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Contribution of Geophysical Approaches to the Study of Priniatikos Pyrgos

Apostolos Sarris[a], Nikos Papadopoulos[a] and Pantelis Soupios[b]

Introduction

One of the conclusions of the Vrokastro Archaeological Survey Project (1986-95) was the importance of the coastal zone of the central to western Gulf of Mirabello area, with emphasis on Priniatikos Pyrgos as it was considered to have expanded the external connections and trade networks of the surrounding settlements. For this reason, the Istron Geoarchaeological Project (Kalpaxis et al. 2006, Hayden et al. 2007) was initiated in 2002 and until 2006 it was focused on the exploration of the Istron River valley and the environs of Priniatikos Pyrgos in an effort to study the nature, extent, condition, resources, and environment of the Istron coastal zone and to broaden our understanding of the cultural development of the site in relation to the changing environmental settings.

The geophysical campaign of the project extended mainly in the area between the promontory of Ioannimiti, where a large Roman harbour site is located, and Nisi Pandeleimon, the centre of the Hellenistic Polis of Istro. Still, the main contextual focus of the prospection survey – which was carried out in three different phases – was the promontory of Priniatikos Pyrgos.

In 2002, geophysical grids were laid out on the promontory of Priniatikos Pyrgos and in its vicinity to the south (Figure 1). The initial stages of the geophysical campaign, which covered more than 10,000m^2, were aimed at determining the extent of the harbour settlement. Most of the areas explored were olive groves or uncultivated fields, where a concentration of sherds and/or worked stones had been noticed. Area A covered the central and southern part of the promontory of Priniatikos Pyrgos. Areas B and C were located to the south of Area A, in the vicinity of Hall's excavation trench (Hayden and Tsipopoulou 2012) and a Second World War cement bunker, while Areas E and F were located even farther to the south. Area D was located about 60m from the west side of the headland of Priniatikos Pyrgos. On the west side of Area D, a small branch of the Istron River runs towards the sea. Grids constituting Area G were laid out on the top of the western edge of the promontory, where continuous marine erosion had revealed parts of Minoan walls and a pottery kiln about 2-3m below the current surface near the base of the western scarp.

In 2003 the geophysical grids were expanded farther to the east (East Grids), south (South Grids), and west (West Grids) of the promontory. The goal was to explore the wider limits of habitation in the region. One of the targets of the geophysical investigations was the modern soccer field, which lies about 50-60m from the coast and consists of a large, flat, fenced area of about 800 m^2. The terrace for the soccer field was cut with a bulldozer into a long gentle slope that rises to the south, towards the direction of the national highway (Agios Nikolaos-Sitia). This area of rising ground is fenced and belongs to Kalo Chorio village ("Village Field" or "Public Field"). In 2003, more than 20,000m^2 were explored by a combination of EM, magnetic and soil resistance techniques.

In the third phase of the geophysical project (2005), emphasis was given to both shallow and deep prospection of the areas located to the south and east of the promontory of Priniatikos Pyrgos and to the west of Nisi Pandeleimon. A small grid of 20x20m within the soccer field was covered by shallow depth electrical tomography and 2-D soil resistance multiplexer techniques in order to obtain a 3-D image of the archaeological features that had already been found during the previous phases of the geophysical survey. Within the village field, two large sections (Area F1 and Area G1) towards the northern side of the property were covered by electromagnetic, soil resistance multiplexer, and magnetic techniques (Figure 1). High depth electrical tomography and seismic prospection techniques covered an area of about 800m (E-W) x 400m (N-S) within and to the east of the village field. This was aimed towards the construction of a 3-D model of the stratigraphy of the area, the mapping of the bedrock, and the study of the possible location of the port. Finally, two more transects were studied to south of Priniatikos Pyrgos, in order to investigate any possible changes in the course of the Istron River, in relation to its current location.

In addition to the above modules of research, a study of the hierarchy of the settlements of the region in different periods was carried out using GIS spatial analysis tools. The particular approach taken made use of the results of the Vrokastro survey and included an attempt to analyze the dynamics of the settlement patterns and the changing geomorphological conditions that influenced habitation in the region. The spatial distribution of settlements, clustering of sites, their correlation with the geomorphic attributes of the environment (altitude, slope, aspect, geology, etc.), site catchment analysis, least-cost-path and viewshed analyses were all included among the main processing procedures that were computed. According to the results of these, the geological and hydrographic network, the altitude and distance from the coast line, and the proximity to cultivated lands all played an important

