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FIRST GEOPHYSICAL RESULTS IN THE ARCHEOLOGICAL SITES OF ΘΟΥΡΙΑ (PELOPONNESE, HELLAS) AND SIBARI-THURII (SOUTHERN ITALY)

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Abstract

High resolution techniques for data acquisition and processing procedures are increasingly applied in near-surface geophysics for archaeology. In this paper we present the preliminary results of two geophysical measurements campaigns aimed to the investigation of buried remains in the archaeological sites of Θουρία (Peloponnese, Hellas) and Sibari (Southern Italy). In the first field survey the geophysical approach involved the integrated application of the geoelectrical and magnetic methods and an innovative tomographic analysis for the inversion of both resistivity and magnetic data. In the second case, we carried out high resolution magnetic measurements, interpreted by means of the use of an appropriate filtering procedure. The applied data inversion allows us to provide reliable space patterns of the most probable specific target boundaries, improving the information quality of geophysical methods. The results obtained at this early stage of data processing confirm some archaeological hypothesis about the investigated areas and confirm that the use of integrated geophysical methods allows the archaeologists to reduce the time and the costs of their surveys.

Key words: *Archaeology, Resistivity, Magnetics, Eforia Kalamata, Saia.*

Περίληψη

Οι τεχνικές υψηλής ανάλυσης απόκτησης και επεξεργασίας επιφανειακών γεωφυσικών δεδομένων εφαρμόζονται ολοένα και περισσότερο στην αρχαιολογία. Στην εργασία αυτή, παρουσιάζονται προκαταρκτικά αποτελέσματα από γεωφυσικές αναλύσεις που στοχεύουν στη διερεύνηση υπόγειων αρχαιολογικών ευρημάτων σε δύο επιλεγμένες περιοχές: στη Θουρία (Πελοπόννησος, Ελλάδα) και στην περιοχή Sibari (Νότια Ιταλία). Στην πρώτη περίπτωση η γεωφυσική προσέγγιση περιλαμβάνει τη συνδυαστική εφαρμογή γεωηλεκτρικών και μαγνητικών μεθόδων και μίας καινοτόμου τομογραφικής ανάλυσης για την αντιστροφή των δεδομένων της ειδικής αντίστασης και των μαγνητικών στοιχείων. Στη δεύτερη περίπτωση, πραγματοποιήθηκαν υψηλής ανάλυσης μαγνητικές μετρήσεις, οι οποίες ερμηνεύτηκαν με εφαρμογή των

κατάλληλων φίλτρων. Η εφαρμοσμένη αντιστροφή των δεδομένων δίνει τη δυνατότητα παραγωγής αξιόπιστων χωρικών μοντέλων και βελτιώνει την ποιότητα των πληροφοριών των γεωφυσικών μεθόδων. Τα αποτελέσματα που προκύπτουν σε αυτό το αρχικό στάδιο της επεξεργασίας επιβεβαιώνουν αρχαιολογικές υποθέσεις σχετικά με τις περιοχές έρευνας, ενώ παράλληλα με τη χρήση των γεωφυσικών μεθόδων επιτυγχάνεται μείωση του χρόνου και των δαπανών κατά την αρχαιολογική έρευνα.
Λέξεις κλειδιά: *Αρχαιολογία, Ειδική αντίσταση, Μαγνητικά.*

1. Introduction

The application of different geophysical techniques in archaeological exploration has acquired an increasing interest during the last few years, thanks to their capability to best direct the explorative excavations and to explore wide areas in short time without damaging the buried features (Bevan and Roosevelt 2003, Patella and Hesse, 1999). In particular, the joint application of electric and magnetic methods for the localization of buried structures has become a standard approach to solve some archaeological problems, due to both their non destructive character and rapidity of execution (Batmunkh *et al.* 2004, Chavez *et al.* 2001, Chianese *et al.* 2004, Gaffney *et al.* 2004). In fact, both the electrical and magnetic techniques are nowadays widely employed for the archaeological aims, because the electric method is applied to estimate the shape and the depth of buried structures in the more promising zones for archaeological excavations (Cammarano *et al.* 2000, Di Fiore *et al.* 2002, Rizzo *et al.* 2005), while the magnetic method is applied to detect the presence of buried objects characterised by a magnetic susceptibility contrast in respect of the surrounding ground or with a remnant magnetization, such as for example remains of furnaces (Aitken 1974).

