Archaeologia Polona, vol. 53: 2015, pp. 343-347

Uphill and downhill geophysical challenges in Delphi, Greece

Apostolos Sarris[a], Nikos Papadopoulos[a], Eleni Kokkinou[b], Pantelis Soupios[b], Michael Teichmann[c], Kleanthis Simyrdanis[a], Georgia Kakoulaki[d], Dimitris Alexakis[a], Cristina Manzetti[a] and Jean-Marc Luce[e]

KEY-WORDS: integrated geophysical survey, ERT, EM, GPR, 3D seismic refraction, magnetics, Delphi, Greece

INTRODUCTION

The first excavations in Delphi started in 1892 with the exploration of the sanctuary of Apollo initiated in 1887 (Luce 2011). Excavations required the old medieval village of Kastri to be moved from the archaeological site to its outskirts, where the modern town of Delphi is located today. A descriptive plan of the site marking the walls of ancient building structures *in situ* was delivered around 1898, whereas a new version of it was made by A. Badie in 1992. The recent archaeological mission had three tasks: topographic mapping of building remains and features from the 19th century trenches after cleaning; re-examination of the original historic documentation; and geophysical mapping of the area, the overall objective being to produce

[a] Laboratory of Geophysical – Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranean Studies, Foundation for Research and Technology – Hellas, Rethymno, Crete, Greece
[b] Educational Institute of Crete, Chania Section, Department of Natural Resources and Environment, Chania, Crete, Greece
[c] German Archaeological Institute, Rome Department, Rome, Italy / Christian-Albrechts-University, Kiel, Germany
[d] University of Massachusetts, School for Marine Science & Technology, Dartmouth, USA
[e] University of Toulouse, Pavillon de la Recherche, Toulouse, France

a documented study of the urban layout and organization of the city, which had not been the focus of research like the sanctuary of Apollo.

The geophysical survey was carried out within the frame of a broader archaeological campaign aimed at studying the city and its development from the beginning of occupation in the 16th century BC to its abandonment in the 7th century AD. The program studied first (Phase I, 2012) the northwestern sector, then the eastern (Phase II, 2013) and western sectors (Phase III, 2014). The respective areas had not been explored in any greater extent so far, although the 19th century archaeologists had opened in some places a series of about 30 roughly parallel exploratory trenches that had uncovered a number of building remains.

GEOPHYSICAL APPROACHES

Geophysical prospection methods used to record the subsurface information in specific areas of the archaeological site included the magnetic method (Bartington G601), soil resistance (Geoscan Research RM15), ERT (Iris Syscal Pro with dipole-dipole configuration of electrodes), EM (GSSI Profiler EMP-400 and Geophex GEM-2) and GPR (Sensors&Software Noggin Plus with 250MHz antennas). The R-24 StrataView of Geometrics was also used experimentally for the acquisition of 3D seismic refraction data in an area of 50 m (E–W) by 40 m (N–S) to the west of the Delphi theater, using 24 P (12Hz OYO-Products) randomly distributed geophones.

GEOPHYSICAL RESULTS

Despite the challenging conditions: steep slopes (up to railway tracks 30–40%), wooded areas, fire-extinguishing system hoses, metal trash and old excavation railway distributed randomly around the site, and deep older trenches, the manifold methodologies (Sarris 2013) employed in the geophysical campaign produced more than encouraging results. Of all the methods used, GPR and ERT measurements, obtained along transects laid out almost north–south toward the falling slope, produced the best results compared to magnetic, soil resistance and EM surveys. These two particular methods were capable of penetrating through the deeper strata, as it was obvious that in most cases the architectural remains lay 1–2 m below the current surface. The magnetic and EM surveys were successful in areas that were relatively undisturbed by anthropogenic activity.

Various targets were identified, ranging from wells to individual structures and sustaining walls. GPR measurements revealed a number of strong reflectors associated with large retaining walls or collapsed architectural relics, sometimes confirmed by partly exposed remains in the open excavation trenches. The alignment of particular structures seems to follow an iso-elevation layout, looking towards the temple or the lower levels of the site. Ground erosion and landslides bringing down the bulk of soil, stones and other building material from collapsed structures from the upper slopes of the site is obvious in the GPR depth slices. In general, the degree of preservation of the structural remains on the higher slopes seems to be relatively better compared to the lower slopes. This may be justified by the lesser quantities of material that had been deposited on them.

The plateau close to the modern theater facilities and the lapidary of epigraphic stones was scanned with three methodologies: seismic, 3D ERT and GPR methods. The GPR located a few linear reflectors aligned almost E–W, mainly in the upper strata. ATOM-3D (Active tomography

