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Integration of archaeological and geophysical Surveys in Hierapolis of Phrygia (Turkey)

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***Abstract* – An in-depth analysis of some areas in the Hellenistic, Roman and Byzantine city of Hierapolis of Phrygia has been carried out using high resolution geophysical methods integrated to the archaeological surveys in order to detect evidence of archaeological features buried under colluvial deposits and to acquire new data of some sectors of the urban area. In particular, three areas were investigated in the northern, central and southern sectors of the ancient city: i) the Northern Agora; ii) the Sanctuary of Apollo; iii) some insulae with houses in the central and southern sectors of the city. Geophysical data were collected in these areas of interest using different surveying methodologies, during different campaigns of activity of the Italian Archaeological Mission: Electrical Resistivity Tomography, Ground Penetrating Radar, Seismic Refraction Tomography, Magnetometry and GEM. All data collected were integrated in the digital archaeological map of Hierapolis, linked to a Geographic Information System (GIS), in order to contextualize the identified archaeological features in the ancient urban plan. In some cases, geophysical measurements were verified during subsequent archaeological excavations. In this paper some results related to the Temple of Apollo are presented.**

I. INTRODUCTION

The integration of archaeological and geophysical surveys provided a useful tool for the knowledge of large not-excavated sectors of the Hellenistic, Roman and Byzantine city of Hierapolis in Phrygia (south-western Turkey) and for the reconstruction of its ancient urban layout. Indeed, some monumental complexes and large sectors of the inhabited areas, divided into insulae according to a regular urban plan, have not yet been completely excavated, with large parts of them still covered by colluvial detritus and calcareous formations deposited in the post-classical epoch. In addition, some of these areas were built in a highly unusual environmental context, characterised by distinctive tectonic phenomena, such as the welling up of thermal spring waters from the subsoil via large cracks caused by earthquakes [1]. The research thus pursued two main objectives: on one hand, to establish size and layout of the buildings, making it possible to assess the extent of the monumental areas in the city's various historic phases; on the other, to reconstruct the tectonic context and the approaches to construction that were adopted in order to cope with the seismic nature of the geological substrate. With these aims, research was therefore conducted on three monumental complexes: i) the Northern Agora, built in the 2nd cent. AD and surrounded by three stoai (to the north, west and south) and a large stoa-basilica (to the east); ii) the Sanctuary of Apollo, in use during the Hellenistic and Roman-Imperial age; iii) some insulae with houses of the Roman and early-Byzantine periods, inside the orthogonal road network of the central and southern sectors of the city. Considering the differerent geomorphological characteristics of the investigated areas and the presence of modern structures linked to tourism, it was not possible to conduct a complete investigation of these contexts. Certain areas of intervention were thus selected and the most opportune geophysical survey methods were adopted depending on the case. In particular, different geophysical methods (Electrical Resistivity Tomography, Ground Penetrating Radar, Seismic Refraction Tomography, Magnetometry and GEM) were applied during various campaigns of activity of the Italian Archaeological Mission. The geophysical results were georeferenced in the digital archaeological map of Hierapolis and managed in the Geographic Information System (GIS) linked to the map, in order to contextualize the identified archaeological features in the ancient urban plan and to allow a correct interpretation of the collected data. In some cases, geophysical anomalies were verified thanks to subsequent archaeological excavations. The results related to the Sanctuary of Apollo, characterized by the presence of the remains pertaining to three temples of the late Hellenistic and Roman-Imperial age (so-called Building A, B and C) and where different geophysical methods were integrated, are presented in this paper.

II. GEOPHYSICAL MEASUREMENTS AND RESULTS: THE EXAMPLE OF THE SANCTUARY OF APOLLO

A comprehensive geophysical assessment of a site is achieved by combining different techniques as it has been demonstrated that no single technique will respond to all detectable subsurface features [2]. For this reason, three geophysical methods were used in the Sanctuary of Apollo, built in the central sector of the city, along the seismic fault running through the urban area: Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), and Seismic refraction Tomography (SrT). The type of physical property measured determines the range of applications [2].

The ERT technique provided a two-dimensional and three-dimensional distribution of the electrical resistivity. The technique can be used to estimate the dimensions and nature of subsurface targets such as the soil/bedrock interface, strata thickness, depth and width of walls, caves, ditches, etc. [2]. The survey is controlled by a computer, which sequentially increases the electrode spacing, thus allowing the investigation of successively deeper subsurface levels. depending on the spatial resolution required, sequentially increased electrode spacing of multiples of 0.5 to 5 m can produce modelled depth sections from 1.5 to 20 m respectively. ERT profiles were measured using a Syscal R1 georesistivity meter.