a)

b)

Figure 1 – Location of the two archaeological sites investigated by means of the geophysical approach: a) Θουρία site; b) Sibari site

In this paper, we explain the preliminary results of geoelectric and magnetic soundings carried out in two archaeological areas of the Mediterranean region: a wide area of the ancient Θουρία, located at about 12 km N to Kalamata (Peloponnese, Hellas) (Fig. 1a) and the archaeological park of Sibari (Southern Italy) (Fig. 1b). In the first archaeological area, since 2005, in the framework of a collaboration (Synegrasia) between the XXXVII Eforia of Prehistoric and Classical Antiquities of Kalamata and the Italian Archaeological School of Athens, we carried out geoelectrical and magnetic measurements. In the second archaeological area, during September 2006 we carried out some magnetic surveys, in the framework of collaboration between Sibari's Archaeological Commission and the Italian Archaeological School of Athens. These surveys were performed with the aim to identify the presence and define the shape of buried structures.

An innovative approach to the interpretation of the geophysical data is presented: in fact, both magnetic and electrical observed data were processed in a tomographic sense. The geoelectrical data have been inverted by means of the standard RES2DINV inversion software (Loke 2001), while for the interpretation of the magnetic data we applied, on Θουρία's data sets, a new tomographic inversion approach able to give information about the probability distribution of the magnetic dipoles in the investigated surface, as sources of the surface magnetic anomalies (Chianese and Lapenna 2006). In this way, it was possible to obtain a direct comparison between the results of the inversion of the two geophysical techniques at the same depths.

2. Outline of the archaeological problems

2.1. Θουρία (Peloponnese, Hellas)

The archaeological site of Θουρία rises on a hill near the city of Kalamata (Fig. 1a) and corresponds to a settlement testified from the ancient historical sources with space of life covering the Mycenaean age until the Roman conquest (II century B. C.), when the city was moved downhill. The most important archaeological remnants are: a Mycenaean Necropolis and the town-walls built during the Hellenistic age (IV-III century B.C.). Other structures are present in the area but in a fitfully way covering a wide area of the hill. The geophysical prospecting has a strategic value because at this stage of collaboration between EFORIA AND SAIA, excavations are not allowed and the research activity carried out is limited to the collection of archaeological data like architectural, archaeological and geophysical surveys, exclusively on the free surface. Thanks to the geophysical prospecting, it is now possible to give a characterization of the ancient traces, so that architects and archaeologists are able to better plan the future activities of excavations.

2.2. Sibari - Thurii (Southern Italy)

The archaeological site of Sibari, also known as Thurii, is located on the Ionic coast (Southern Italy) (Fig. 1b). Thurii is a city founded in classic age in the place where the ancient Sibari was destroyed by the Crotoniati, the inhabitants of the near city of Crotone, during the 510 BC Thurii was a Pan-Hellenic colony leaded by Athens; it was founded in the 444 BC and planned by Ippodamo da Mileto (architect and city planner, VI century BC) in agreement to a regular square system of $300x400m$ approximately, subdivided also in more small isolates. The main part of the city is nowadays covered by the alluvial deposits coming from the activities of Crati river. In some points the alluvial deposits reach more than 5 m height. Since 1993, a research program leaded by Prof. Greco in collaboration with the Direction of Sibari Museum, has started with the aim to identify the city plan through the archaeological excavation activities. The geology of the Sibari plain marked out to a continue subsidence phenomena, a very strong alluvial deposition by the Crati river and a marine ingression into the water table that lies all around the plain, not more 1.5 m –2 m depth. This geological situation weighs upon the budget strongly because increases the costs that archaeological excavations request mainly by the presence of the water table near the ground surface. The geophysical researches, integrated in the frame of the archaeological program, seem to be able to give two types of scientific result: the first concerning the possibility to outline the ancient plan roads that now are covered both by about 5 m of alluvial sediments and a wide water-table; the second relating to the possibility to mark out also the Roman town-walls that have cut the ancient city with the aim to limit the extension of the city during the Roman period. The prospecting, as in the case of Θουρία, was integrated with the topographical activities: merging the data coming from the two activities we hope to obtain the plans of Thurii during both the Hellenistic and Roman ages.