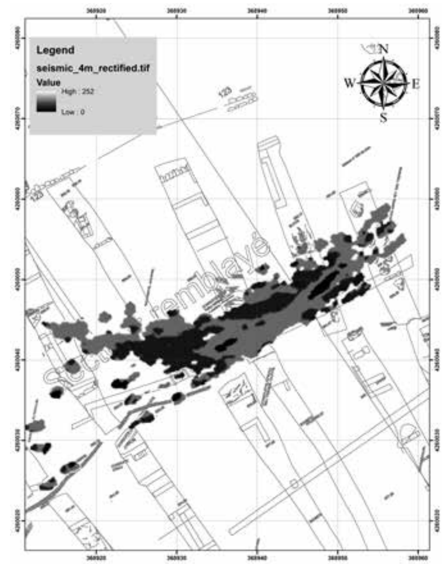

Fig. 1. Seismic depth slice for a depth of 3 m

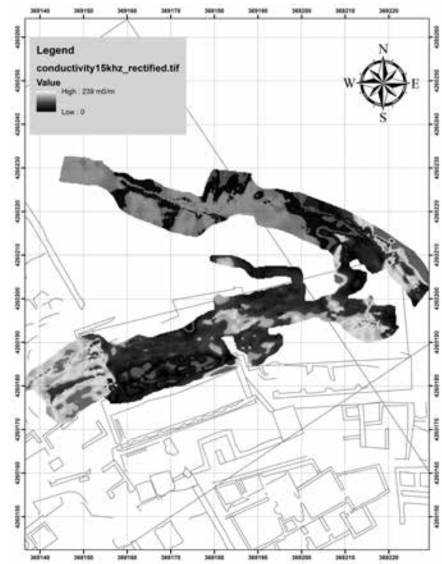

Fig. 2. GSSI EMP-400 EM conductivity measurements for 15kHz

in 3D) was employed for the 3D tomographic inversion of the seismic data (Koulakov 2009; 2011), based on ray-tracing methods and reconstruction of the 3D velocity structure based on travel times of the first-arrival refracted seismic rays from active sources. 73 shots were used to collect about 1752 traveltimes. Horizontal tomograms of velocity (11 depth slices) at various depths (0.5–5.5 m) were produced for the 3D seismic refraction data. In all the tomographic models a linear high-velocity feature was found at 3.0 m to 5.5 m depth; it belongs most likely to a NE–SW oriented structure, in good correlation with the ERT data (Soupios *et al.* 2013) (Fig. 1).

ERT was most successful in cases where deep penetration was needed (such as the mapping of the cistern to the west of the excavation house of the French School at Athens, found to extend within a 2–4 m range below the surface with soil resistivity of more than 2000 ohm-m) and where other methods were impossible to apply owing to difficult terrain and scattered modern metal. Some of the features that were identified with the ERT method were also verified with the GPR, which provided a more precise outline of the underground remains.

The highest frequency (15 kHz) electromagnetic survey that was carried out with the GSSI EMP-400 in the eastern sector indicated areas of low conductivity at shallow depths, and especially to the north of the already excavated monuments, suggesting the continuation of structures in this part of the settlement (Fig. 2).

FINAL REMARKS

Settlement structures clearly extended from the westernmost entrance of the protected archaeological site to the Castalia spring. Sustaining walls followed iso-elevation plateaus and

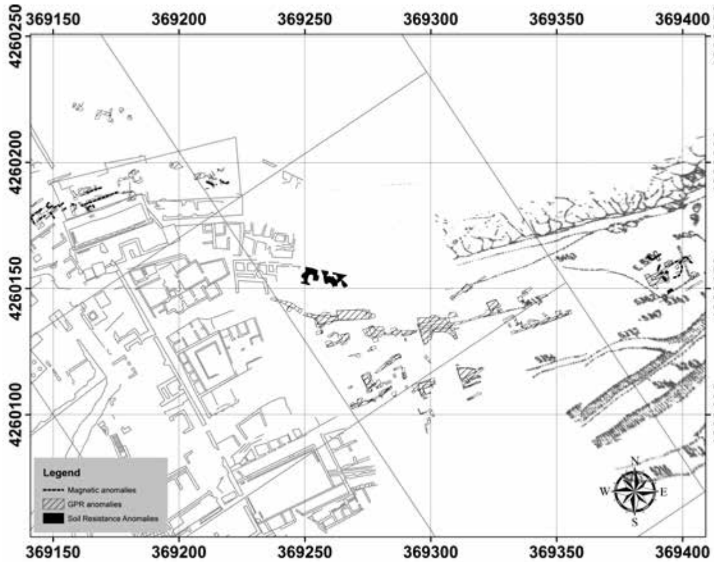

Fig. 3. Integrated image of geophysical features recorded in the eastern sector of the archaeological site at Delphi

structures were built along the slopes, leaving various horizontal and vertical corridors and streets between them (Fig. 3). Deposition depth of architectural features varied considerably on the different levels of the sloping terraces. Combined with test excavations and standing buildings, the geophysical results will contribute to a reconstruction of the settlement plan and fill in the gaps in areas that remain completely unexcavated until today.

ACKNOWLEDGMENTS

The research has been carried out with the support of the Ecole Française d'Athènes (EFA). The archaeological expedition was led by Prof. Jean-Marc Luce of the Université Toulouse. An EFA team led by Lionel Fadin was responsible for laying out the geophysical grids and for the topographic positioning of the ERT electrodes and seismic geophones.

REFERENCES

Koulakov, I. 2009. LOTOS code for local earthquake tomographic inversion. Benchmarks for testing tomographic algorithms. *Bulletin of the Seismological Society of America* 99(1): 194-214.

Koulakov, I. 2011. High-frequency P and S velocity anomalies in the upper mantle beneath Asia from inversion of worldwide traveltime data. *Journal of Geophysical Research*, 116: B04301.

Luce, J-M. 2011. Delphes, sa cité, sa région, ses relations internationals. *Revue d'études Antiques* 87.

Soupios, P., Papadopoulos, N. and Saris, A. 2013. *Reconstructing Concealed Cultural Remains Through Integrated Geophysical Tomographic Methods*, 13th International Congress of the Geological Society of Greece, Chania, Crete.

Sarris, A. 2013. Multi+ or Manifold Geophysical Prospection. In G. Earl, T. Sly, A. Chrysanthi, P. Murrieta-Flores, C. Papadopoulos, I. Romanowska and D. Wheatley (eds), *Archaeology in the Digital Era* II, *e-Papers from the 40th Conference on Computer Applications and Quantitative Methods in Archaeology (CAA2012), Southampton, 26-30 March 2012,* Amsterdam.