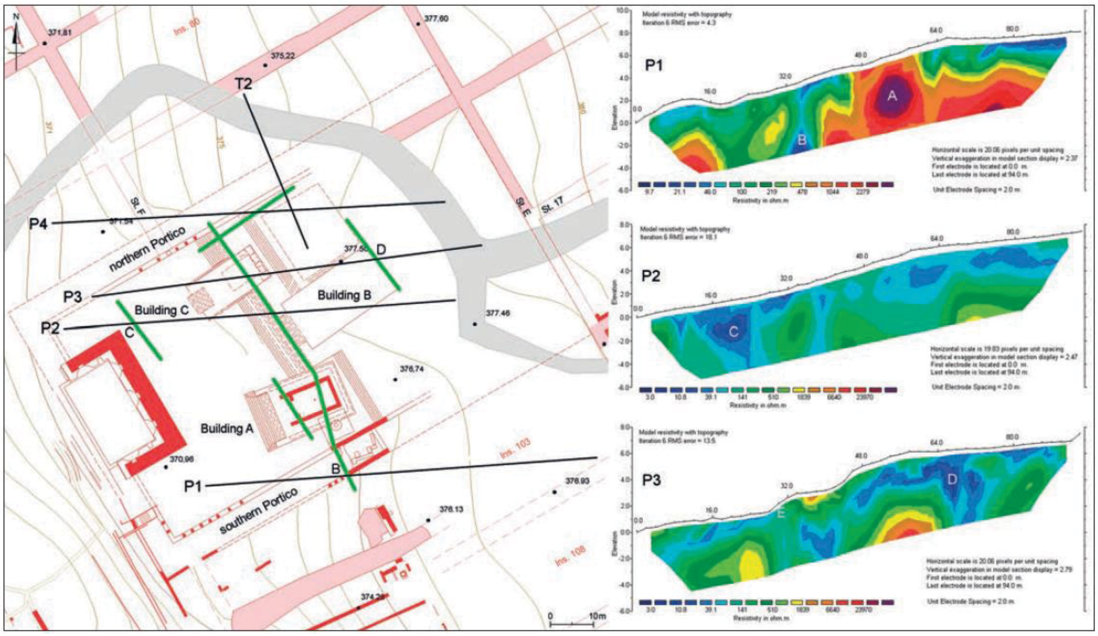

Fig. 1. Sanctuary of Apollo, ERT profiles georeferenced in the archaeological map: hypothetical position of the fissures in the bedrock indicated by green lines.

Several 2d ERT profiles were measured inside the Sanctuary of Apollo. Particularly three north-east/south-west parallel profiles (Fig. 1, P1-P3) were acquired using the Wenner-Schlumberger array with a constant electrode separation of 2 m. Forty-eight electrodes were used [5]. The data were contoured in the form of a pseudo-section. To obtain a more accurate picture of the subsurface it was necessary to invert the apparent resistivity data. The inversion method was based on the smoothness-constrained least square method (Gauss-newton method) [2]. The P1 resistivity section shows a high resistivity ($\rho >$ 1,000 Ωm) zone, which may be related to the travertine bedrock (Fig. 1, a). The anomaly with low resistivity values ($10 < \rho < 40$ Ωm), which appears at the abscissa of 36 m, may be caused by the presence of a fault (Fig. 1, b). The P2 and P3 resistivity sections show low resistivity values ($20 < \rho < 60$ Ωm), which may be caused by the presence of a fault (Fig. 1, c-d). The anomaly zone labelled e in Figure 1 ($100 < \rho < 140$ Ωm) could be related to detrital materials, which were used to make viable the middle terrace of the sanctuary. The tomographies show that the north-north-west/south-south-east main fault passes under the Buildings A and C.

The SrT technique provided a two and three-dimensional distribution of the seismic wave propagation velocity. This is the best method in mapping undisturbed layers and it is particularly useful in case of velocity inversions, representative of human cultural disturbance, or highly 3d objects, such as caves or buried structures [2]. Both the seismic wave velocity and depth of the interfaces in the subsurface can be esteemed by measuring the seismic signal travel time between the sources and the receivers. non-linear travel time tomography method was used. It considers the ray tracing for forward modelling and the simultaneous iterative reconstruction technique (SrT) for inversion. In this case the velocity model is represented by quadrangle cells with dimensions that are chosen as the receiver interval [2]. defining the ray as a line connecting the nodes arranged on the edges of the cell, the first-arrival travel times (i.e. the fastest travel time of all ray paths) and ray paths are calculated by the ray tracing method based on Huygen's principle [2]. Similarly, in this case the starting model is updated by the SrT [2]. SrT surveys were performed using Geometrics Strataview seismograph. For seismic refraction tomography data processing and interpretation, the software reflexw 6.0 was used [4].

Fig. 2. Building A, left: acquisition geometry for seismic refraction tomography (geophones = red points; shots = black points) and GPR profile location (1 = area of profiles R7-R18; 2 = area of profiles R19-R30); right: GPR profile location on the northern side of the podium.