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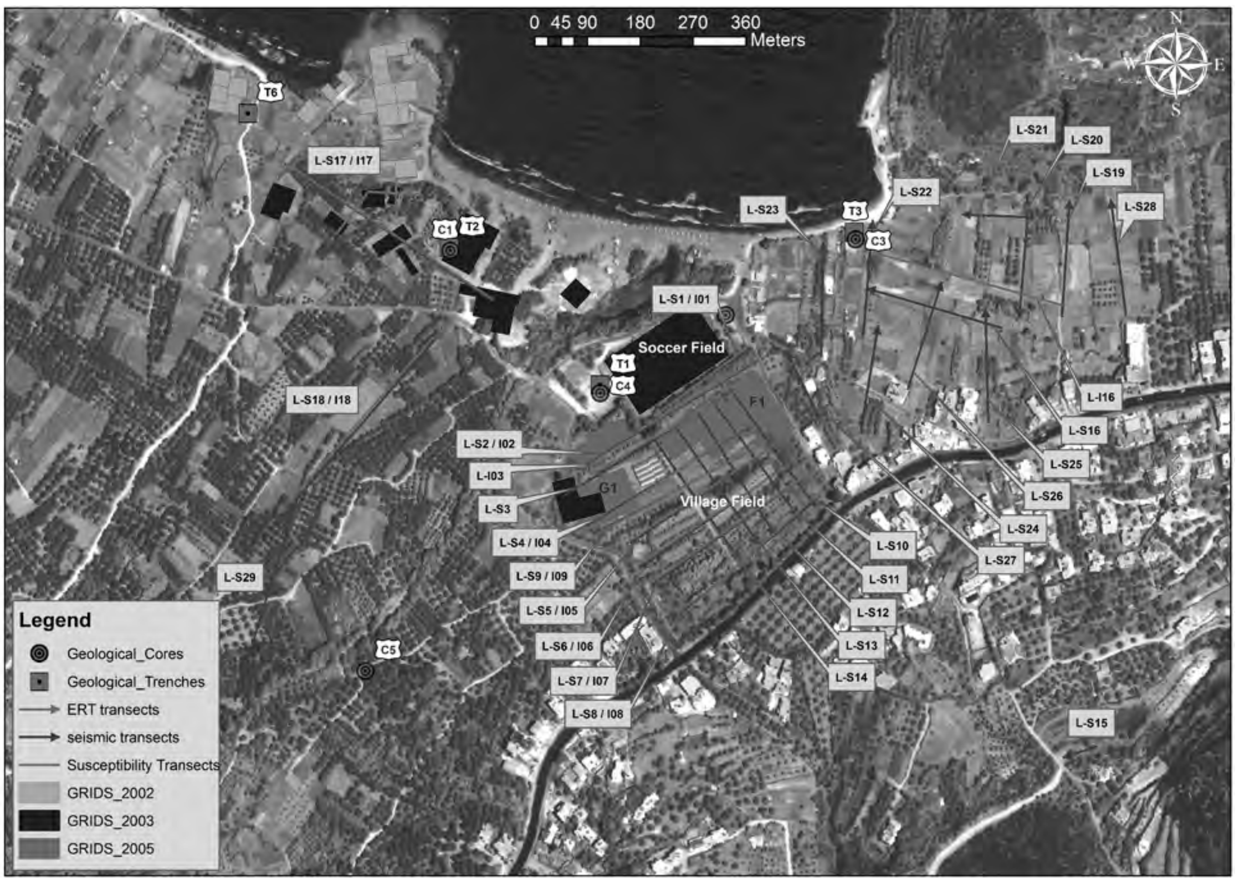

Figure 1. Location of the geophysical grids that were scanned by various methods in the 3 different fieldwork campaigns from 2002 to 2005 (above). Location of the transects across which electrical resistance tomography, seismic and magnetic susceptibility measurements were conducted (below). Most of them are located to the south and east of Priniatikos Pyrgos. The location of the spots where geological cores and geological trenches were conducted is also indicated on the map.

part in the establishment of settlements in the region (Sarris et al., 2005, 2007).

Methodology

The geophysical prospection of the prehistoric and historical coastal site on the limestone headland of Priniatikos Pyrgos was implemented through a ground-based prospection approach and a satellite remote-sensing module, which were used for mapping the area and recording subsurface features. The prospection survey utilised ground-based survey techniques (EDM and GPS mapping, magnetic, soil resistance, and electromagnetic), auger coring for studying the distribution of magnetic susceptibility, and aerial and satellite imagery for mapping, including digitization techniques and GIS for plotting the wider distribution of settlements in 3-D relief in order to study their relation to the topography of the region. Ikonos satellite imagery and a time sequence (1960 to present) of aerial photographs were used for capturing changes in the land-use patterns of the region.

The measurement of the local magnetic field and electrical resistance variations are standard techniques employed in archaeological subsurface surveys. These non-destructive soil resistance techniques are ideal for detecting subsurface features that differ from their surroundings in porosity, density, or water content. The magnetic methods detect features that contain concentrations of magnetic minerals (such as pits, ditches, burned sediments, organic material, and pottery concentrations). The electromagnetic methods are ideal for obtaining information on both the conductivity and magnetic susceptibility of soils. 2-D electrical resistivity surveys use the variation in the horizontal and vertical resistivity of the subsurface to determine the possible location of features, particularly constructed features such as walls. Finally, seismic techniques can be used for large depth investigations (similar to large electrode spacing electrical tomography techniques), for modelling the subsurface geological stratigraphy (Sarris 2008).

More specifically, soil samples were taken along transects within the site and in the fields just south of the promontory. The magnetic susceptibility of the soil samples was measured in order to examine the extent of potential workshop activities in the area. Magnetic susceptibility analysis was employed complementarily to magnetic survey (measurement of the vertical magnetic gradient). In the geophysical survey, a Geoscan FM36 fluxgate gradiometer (Figure 2) was used for measuring the vertical magnetic gradient with an effective investigation depth of about 1-1.5m. The Geoscan RM15 soil resistance meter (Figure 2) with a twin probe configuration of electrodes was used for the measurements of the soil resistance, and electrode spacing was set to ca. 0.5-1m in order to achieve a penetration depth of 1.0-1.5 m. Complementary to the magnetic and soil resistance techniques was the use of a Geonics EM31 conductivity meter (Figure 2) for measuring both the soil conductivity and soil magnetic susceptibility with an effective investigation depth of ca. 4-6m.

Though normally employed in mapping mode, soil resistance techniques can also be adapted to measuring the vertical distribution of resistance and thus the depth of a feature. Electrical Resistivity Tomography (ERT) is a combination of both lateral profiling and vertical sounding procedures and it provides information about both vertical and lateral variations of resistivity. ERT measurements were carried out using two different approaches. The first involved shallow depth ERT measurements through the use of the Geoscan Research RM15 soil resistance meter along with the Multiplexer MPX15 and the multi-probe frame PA5, using the twin probe configuration with 3 different electrode spacings: 0.5m, 1m, and 2m. The gradual increase in distance between the mobile probes leads to a gradual increase in the penetration depth below ground surface.