3. Data acquisition

3.1. Geoelectrics

The geoelectrical technique was carried out only in the archaeological area of Θουρία, on more than 10 areas where the presence of buried structures is strongly suspected by the archaeologists and the architects. In this paper we show the most interesting results obtained in three investigated areas (Fig. 2). The measuring grids were built in the three Geophysical Areas (named **GA1, GA2,**

GA3) so that the measurement profiles have the direction of NS and the distance between the measuring electrodes and the measuring profiles was set in the range of 0.5 m–1 m and 1 m–2 m, respectively. To investigate the GA, we acquired the geoelectrical data in dipole-dipole (**DD**) configuration by the use of a SYSCAL R2 resistivitymeter of the Iris Instruments. It has been set so that for each profile the acceptable standard deviation has to be not greater then 3 % with stacking cycle from 3 up to 10.

3.1.1. Data processing

The software RES2DINV was used to obtain the geoelectrical inversion. It's a commercial software based on classical forward modelling approach to solve the geophysical inversion problem, defining a possible electrical model of the subsoil that explains the measured data sets. The subsoil is split in elementary cells in which the resistivity values and dimensions are varied using the finite-differences method to the better approximation between the answer of the model and of the measured resistivity values (Dey and Morrison 1979, Hoversten *et al.* 1982).

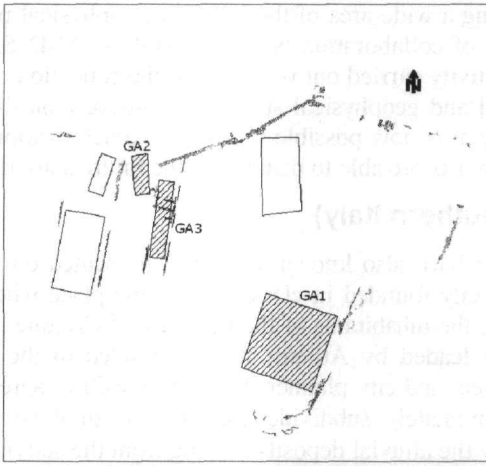

Figure 2 – Location of the three investigated areas (GA1, GA2, GA3)

All the buried structures are characterized by 3D anisotropy in the physical parameters, so that they should be investigated by surveys with a 3D configuration. Nowadays, the 3D surveys have not reached the same degree of reliability of the 2Ds, which can be considered as the standard approach in geophysical community. Anyway, sometimes exists the possibility to represent and/or treat 2D data sets as 3D (Loke 2001). For the surveys carried out in Θουρία, due to the high grid-density of the measurements, we choose to represent the results of the 2D profiles as pseudo-3D, plotting on the same slice the data coming from all the profiles and placed to the same depth. The slices depths we calculated are in agreement with the Edwards correction (Edwards 1977), in such a way to obtain the best information from the data sets. This way of plotting both the collected data sets and inversion results is easier to read and best emphasizes the shape of the structures with a strong horizontal development as those present in the archaeological areas.

