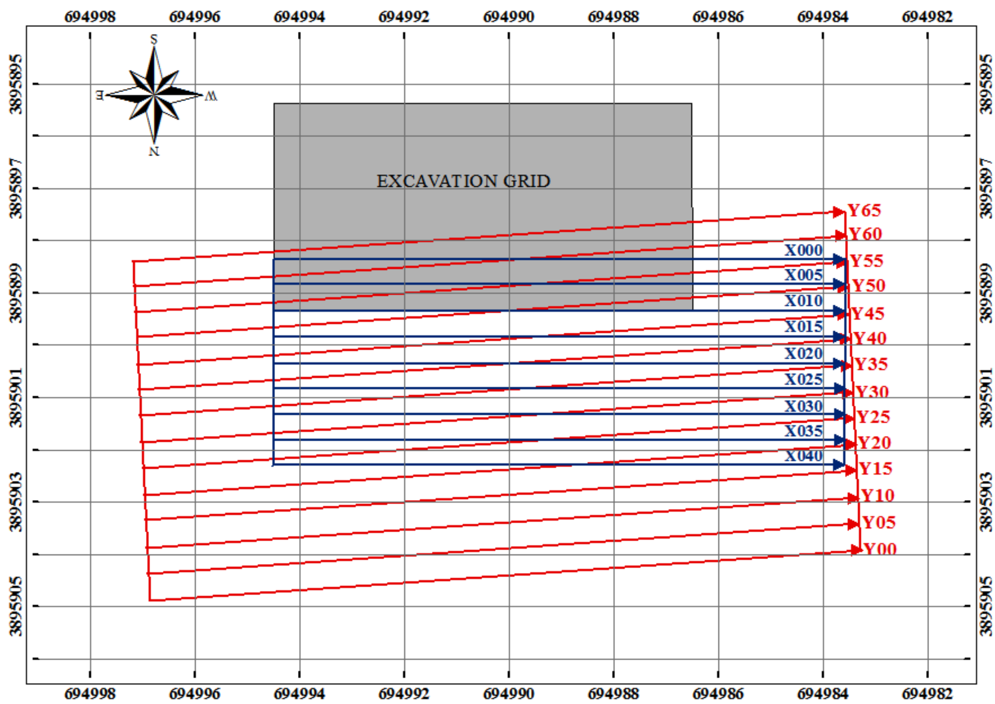

Figure 4. Layout of the geophysical transects in relation to the excavation trench. Blue lines represent the GPR and RM15 transects (2004 geophysical campaign) and the red lines indicate the electrical tomography transects (2005 geophysical campaign).

Extreme high or low resistivity values due to poor ground contact of the inserted electrodes were removed from the original electrical tomography data sets. Afterwards, each resistivity tomography set was processed separately using a two-dimensional non-linear inversion algorithm. The interpreted 2D sections were combined to produce quasi-3D depth slices of the resistivity distribution. In the end, all the electrical tomographies were combined into one single data and full 3D inversion algorithm was used to process the data.

The 2DINVS and 3DINV software packages were used to invert the surface 2D tomographies. The software performs a smoothness-constrained (Occam's) inversion and it is based on a 2.5-D (Tsourlos, 1995) and a 3D finite element (Tsourlos, 1999) forward scheme respectively. The aim is to calculate a subsurface estimate of the apparent resistivity for which the difference between the observed and the calculated data is minimized.

Since the resistivity problem is a non-linear problem, this procedure has to be iterative. In each iteration, an improved resistivity estimate is sought and eventually the procedure continues until certain criteria are met (for example more or less stable RMS).

The resistivity estimate at the k+1th iteration is given by the formula (Constable, et al, 1987, deGroot-Hedlin and Constable, 1990, Sasaki, 1989, 1992)

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{dx}_k = \mathbf{x}_k + [(\mathbf{J}_k^T \mathbf{J}_k + \lambda_k \mathbf{C}^T \mathbf{C})]^{-1} \mathbf{J}_k^T [\mathbf{y} - \mathbf{F}(\mathbf{x}_k)]$$

where:

y is the measured data vector, J_k is the Jacobian of the x_k resistivity distribution, $F(x_k)$ is the forward modelling operator, C is the smoothness matrix and m_k is the Lagrangian multiplier.