For the work in the soccer field, the pole-pole array was employed. The goal was to gather parallel tomographic resistivity data with the pole-pole array along the west-east and south-north directions. Both tomographic surveys were conducted with a 0.5m step interval resulting in 80 tomographic profiles: 40 parallel to the north-south, and 40 parallel to the west-east direction. Each one of these data sets was inverted separately in order to reconstruct the true resistivity distribution of the subsurface. Shallow depth ERT readings were also acquired using the Sting R1 resistivity meter together with the Swift switching unit and a multiclone cable employing the dipole-dipole configuration along the west-east direction (X-Survey). Twenty electrodes were laid out along each line with a 1.0m inter-electrode and inter-line spacing respectively.

The second method involved deep ERT measurements through the use of Syscal Junior 48 (Iris Instruments) and 2 polyclone cables, each consisting of 24 electrode outputs. The electrode spacing was set to 4-5m. Twelve transects were explored, following the location of the seismic transects, and they were used for a better refinement of the results of the seismic survey to the south of Priniatikos Pyrgos and Nisi Pandeleimon. More specifically, 9 tomographies were conducted in the area of the village field (Figure 1). Tomographies I01 to I09 were parallel to each other, in order to obtain systematic measurements of the subsurface within the village field and to create horizontal slices of the subsurface. Tomographies I16 to I18 were conducted to the east of the village field (I16) and to the south of the promontory of Priniatikos Pyrgos (I17 & I18). The goal of the tomography measurements was to investigate the geological formations along the direction of the transects. After running a number of controlled experiments, it was decided to proceed with the rest of the survey using the Schlumberger array. The Schlumberger array provided smoother measurements and larger penetration compared to the Wenner array.

The investigation of past natural geological processes in the region required the use of seismic refraction techniques which have the ability to deeply penetrate the subsurface. The objective of the seismic refraction survey was to determine soil thickness and identify differences in the acoustic properties of fractured and non-fractured rock. The Geometrics R-24 Strataview digital seismograph was used for the acquisition of the seismic data from Priniatikos Pyrgos. The generation of the Primary (or compression) (P) waves was achieved by the impact of a 7kg sledgehammer against a metal plate on the ground (struck vertically down). A total of 29 seismic lines (Line01-Line29) were conducted in the study area (Figure 1). The geophones spacing was different in every line (~7-10m) depending on

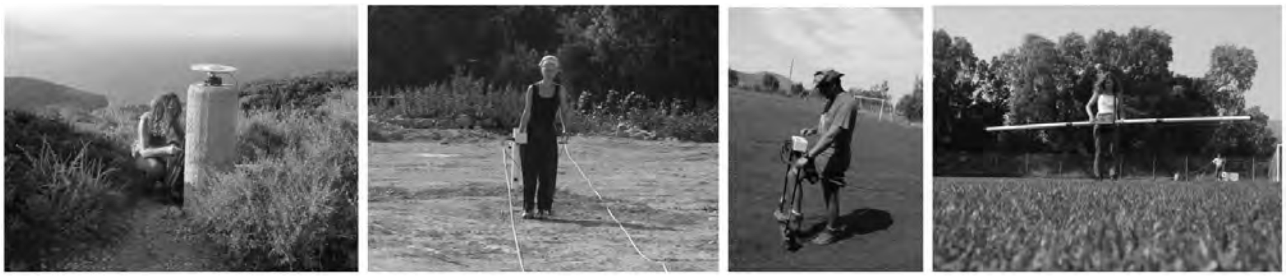

Figure 2. Snapshots from the geophysical survey in the wider area of Istron (from left to right): GPS mapping survey, fluxgate gradiometer survey, electrical resistivity survey and electromagnetic survey.

the available space for the seismic acquisition. A setup of 24 12Hz OYO-Products geophones was used in all seismic lines except in lines 20 to 24 where 12 geophones were used.

A specific map coordinate system was chosen for each geophysical mosaic of grids, which was registered to the appropriate geodetic system of coordinates (namely EGSA'87), based on the GPS/EDM mapping data. Thus, after the rectification of the satellite image, it was possible to overlay the geophysical maps at their corresponding location. The above information was entered into a Geographical Information System which was connected to an elaborated database regarding the archaeological sites and their surrounding landscapes.

Results

Magnetic, Soil Resistance and Electromagnetic Measurements

Some strong dipole magnetic anomalies in Area A, in good correlation with the EM31 in-phase measurements, were suggested at the central section of the promontory, pinpointing the existence of a cluster of kilns, extending over an area of 5-6m in diameter (Figure 3). The high density distribution of slag fragments at this location suggested that at least some of the above facilities may have been used for metal production. The relatively high values of the soil resistance measurements (up to 101 Ohms) and their loose correlation with the magnetic data indicated that most of the features in Area A are in close contact with the bedrock, justifying the failure to register the badly preserved wall foundations that were located in the central region of Area A by subsequent excavations (trenches A1000, A2000, A4000 and A5000 (Hayden & Tsipopoulou 2012). Similar results were drawn from mapping the soil conductivity through the measurements of Geonics EM31. Furthermore, the results of the geophysical survey suggested a possible wall enclosure of the promontory to the north.