3.2. Magnetics

The magnetic surveys were carried out both in Θουρία and Sibari archaeological sites. We employed an optical pumping magnetometer Geometrics G-858 in gradiometric configuration (Bavusi *et al.* 2004). In the case of Θουρία the geometries were exactly the same of geoelectrics even if the direction of data acquisition was slightly different. The magnetic measurements were acquired with a mark spacing of 0.5 m and with a profile distance of 1m. The sample rate was of 10 measurements per second (10Hz).

In Particular, in Sibari the magnetic survey covers an area of about 17.500 m^2, by jointing 7 square areas of $50x50m$. In each square the measurements were carried out using both mark spacing and profile distance as 1 m.

3.2.1. Data processing

A first preliminary filtering procedure has been performed to remove the spikes observed in the magnetic map, due to the presence in the subsurface of little metallic remains of various nature, such as containers and cables. To this aim, we used an automatic procedure, based on statistical criteria, which allows us to detect and remove the spikes from the magnetic maps (Chianese *et al.* 2004). This procedure was applied both in Θουρία and Sibari, but in Sibari we carried out a trend surface analysis to remove coherent error offsets from data collected in parallel line mode over wide areas and to render the measurements coming from the different squares compatible between themselves (Swan and Sandilands 1995). These types of error are known as *heading errors*, i.e. errors that are dependent on the direction of travel. When a survey is performed as a series of bi-directional parallel lines, these errors can be very noticeable and significant. Heading errors can be created by any number of sources, but the primary sources are heading error of the sensing system itself (often in the 1nT-2nT range), offsets due to carrying some ferromagnetic object on the operator, or from the logging console or some other sensor device, or micro-oscillation of sensing system by the operators.

3.2.2. Tomographic Inversion

We applied a new statistical procedure for the inversion of magnetic data, based on an algorithm developed firstly by Patella for the interpretation of self potential data (Patella 1997a, 1997b). In particular, for the inversion of the magnetic data (Chianese and Lapenna 2006, Mauriello and Patella 2005), this approach allows to obtain horizontal sections, put at different depths, related to the probability distribution of finding for every point of the investigated subsoil the centres of magnetic dipoles as sources of the experimental gradiometric anomalies detected on the surface.

For the sake of brevity, we do not report the detailed mathematical aspects of this theory, which have been explained in a previous paper (Chianese and Lapenna 2006).

We want only underline the fact that, thanks to this procedure, we obtain three normalised functions, namely $\beta_x(x_d, y_d, z_d)$, $\beta_y(x_d, y_d, z_d)$, and $\beta_z(x_d, y_d, z_d)$, which can be interpreted as the probability to locate in a point of the investigated subsoil, $D(x_d, y_d, z_d)$, the centre of an elementary magnetic dipole, oriented along one of the three main directions, as source of the magnetic gradient anomalies detected on the ground surface; such a probability function can be defined as Dipolar Occurrence Probability (D.O.P.).

4. First Results

4.1. Geoelectrics and Magnetics in Θουρία

4.1.1. Geoelectrical results

Area GA1

In this area inverted geoelectrical results show a high resistivity signal in a depth range comprised within 1.5 m, with values coming from 100 Ωm to 3.000 Ωm. Although the suspected archaeological structures are not clearly delineated, it is possible to define some areas, between 0.5 m and 0.8 m in depth, in both South and North direction of the slices (Fig. 3), that leave to suppose the possible presence of buried elements with rectangular shape in the first case and linear in the second. The shape of resistivity bodies allows to suppose the existence of two different levels for them, one more superficial located at about 0.5 m with a prevailing linear development and a second deeper and wider located in the South part, at 1 m.