The GPR sections were also treated in a systematic way. The first peak for each different line was determined based on the intensity percentage of the first reflected wave. Then the line equalization based on the first peak tried to bring the first reflections of each line into a common starting time. The application of AGC, Dewow and DCshift filters enhanced the reflected signal while a trace-to-trace averaging filter was applied so as to remove the background noise and smooth out the data. Finally vertical cross sections and horizontal depth slices were created using the EKKO MAPPER and EKKO 3D softwares.

RESULTS

Twin Probe geoelectrical mapping

The resulting maps of the Twin Probe configuration measurements are shown in figure 5, where a, indicates the mobile electrode spacing (0.5 and 1.0m respectively). Nine east-west transects (X00 to X040) were measured (Fig. 4) and an area of $44m^2$ was covered.

The distribution of the subsurface apparent resistivity from the two depth slices exhibits a number of areas with higher values in relation to the background resistivity. These areas appear mainly at the center, west and northwest sections of the 2004 geophysical grid. These features may be indications of the existence of the large parts of *Deinotherium* bones, as they seem to appear quite superficial.

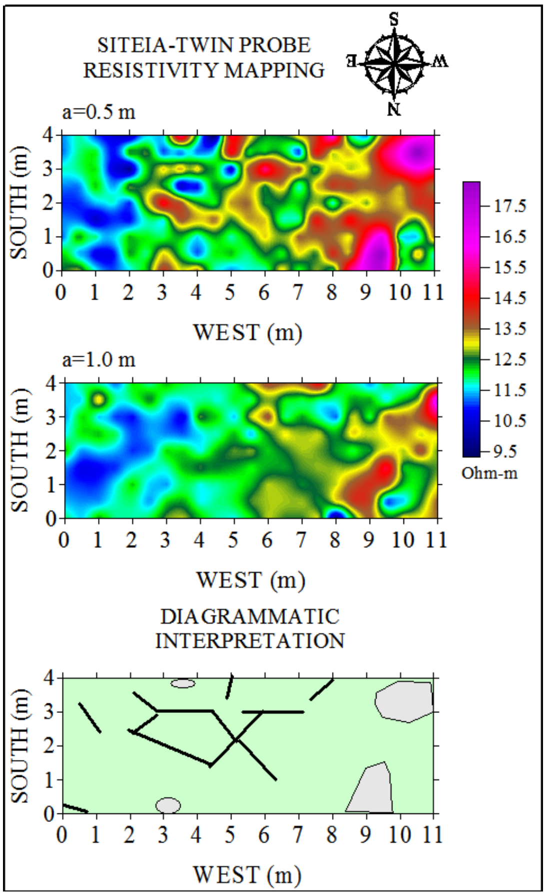

Figure 5. Soil resistivity maps for two electrode spacings (a=0.5 & 1.0m) and the corresponding interpretation of the soil resistivity anomalies.

2D Resistivity Tomographies

The resistivity tomographies were processed using the 2DINVS software, which tries to reconstruct the true resistivity distribution of the subsurface from the original apparent resistivity data. It can deal with a wide spectrum of electrode arrays while the parameters of the problem can either be decided automatically or by the user, including the adjustment of the model smoothness.

The maximum number of iterations was set equal to twelve and all the inversions completed them. A value of 0.01 was chosen for the lagrangian multiplier, which besides the smoothness matrix it controls the smoothness of the inverted model and stabilizes the inversion procedure,. The root mean square error of the inverted models was quite low and ranged from 1.8% to 3.8%. This indicated that the collected data were of high quality with very low levels of noise. At the last processing stage the inverted depth sections were combined *a-posteriori* and horizontal slices of increasing depth were created (Fig. 6). **Deleted:** the