Massive rubble walls forming corners and rooms were also present along the rocky plateau to the west of the promontory. Multiphase occupation of the site was suggested on the basis of stratigraphic evidence, partially uncovered due to the gradual erosion of the western scarp. The measurements of the vertical magnetic gradient which were carried out on the top of the west region of the promontory (Area G) revealed a number of linear features, probably related to the existence of architectural remains (Figure 4). Although most of the linear features were aligned in a north-west to south-east direction, the fuzziness of the magnetic signals suggests that the architectural features may belong to more than one occupation phase. Two strong dipole anomalies towards the south-east section of Area G could also be correlated to kiln structures, probably used for pottery production as there was no evidence of any surface slag distribution. Furthermore, soil magnetic susceptibility values indicated a decreasing tendency towards the south-west edge of Area G, designating the probable limits of the intensive occupation of the site.

Low frequency magnetic susceptibility values in Area A ranged from 13.1emu/gr to 423.8emu/gr, while the frequency dependent susceptibility reached the value of 17.65%. Although the maximum values of both high and low frequency magnetic susceptibilities were shown around the central part of Area A, where possible kilns and furnaces have been suggested, the high values of the frequency dependent susceptibility extend farther towards the southern and eastern sections of the area, signifying a possible expansion of the settlement in certain phases in these directions. Two magnetic features in the south-east part of Area C outlined architectural complexes of dimensions 5x4m and 3x2m together with a few more isolated anomalies reaching the value of 25nT/m. The particular features could be correlated to remnants of rubble walls that extend to the east of Area C towards the sea from the eastern scarp of the promontory. A few more architectural features and a possible kiln feature (~2x2m) were indicated farther to the south in Areas E and F.

All of the geophysical data suggest that the locus of habitation and workshop activities was the main headland of the promontory. This is also supported by the magnetic susceptibility measurements: after exhibiting its highest values in Areas A and G, magnetic susceptibility falls close to background levels (around 35-40emu/gr) to the south of Area C. In contrast, frequency dependent susceptibility values are kept at relatively high levels (above 10%, reaching a maximum of 29.51% compared with 17.65% in Area A). This may imply either that the habitation of the region was expanded farther to the south of the promontory, or that the specific values may have been caused by the disturbed upper soil horizons. Indeed, the high soil resistance values to the west of Priniatikos Pyrgos (Area D) and close to the small branch of the Istron River suggested areas of disturbed soil and rubble, probably deposited by the repeated cycles of seasonal flooding of the river.

Taking into account the direction (towards the sea) of a pair of wide, high resistance anomalies (probably correlated to disturbed soil, rubble deposition and other alluvium carried away from older branches of the Istron River) located towards the south-west and south-east side of the promontory, it may be also suggested that the older Istron

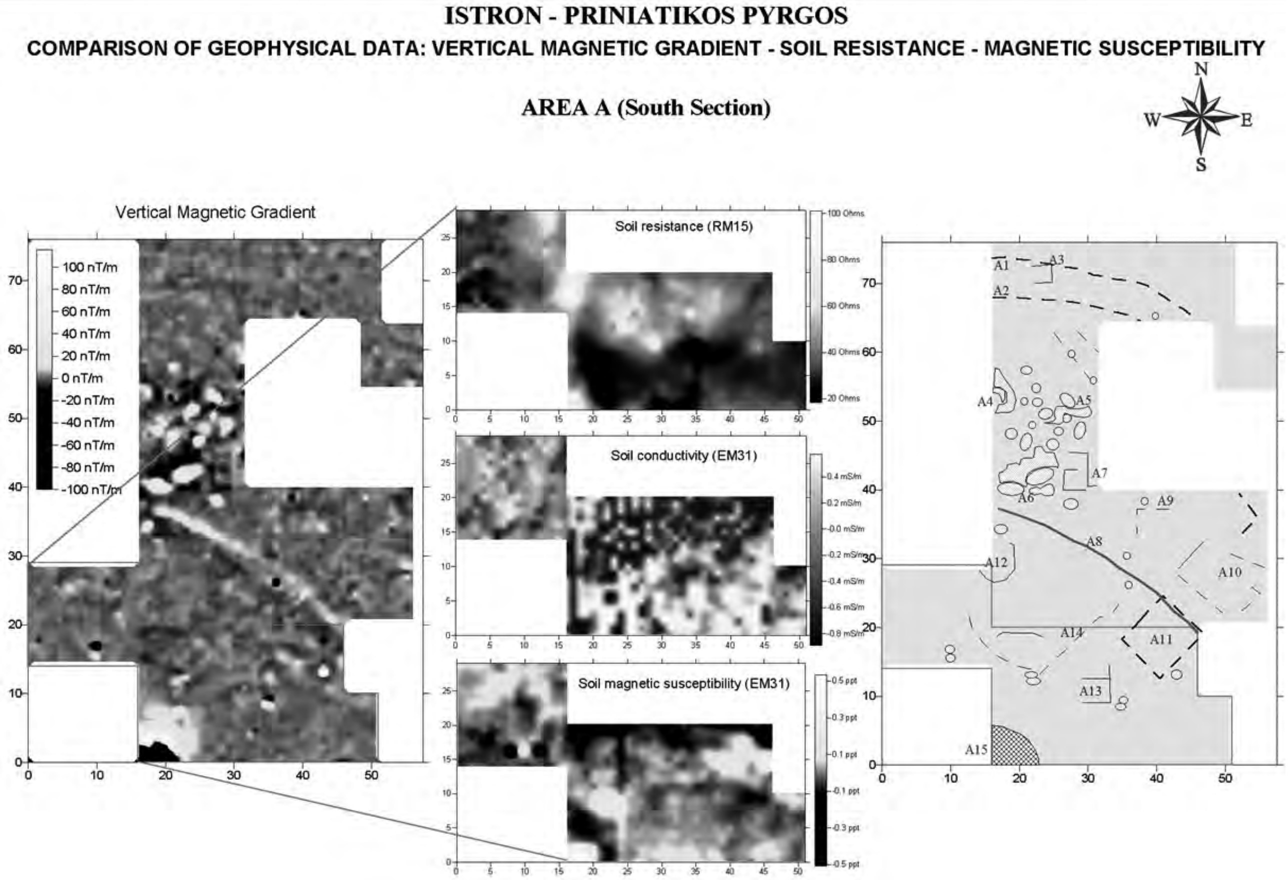

Figure 3. Results of the magnetic survey in Area A (left) and their corresponding diagrammatic interpretation (right). The southern part of Area A was scanned by both magnetic and electromagnetic methods (middle), resulting in a large degree of correlation of the suggested anomalies.