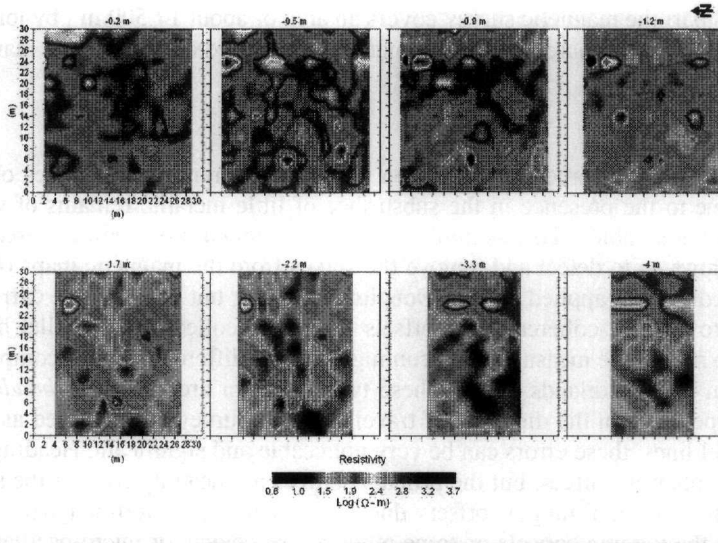

Figure 3 – Inverted Electrical resistivity slices relating to the GA1 area

Area GA2

The GA2 (Fig. 4) is more detailed then GA1, mainly because in this area the archaeologists suppose that a part of the ancient wall surrounding the ancient Θουρια have a turning point. From slices we can observe that many traces exist both in the North and South part of the GA2 area. All the archaeological information is generally contained in 1.35 m, even if between the 0.45 m and the 0.85m in depth in the northern part of the area a marked and well-defined not natural "basin" is clearly visible. Also in the South part of the explored are at the same range of depth is possible to observe other very well defined features, that are sometimes present in the magnetic maps. In conclusion, in this area the sources of the electrical anomalies are extremely superficial, as expected, and strongly defined.

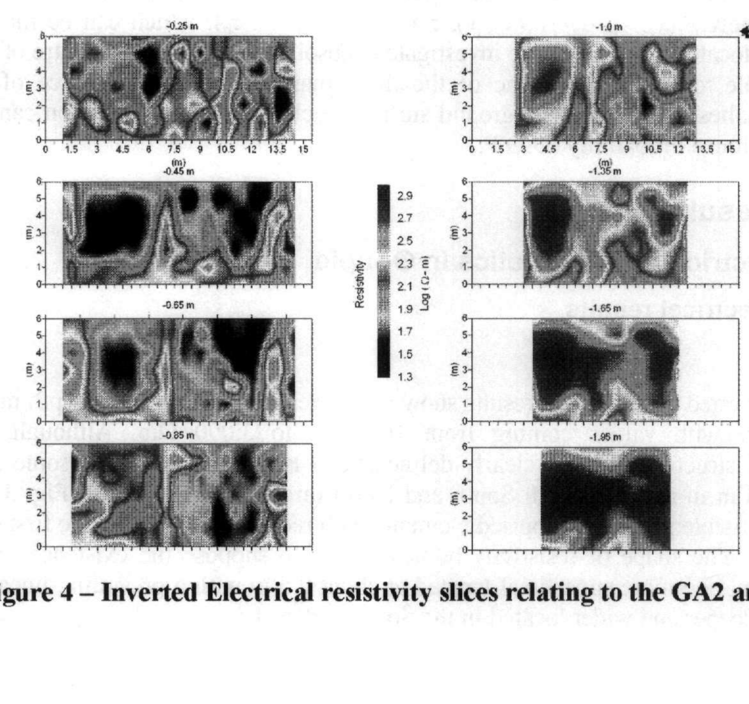

Figure 4 – Inverted Electrical resistivity slices relating to the GA2 area

Area GA3

This area is on a terrace placed near the GA2, but slightly more elevated. In the slices (Fig. 5) are present remarkable features in the EW direction at 4 m, 12 m, 14 m, 16 m, 24 m, approximately. Among those, two are particularly interesting: at 12 m and 15 m, located at about 1 m in depth. As for GA2, also in the GA3 slices are present elements looking like "basins", as the substrate it acted as basin to the accumulation of melted sediments (more conductive) bordered by lateral elements built with the substrate, which seems to be not continuous with the depth existing a clean interruption between 17 m and 19 m.

