Non-invasive Geophysical Surveys in Search of the Roman Temple of Augustus Under the Cathedral of Tarragona (Catalonia, Spain): A Case Study

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Abstract

An integrated geophysical survey has been conducted at the Tarragona's Cathedral (Catalonia, NE Spain) with the aim to confirm the potential occurrence of archaeological remains of the Roman Temple dedicated to the Emperor Augustus. Many hypotheses have been proposed about its possible location, the last ones regarding the inner part of the Cathedral, which is one of the most renowned temples of Spain (twelfth century) evolving from Romanesque to Gothic styles. A geophysical project including electrical resistivity tomography (ERT) and ground probing radar (GPR) was planned over 1 year considering the administrative and logistic difficulties of such a project inside a cathedral of religious veneration. Finally, both ERT and GPR have been conducted during a week of intensive overnight surveys that provided detailed information on subsurface existing structures. The ERT method has been applied using different techniques and arrays, ranging from standard Wenner–Schlumberger 2D sections to full 3D electrical imaging with the advanced Maximum Yield Grid array. Electrical resistivity data were recorded extensively, making available many thousands of apparent resistivity data to obtain a complete 3D image after a full inversion. In conclusion, some significant buried structures have been revealed providing conclusive information for archaeologists. GPR results provided additional information about shallowest structures. The geophysical results were clear enough to persuade religious authorities and archaeologists to conduct selected excavations in the most promising areas that confirmed the interpretation of geophysical data. In conclusion, the significant buried structures revealed by geophysical methods under the cathedral were confirmed by archaeological digging as the basement of the impressive Roman Temple that headed the Provincial Forum of Tarraco, seat of the Concilium of Hispania Citerior Province.

Keywords

Archaeological exploration, 2D and 3D ERT surveys, GPR Cathedral of Tarragona, Augustus Roman Temple

1 Introduction

The Cathedral of Tarragona is located on the higher platform of the ancient town (Fig. 1), and is believed to hide a huge imperial cult complex dedicated to Augustus. The cathedral has been investigated over the past 100 years through urban archaeology and the available archaeological information suggests that the temple could be situated under it. The imperial cult complex is supposed to consist of a rectangular square enclosed by a portico, with a temple dedicated to the Roman emperor in a prominent position (Macias et al. 2007). Many historical remains are still visible today offering plentiful information on the history of ancient Tarraco (Fig. 1).