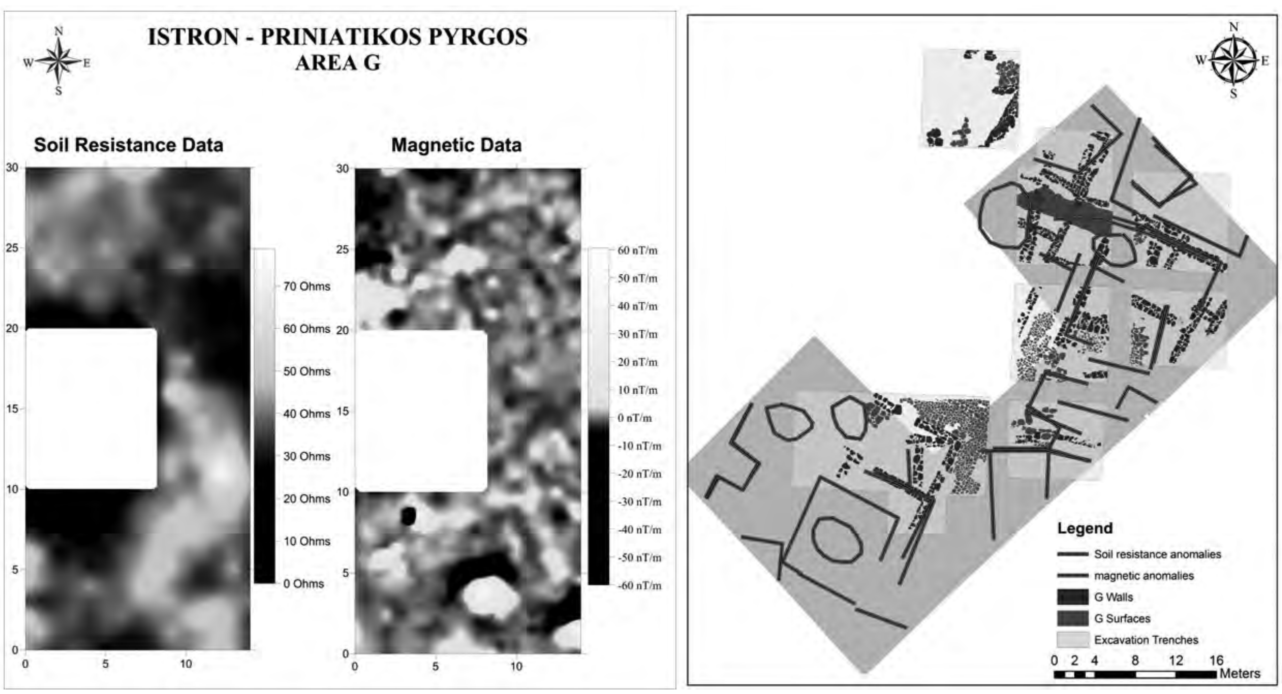

Figure 4. Results of the soil resistance and magnetic survey in Area G (left). To the right is the diagrammatic interpretation of the geophysical anomalies in relation to the results of the excavations that were carried out in specific trenches within the area.