In order to obtain information about the structure present below the Building A, a 3d seismic refraction tomography survey was performed. A rectangular area of 15 × 12 m located around the building a was selected; 48 vertical, 50 Hz, 0.25 m spaced geophones were used on the north side and 32 seismic source points (shots) were located on the south and east sides, on the ground (Fig. 2, red and black points respectively). A total of 48 seismograms were made. The seismic source was a 5 kg hammer. The results of the inversion of seismic data are displayed as seismic wave velocity distribution depth slices, showing the variation of seismic P-wave velocity (Vp) in the subsurface. The seismic refraction tomography survey indicates that the shallow subsurface may be divided into two main zones. The first one, where Vp ranges from about 1,000 m/s to about 2,000 m/s, corresponds to compact material. The second one, characterized by the lowest seismic velocities (Vp ranging from about 400 m/s to about 600 m/s), corresponds to the location of caves or voids. The most significant depth slices (at -1.5 m and -3.0 m) were superimposed to the building a plan to better visualize the results (Fig. 3). It is thus possible to observe the evident lower Vp zone corresponding to a fracture in the bedrock. Moreover, at the deeper slice, the lower Vp zone could be related to a void below the western part of the building.

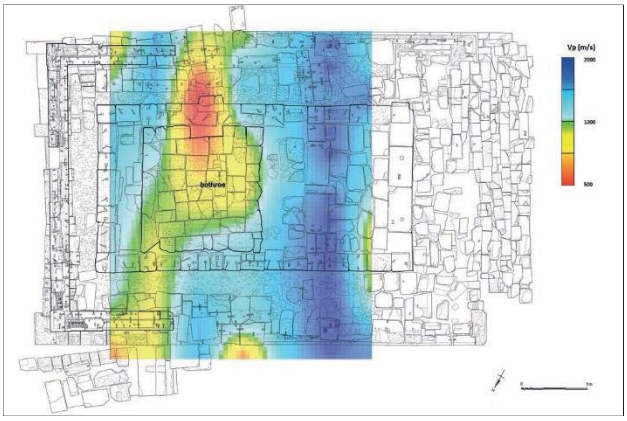

Fig. 3. Building A: seismic time slice at 4 m depth georeferenced on the monument plan.

Furthermore, seismic data were visualized as a complete volume, allowing the three-dimensional plotting of the data within pre-definable spatial limits (options x_{min}, ..., z_{max}) and an arbitrarily definable observation point (x°, y° and z°) superimposed with the iso-Vp surfaces. in this representation, the transparency function is defined by two threshold values of the velocity, Vp1 and Vp2 (Vp1 < Vp2). In the intervals Vp < Vp1 and Vp > Vp2, data are rendered as transparent. Therefore, only the data in the interval Vp1 < Vp < Vp2 are visualized. The seismic data set is displayed with iso-velocity surfaces (Fig. 4), using a threshold value ranging from 200 to 500 m/s. This Vp threshold value makes the possible location of the caves more evident.

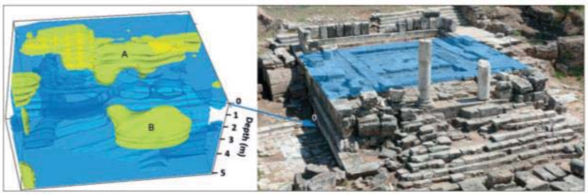

Fig. 4. Building A: 3D seismic refraction tomography: 3D visualization as contouring of iso-velocity surfaces (A-B: main voids in the bedrock below the podium).

The GPR prospecting was performed using a Sir2 by GSSi (500 MHz centre frequency antenna) on the Building A. Data were acquired in continuous mode along 0.5-m-spaced survey lines, using 512 samples per trace, 80 ns, and a manual time-varying gain function. The data were subsequently processed using standard two-dimensional processing techniques by means of the GPR-Slice Version 7.0 software [3]. The processing flow-chart consists of the following steps: (i) header editing for inserting the geometrical information; (ii) frequency filtering; (iii) manual gain, to adjust the acquisition gain function and enhance the visibility of deeper anomalies; (iv) customized background removal to attenuate the horizontal banding in the deeper part of the sections (ringing), performed by subtracting in different time ranges a "local" average noise trace, estimated from suitably selected time-distance windows with low signal content 5; (v) estimation of the average electromagnetic wave velocity by hyperbola fitting; (vi) Kirchhoff migration, using a constant average velocity value of 0.07 m/ns.