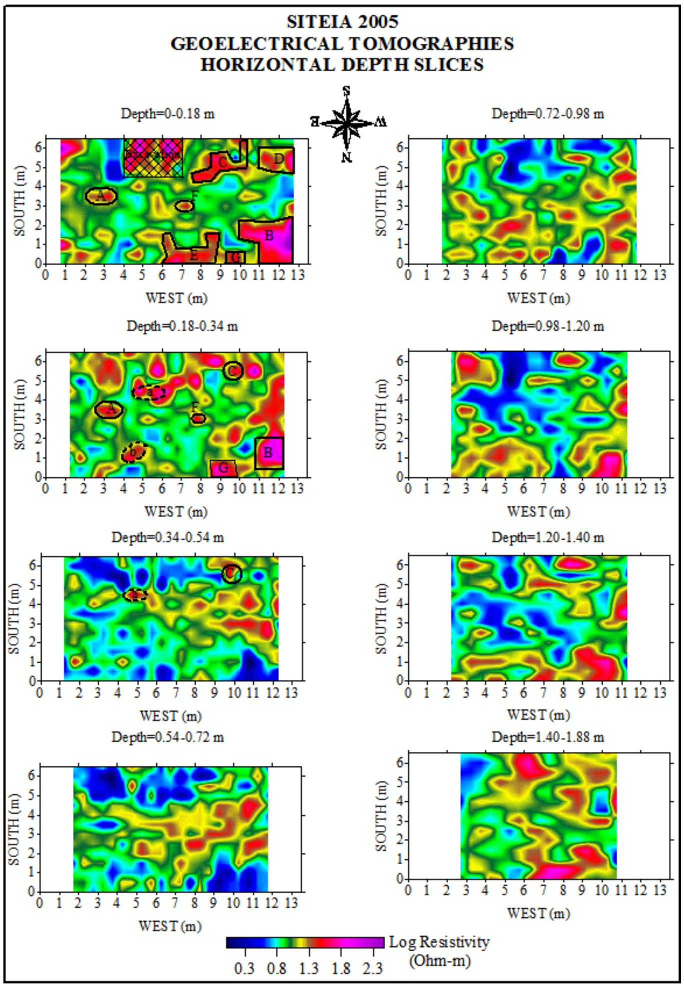

Figure 6. Horizontal depth slices of soil resistivity for depths up to 1.88m. Data were obtained through synthesis of the parallel electrical tomography transects.

The quasi-3D depth slices from 0 to 0.54 meters below the ground surface indicated a number of high resistance locations (B, C, D, E, F, G), mainly at the west side of the area. These areas may be correlated with the big buried bones of the *Deinotherium*. Furthermore one more promising resistive anomaly (feature A) is appeared at the east side of the geophysical grid, at the first and the second depth slice (depth: 0-0.34 m). It has to be noted that the high resistive values in the hatched rectangular at the first depth slice were caused by a local elevation difference due to the previous excavations.

The individual resistivity tomographies were combined to a single data set and a 3D inversion algorithm was used to reconstruct the 3D subsurface resistivity model of the site. The algorithm converged to an acceptable solution after eight iterations with RMS=4.707%. It can be seen that the first three depth slices of the 3D resistivity model exhibits a good correlation with the corresponding depth slices from the quasi-3D model, while the resistivity anomalies at the remaining depth slices are due to the surface geology of the area (Fig. 7).