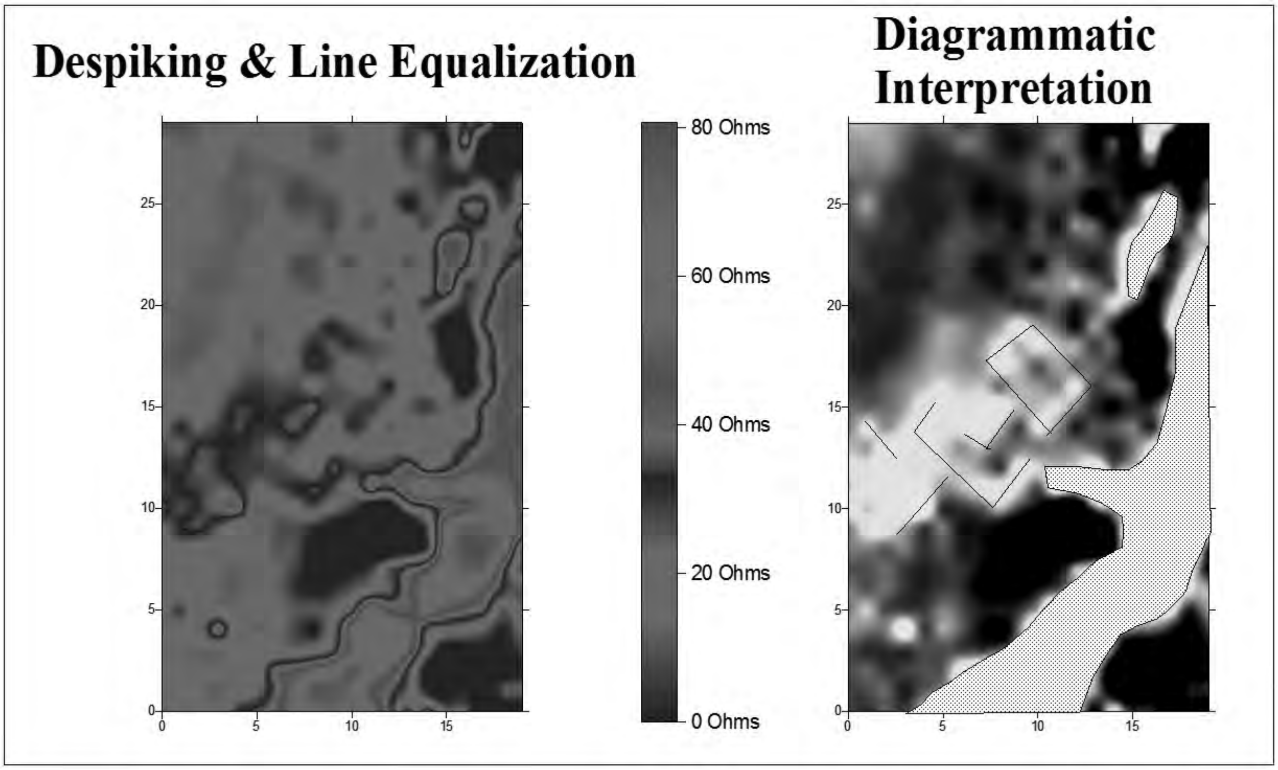

Figure 5. Results of the soil resistance survey carried out in grid F to the south of the promontory of Priniatikos Pyrgos (see Fig. 2). The approximately 5m wide, high resistance linear anomaly that extends in a south-west to north-east direction seems to project towards the east side of the promontory. To the west of it there are also indications of the presence of an architectural complex.

River branches were directed to the sea from both sides of the Priniatikos Pyrgos promontory, probably leaving a small path to the mainland from the south-west direction (Figure 5). This is also supported by the sedimentological analyses and OSL datings (Zacharias et al. 2009). If this hypothesis is true, then the settlement might have been expanded slightly away from the workshop area, as has been noticed at Gouves (Vallianou, 1997, 333), where in similar river delta settings, the centre of ceramic production seems to be separated from the main settlement.

The density of architectural remains increases to the south and to the east, in the area of Kambos (about 250m to the east) where the village and soccer fields are located. Massive walls were registered by magnetic and soil resistance techniques under the modern soccer field. Almost all techniques pinpointed that architectural remains extend farther to the south (in the village field and to the west of it), located up to a depth of less than 2m below the modern surface and having an alignment deviating from the north (north-east to south-west, or north-west to south-east).

Shallow Depth Tomography in the area of the Soccer Field.

Only a small section (20x20m) of the soccer field was explored through ERT techniques (AGI Sting with a Dipole-Dipole array), aiming at verification of EM and resistivity data that suggested the presence of an underlying building. The individual tomographies were combined into one single data set and processed with a 3-D inversion algorithm in order to reconstruct the subsurface resistivity distribution in three dimensions as horizontal slices of increasing depth. Indeed, the remnants of a rectangular wall structure began to appear in the first depth slice (depth 0-0.35m), and extend up to a depth of about 1.5m below the current surface (Figure 6). The same region was also scanned through the modification of Geoscan RM15/MPX15/PA5 for acquiring tomographic data with a pole-pole array in different directions (along east-west and south-north directions). The inversion along X, Y and XY directions resulted in identical reconstructed models showing excellent agreement with the conventional ERT approach (Figure 6). The angular feature probably represents part of a building of dimensions larger than 15x15m which extends farther to the south of the soccer field. Similar types of near-to-surface targets were identified all over the soccer field, and to the south in the village field.

Deep Electrical Tomography

Most of the deep tomographies were conducted in the region between Priniatikos Pyrgos and Nisi Pandeleimon. The extension of the electrical tomography profiles reached a length of almost 200m, achieving a penetration depth of more than 20m at the centre of the profiles.

Immediately to the south of the soccer field, all transects suggested that the superficial cover of the area consists of alluvial/Quaternary deposits with resistivity values ranging between 50-150 Ohm-m and variable thickness up to 2-4m. A second layer was also recognized to consist of cohesive sediments with resistivity values between 20-40 Ohm-m. From the depth of approximately 20m and below, a transition zone occurs between sediments and bedrock, probably highly weathered and filled with water, having resistivity values below 10 Ohm-m. Moving to the south, electrical tomography data suggested increasing thickness