4.1.2. Magnetic results

The magnetic measurements have been carried out by means of a Magnetometer G-858 in gradiometric configuration, with the two magnetic probes set at a distance of about 1m between. The experimental data were collected on a regular grid obtained by using a mark spacing of 0.5 m and with a profile distance of 1 m. The sample rate was set at 10 measurements per second (10 Hz). Among the three possible directions of the probability inversions, we chose the z-direction, because in this direction we observed the most intense values of dipolar occurrence probability. The probability maps related to the z-direction inversion of the magnetic data have been arranged in such a way to be at the same depths of the geoelectrical sections, to obtain a direct comparison between geoelectrical and magnetic data.

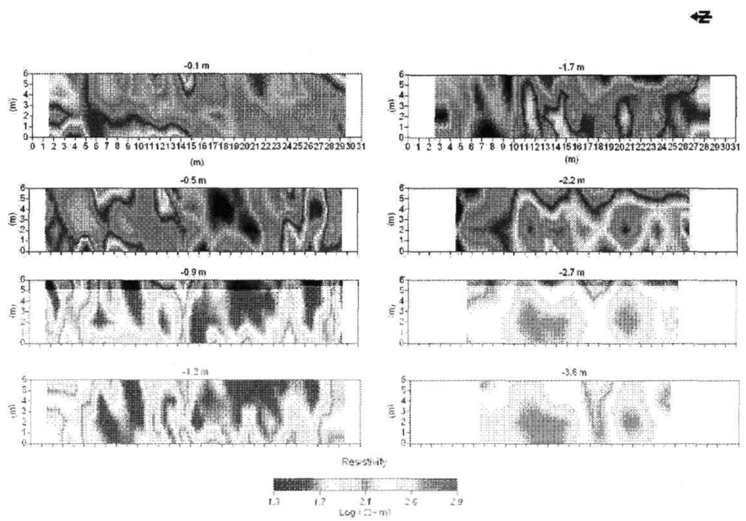

Figure 5 – Inverted Electrical resistivity slices relating to the GA3 area

Area GA1

The surface gradiometric map shows an anomaly in the east upper side of the investigated site with a gradiometric intensity of about 25 nT/m (Fig. 6). The tomographic inversion shows that the magnetic sources are located at a depth between 2.2 m and 3.3 m, with a probability of about 40 %. Making a comparison with the electric results, it seems that it is possible to observe the same trend detected in the north side of the electrical surface map (Fig. 3).

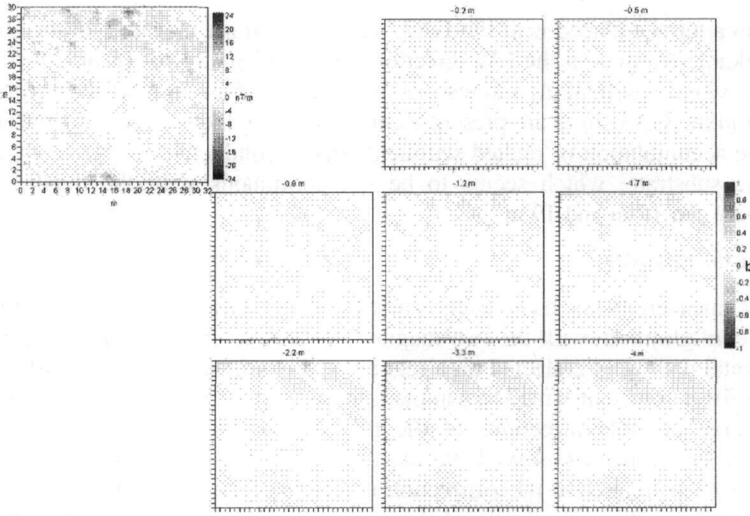

Figure 6 – Gradiometric map and tomographic inversions relating to the GA1 area carried out at the same depths of the electrical slices