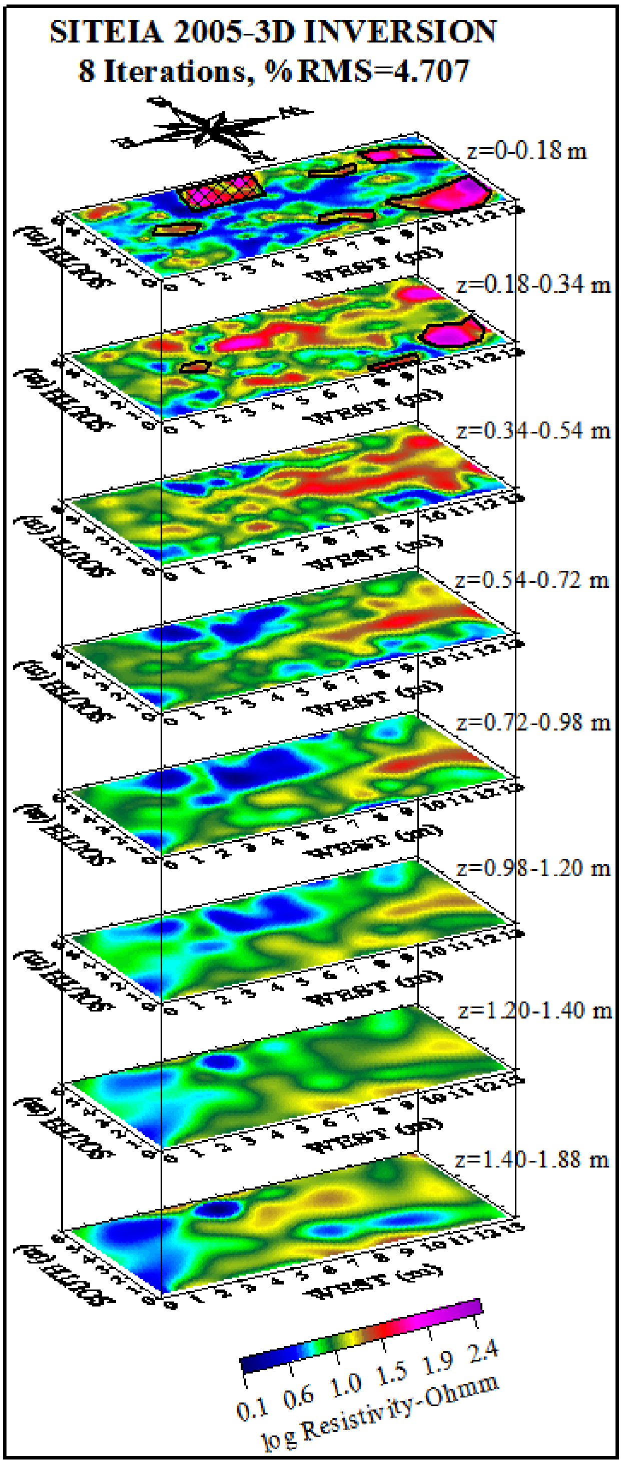

Figure 7. Depth slices resulting from the 3D inversion of the electrical tomography measurements.

Ground Penetrating Radar

The GPR method was used to survey the same lines investigated with the Twin Probe resistance method. Vertical depth sections and horizontal depth slices of the area were created. The interpreted maps indicated some promising reflections which may suggest the presence of buried bone fossils (Fig 8).

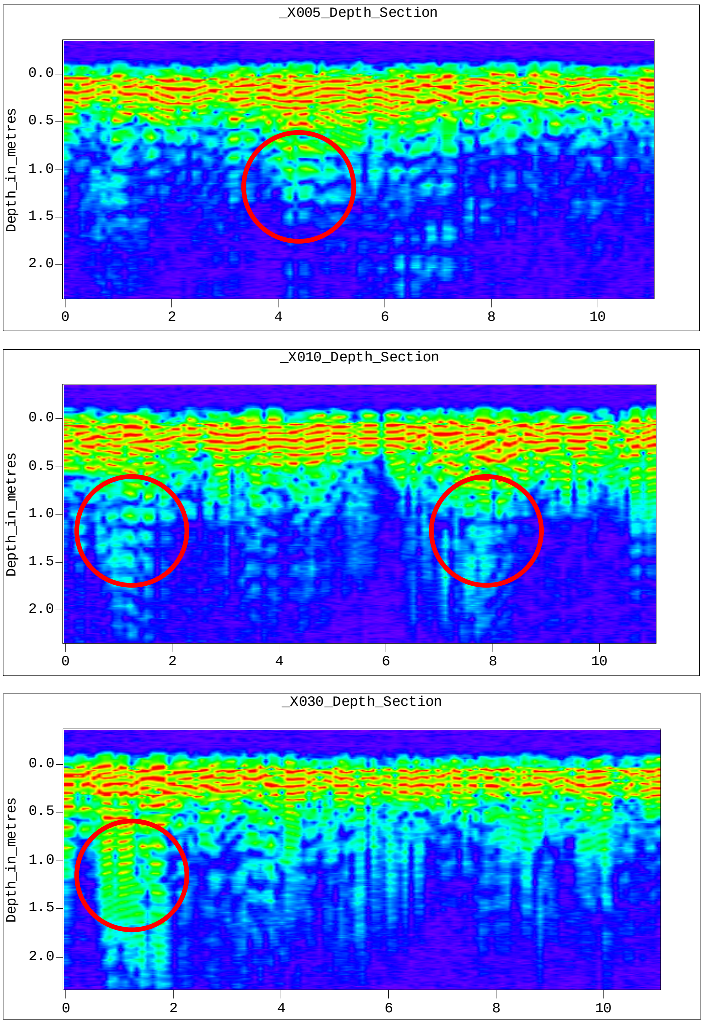

Figure 8. GPR radargrams for transects X005, X010 & X030. The circles indicate the most prominent reflections, possibly related to buried features.

CONCLUSIONS

A Leica GS20 GPS unit was used to georeference the 2004 and 2005 geophysical grids in the Greek Georeference System (EGSA ’87). The corresponding geophysical maps were imported into a GIS platform and their overlay contributed in the better correlation and interpretation of the geophysical anomalies.