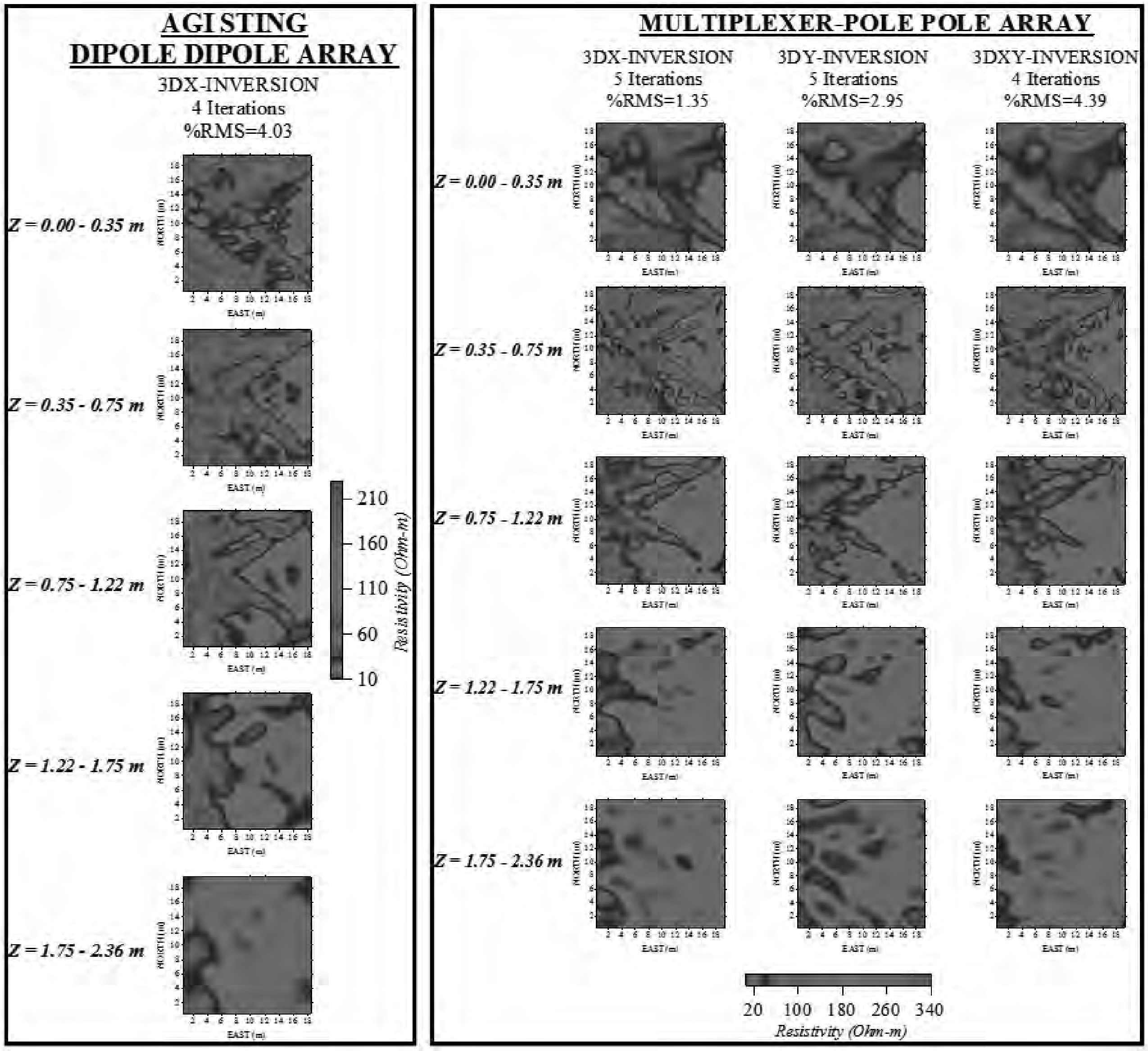

Figure 6. 3-D resistivity model (presented in slices) resulting from ERT dipole-dipole configuration of electrodes (left) and the corresponding resistivity models along X (west-east), Y (south-north) and XY (west-east and south-north) direction of the pole-pole data collected with the RM15/MPX15 (right).

of the upper alluvial deposits (5-6m) which is in agreement with the slope of the terrain, and a fracture zone that extends below the medium weathered layers was recorded. The particular fracture zone seems to shift towards the east and to expand within the public field to the south, and can be related with a geological fault, filled with water, which could also explain the corresponding low resistivity zone that appears in that specific region. This fault, which has also been suggested by the seismic data, has a north-east to south-west orientation, and may also be correlated with past heavy landslide episodes that have been reported by the locals originating from the southern hills located to the south of the national road.

Seismic Refraction Survey

A general observation of the travel times of the seismic waves suggested that low velocities dominate, indicative of the alluvial deposits that cover the top surface of the area under study. All profiles showed very strong variations in the interface between the second and third layers. This was considered to be indicative of the strong velocity anomalies caused by the existing inhomogeneity of the bedrock. In an effort to classify the resultant velocity models based on the corresponding formations, they were distinguished in four different layer velocities as well as four geological formations. Based on this refined categorisation (velocity based on geology), four layers were recognised that correspond to specific geological units. According to this scheme, the presence of specific formations in the area was able to be mapped by creating an approximate buffer around the seismic transects (Figure 7).

Six backhoe trenches (4–5m deep) were excavated in order to collect soil samples for sedimentological analyses (Zacharias et al. 2009). Comparison between the results of the seismic survey and the geological test trenches shows that they seem to be in agreement, at least in areas where trenches were excavated in the vicinity of the seismic lines. More specifically, trench T2, which was located close to the middle of transect L-S17/I17, identified the upper layer (which was modelled as sedimentary deposits of quaternary