Area GA2

The surface gradiometric map of the area 2 shows two parallel anomalies in the y direction at a distance of 10 m from the origin of the investigated site, with a no very marked gradiometric intensity of about 10 nT/m (Fig. 7). A more intense anomaly can be instead observed in the west part of the area, with values of about 15 nT/m in modulus. These occurrences seem to be in agreement with the results coming from the most superficial electrical data (Fig. 4). For the magnetic inversion, the most probable positions for the magnetic sources related to the two parallel anomalies are observed at depths between 0.45 m and 0.85 m, with a probability of about 20 %, while for the west anomaly the most probable depth of the sources is at 1.35 m, with a probability value of about 40 %.

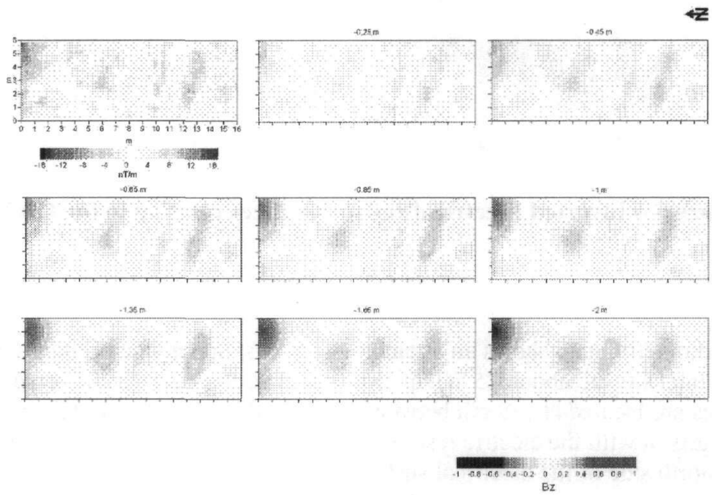

Figure 7 - Gradiometric map and tomographic inversions relating to the GA2 area carried out at the same depths of the electrical slices

Area GA3

In area 3 we did not observe clear anomalous patterns (Fig. 8), but only few anomalies with low magnetic intensity in correspondence of the most superficial electrical anomalies (Fig. 5). For the magnetic inversion, the most interesting results are observed for an anomaly located in the north part of the investigated area, with probability values of finding the magnetic sources of about 40 % at depths between 2.7 m and 3.8 m.

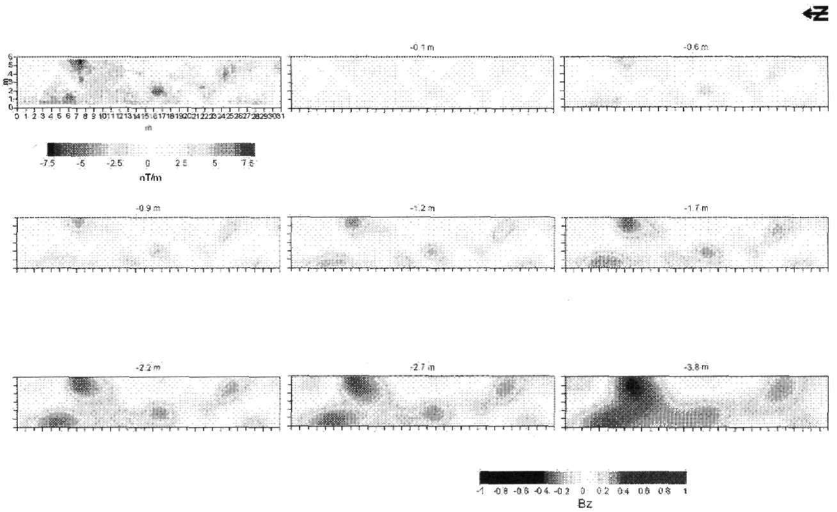

Figure 8 - Gradiometric map and tomographic inversions relating to the GA3 area carried out at the same depths of the electrical slices