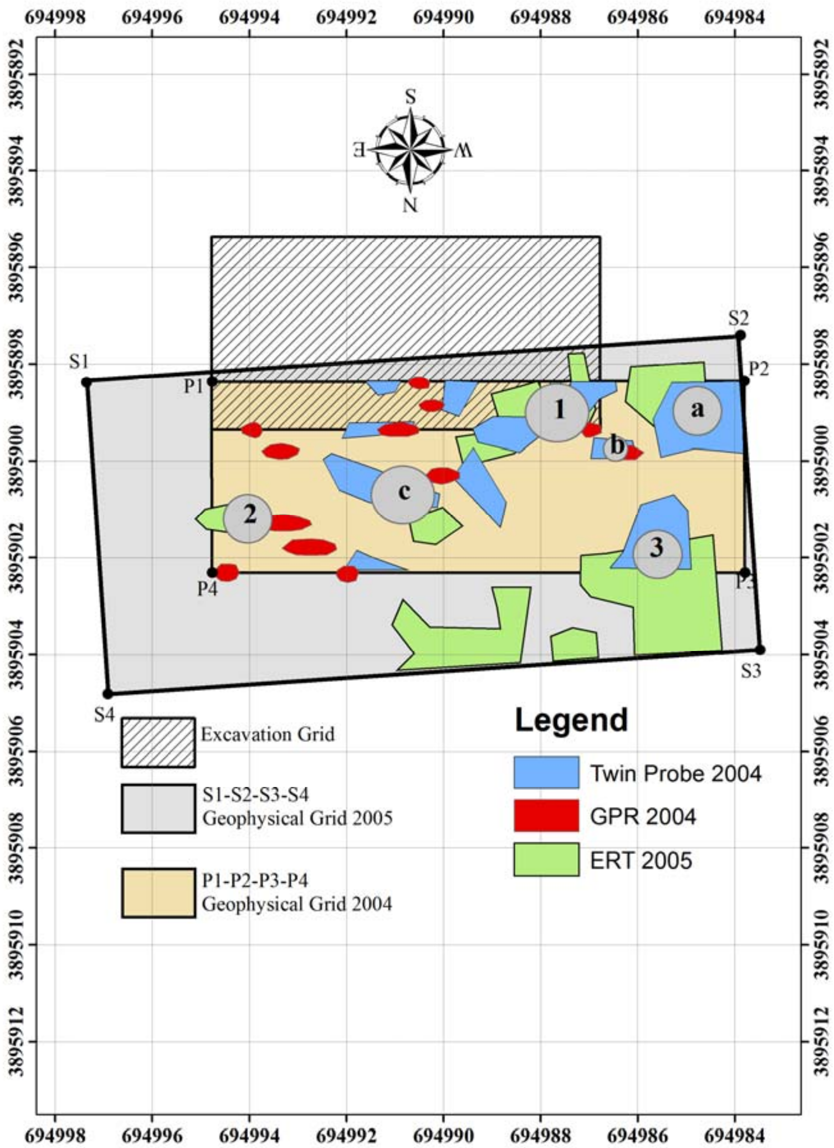

Figure 9. Diagrammatic interpretation of the corresponding geophysical anomalies for each one of the geophysical techniques applied in the area of interest.

Figure 9 shows the layout of the excavation and the geophysical grids with the corresponding candidate targets. It is evident that the features suggested by the electrical resistance mapping technique and the electrical tomography method show a quite good correlation between them. These anomalies are scattered mainly at the center and the west side of the area. GPR measurements indicated some additional candidate targets at the east side of the 2004 geophysical grid. The letters and numbers in the grey circles indicate locations having a higher probability to hinter buried bones.

At the end of the summer of 2004, the Natural History Museum of Crete conducted an excavation based on paleontological as well as on geophysical evidence. A relatively small area, in relation to the one that was surveyed with the geophysical methods, was excavated and a number of important skeletal parts were collected. The recorded radar and twin probe resistance anomalies recorded at the square with coordinates E=694994-694992m, N=3895900-3895898m, coincided with teeth and rib bones of the *Deinotherium*.

Generally, the geophysical investigations in the locality of Gela identified a number of geophysical anomalies that are possibly related with parts of *D. giganteum*. The 2004 excavation program confirmed some of them, indicating the complementary role the geophysical methods can have in paleontological research.

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