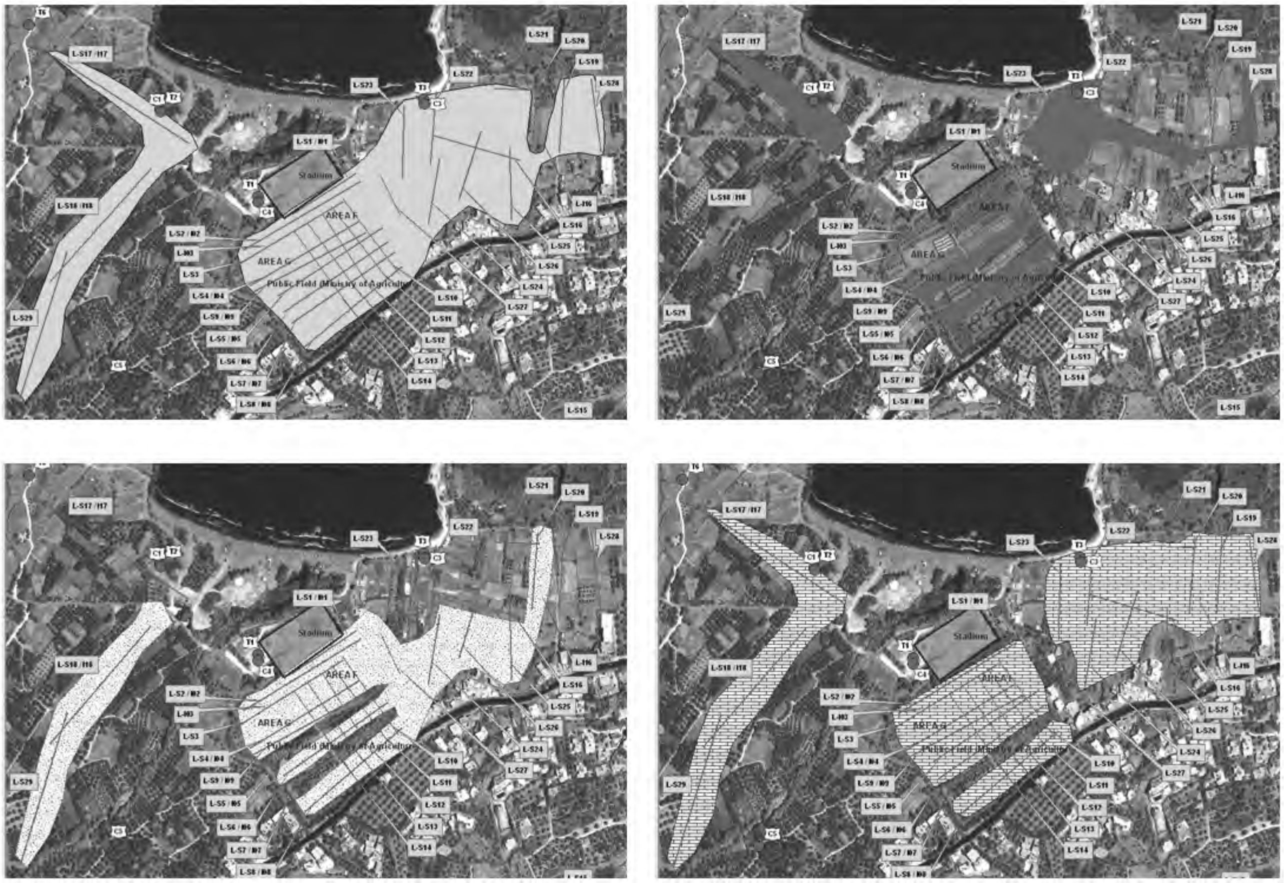

Figure 7. Distribution of the different geological formations in the wider area of Priniatikos Pyrgos.
- Upper left: Presence of alluvial deltoid deposits (sand, gravel, silt, organic mud, clay). Average velocity of 491m/sec. Found in all seismic transects, except Line 20.
- Upper right: Presence of lower and upper terrace deposit (slightly cemented gravels, sand and clay), possibly saturated in places. Average velocity of 1830m/sec. Found in all measured lines except lines 05, 07, 13, 15-17, 19, 21-23 and 28.
- Lower left: Presence of sandstone, mudstone, conglomerate (Kilic & Bakacak formation). Average velocity of 2400m/sec. Found in lines 05, 07, 13, 16, 17, 22, 23 and 28.
- Lower right: Presence of weathered limestone or cohesive conglomerate. Average velocity of 4589m/sec. Found in all measured lines except lines 01, 07, 15, 25 and 27.

alluvial formation) as consisting of silty sand/silt/clay. Similarly, trench T3, which was located at the end of profile L-S22, identified the upper layer to consist of sand with gravels/silty sand with clay and angular pebbles.

The 3-D model of the boundary between the sediments (soft and grained materials) (2nd layer) and the bedrock (cohesive conglomerate or weathered limestone) (3rd layer) was constructed in a similar way. Emphasis was given to the area to the west, where a denser network of seismic lines was laid, providing a better interpolation for the interface mapping. The depth of the bedrock was found to range from 20m to 40m.

According to the geological data, most of the valley of Istron village consists of alluvial/quaternary deposits and fragmentary pockets of limestone sediments. A vertical coastal subsidence of 2-3m that followed the Roman period (Shaw 1990, Raban 1991) submerged a number of coastal sites in the area, as can be seen even today within the shallow coastal waters. An extension of the ancient coastline farther to the north does not leave much space for natural harbour sites (Theodorakopoulou et al. 2005; Pavlopoulos et. al. 2007). However, there are a few possibilities. One is the estuary of the Istron River that today is observed to flow into the sea from the west of Priniatikos Pyrgos. Although its location may have shifted over time, moving to the west and east of Priniatikos Pyrgos, its estuary may have typically been used as a protected harbour in antiquity. Other potential locations are the areas to the south of Nisi Pandeleimon. This large promontory, to the east of Priniatikos Pyrgos, may have once been separated from the rest of the mainland (as its name 'nisi' suggests). Landslides have been reported by the locals and may have been responsible for connecting Nisi Pandeleimon with the rest of the mainland. The above suggestions are also in agreement with the hydrogeological data of the region, which indicate that most of the coastal areas in the vicinity of Priniatikos Pyrgos consist of carstic formations of medium to high permeability and alluvium deposits of variable permeability**.**

Final remarks

The data presented above indicate that the coastal site of Priniatikos Pyrgos was used as a primary industrial centre of the Vrokastro region for millennia; probably as a pottery workshop in the prehistoric period (Nodarou and Moody, this volume) and as a metal working facility (Filippaki et al., this volume) during the later phases of its occupation.

Located on a coastal hill in the middle of the flood plain of the Istron River, the site offered ideal conditions for the operation of ceramic kilns and metal furnaces, as the north-westerly winds could provide the necessary conditions for their firing. Furthemore, it can be suggested that the establishment and evolution of the settlements and the related workshops in the area of Priniatikos Pyrgos may have been closely related to their proximity and access to raw resources, such as granodiorite ores that have been located in the local geology.

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