4.2. Magnetic survey in Sibari

The gradiometric map carried out at Sibari archaeological site was obtained combining seven square maps with a surface of 50mx50m for each of them. After the application of the filtering procedure described in section 3.2.1, we put together the seven maps, obtaining the results showed in figure 9. As can be easily observed, there is a well defined straight gradiometric anomaly which goes throughout the entire length of the investigated area from west to east, with a gradiometric intensity of about 10 nT/m. In the west part of the area, it continues in the south direction, even if with lower gradiometric intensity. Its direction, dimension and gradiometric intensity seems to be in perfect agreement with the continuation of the ancient city wall of Sibari, as confirmed by previous excavation tests performed in other areas of the same archaeological site.

5. Conclusions

In this work we showed the preliminary results of a geoelectrical and magnetic surveys in Θουρία and Sibari, carried out to study the presence of archaeological features at shallow depths. In both cases the geophysical research is a part of a multidisciplinary approach to the archaeological survey. In Θουρία, the joint application of electrical and magnetic techniques is the only tool which could be used at the moment to supply information to archaeologists and architects where excavations are not allowed. Geophysical approach revealed the presence of straight long anomalous patterns probably due to the presence of walls (geoelectrical and magnetic measurements). The inversion of the electrical data allowed us to obtain information about the most probable depth of the anomalies sources, and the obtained depths are in agreement with the archaeological hypothesis. Successively, by means of the use of a new tomographic inversion of the magnetic data, developed in a probabilistic sense, we obtained information about the probability to found the magnetic sources at the same depths of the geoelectrical inversion.

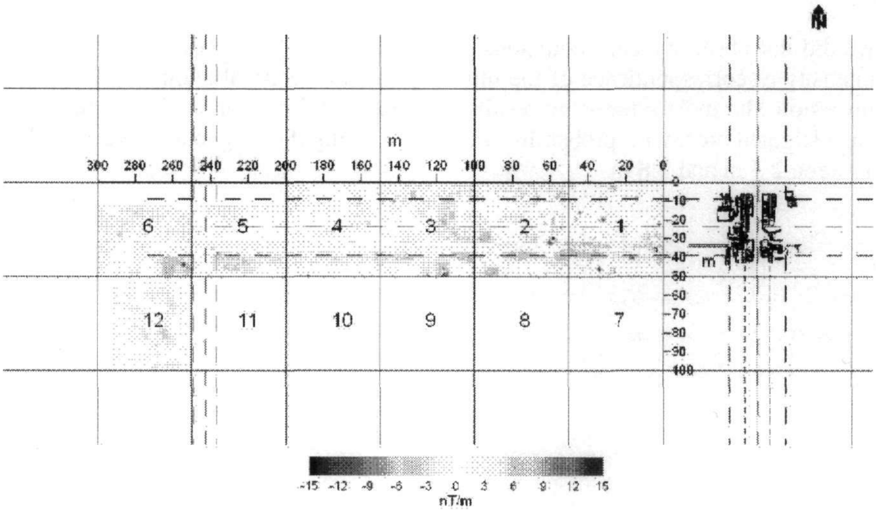

Figure 9 - Gradiometric map relating to the Sibari archaeological site

In Sibari, the possibility to apply both the magnetic and the geoelectrical methods for the recognition of a wide area was not possible and only magnetic surveys were carried out. The results obtained are impressive; the trace of the ancient roman wall is clearly depicted as well as its breakdown. As concern the integration of magnetic data with other geophysical methods, in Sibari due to geological condition only geoelectrics could be applied. For the future, we plan to use this method as control-check in the areas that will be choose to be excavated by archaeologist, with the aim to define the depth of the magnetic sources.

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