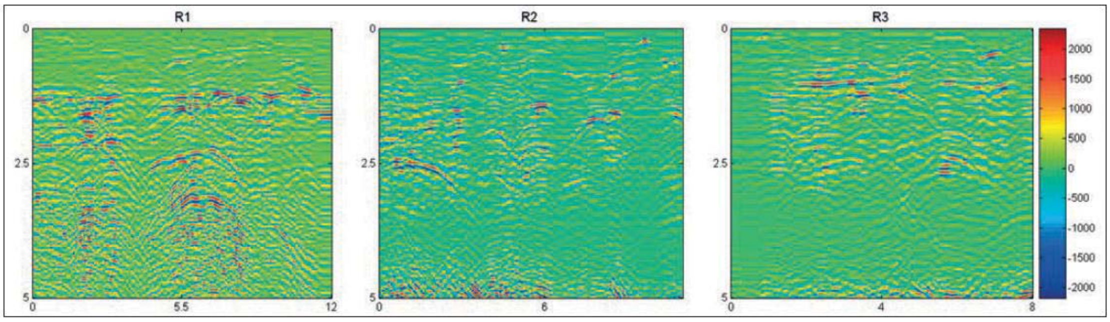

Fig. 5. Building A: GPR profiles (500MHz antenna) measured on the stylobates of the 1st cent. AD cella.

Three GPR profiles (r1, r2 and r3) were measured along the north, south and east stylobates of the Julio-Claudian Building A (Fig. 5). Particularly interesting are the hyperbolic reflection events showing an inversion of trace polarity. It is possible that these anomalies mark the interface between the building structure of the podium and the natural bedrock below.

Moreover, 11 GPR closely-spaced profiles were collected in the western sector of the building a. depth slices were obtained to produce a sequence of two dimensional plots showing the spatial variation in amplitude response for different depths. The thickness interval for each depth slice is 0.4 m. High-amplitude anomalies (Fig. 6 A) are related to cavities, confirming the hypothesis based on the SrT.

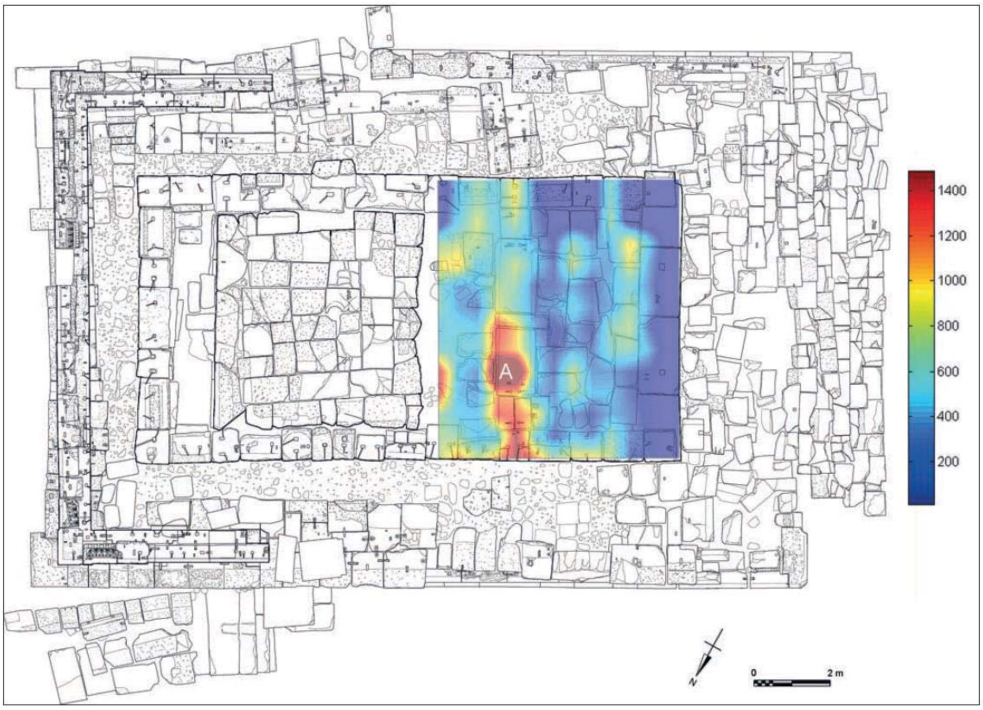

Fig. 6. Building A: GPR time slice (500MHz antenna) at 1.6-2 c depth, georeferenced on the monument plan.

III. CONCLUSIONS

In this paper, geophysical results within the Sanctuary of Apollo have been presented. This approach revealed the effectiveness of the integrated methods to identify a series of anomalies that could be ascribed to natural and anthropogenic features. Indeed, it is definitely probable that at least part of the anomalies is ascribable to remains of archaeological interest, and it is possible that some of them are ascribable to cavities and fractures in the subsoil linked to the seismic fault, because their apparent shape and size are comparable with other similar features frequently discovered in the area of Hierapolis.

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