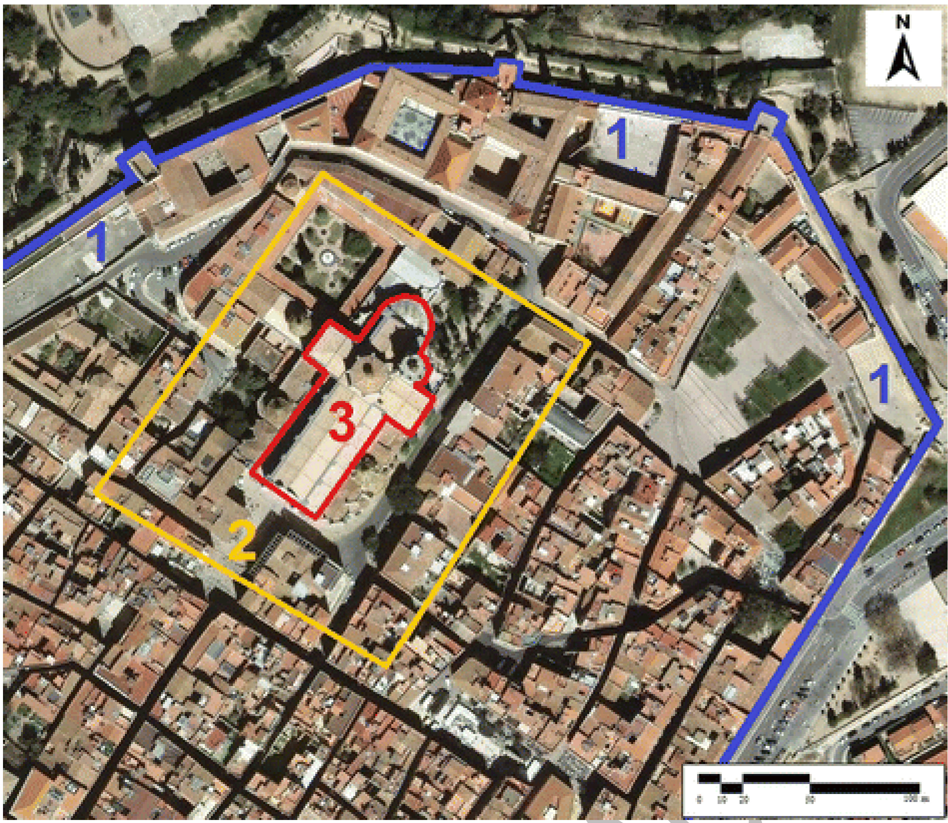

Figure 1. Map of the main archaeological references at Tarragona. 1 Cyclopean Roman wall. 2 Colonial Forum of Roman Tarraco. 3 Gothic Catholic Cathedral

The uncertainties on the location, shape, dimensions and depth of the remains, and the possible existence of other buildings between the temple (ca. first century AD) and the mediaeval cathedral (ca. twelfth century AD) led to a geophysical investigation programme.

The usefulness of geophysical techniques (e.g., DC current, electromagnetic, and magnetic methods) for archaeological investigation inside historical buildings is well known and has been reported in many papers, for instance Casas et al. (1995), Dabas et al. (1993, 2000), Pérez-Gracia et al. (2000), Carrara et al. (2001), Negri and Leucci (2006). Therefore, as the latest archaeological researches from Macias et al. (2007) assumed that there are remains of older buildings under the Medieval cathedral, related to the Roman emperor, a geophysical survey was considered—also taking into account the potential interest of the remains. The objective was to obtain a geophysical imaging of the archaeological remains existing in the subsoil without disturbing both the religious cult and the cultural visits to the cathedral.

On the other hand, the obtained results will be considered of interest to define some strategies in the future fourth phase of Director Plan for the Cathedral of Tarragona (Figuerola et al. 2002). The aim of the geophysical survey was to get as much information as possible on the structure and composition of the materials existing in the subsoil and, particularly, to detect remains of foundations of previous buildings. For this reason, a detailed geophysical mapping has been conducted.

2 Historical and Archaeological Outline

The city of Tarragona (Catalonia, NE Spain) is very rich in Roman remains, like the well-preserved Roman Wall that surrounds the historic centre, the Amphitheatre and dispersed vestiges of the Circus. In fact, since the III century B.C. Romans have occupied this space because of its strategic location in the Punic war against Hannibal, and, subsequently, to conquer Spain (Aquilué 2004). At the time of Emperor Augustus Tarraco was elevated to the rank of capital of the Provincia Hispania Citerior and a series of urban transformation began under the new rank. The historian Tacitus reports that in 15 AD a representation of citizens of Tarraco asked Tiberius for permission to erect a temple dedicated to the cult of Emperor Augustus. Epigraphic writings also refer to the existence of Concilium Provinciae Hispaniae, the highest provincial court. Most archaeological studies conducted to date agree in identifying the temple of Augustus at the site of the old acropolis of the city, which is currently occupied by the mediaeval cathedral of Tarragona. Archaeological studies in this site documented a sacred area of size 132.98 × 156.04 m surrounded by a portico of the mid first century AD. In front of the portico, there was a series of exedras dedicated to the cult, and a large axial hall about 27.6 m wide. The most recent historiography, as for instance, Aquilué (2004) and Macias et al. (2007), suggests that the square is more recent than the Temple of Augustus, while remaining unknown is the destination of the great axial hall: probably another place of cult or of meeting of the Concilium Provinciae.

Following the proclamation of Christianity as the official religion new laws were introduced that promoted the conversion of pagan areas into Christian places of worship. This urban transformation was found in the archaeological area of the cathedral of Tarragona starting from the fifth century.

Since the V century AD the Roman forum, with its buildings, had been progressively abandoned and spoiled. In fact, starting from the sixth century, dismantling operations of the portico are evident. Historiographical and archaeological evidences suggest the possibility that in this area a Visigothic church was built. This follows from the information given by the Codex Veronensis (a liturgical text of the eighth century) and from the presence in this zone of Visigoth tombs and decorative architectural elements of religious sculpture of the same period (Muñoz 2001).

The mediaeval cathedral was erected in the middle of the XII century inside the ancient Roman forum, after the Islamic domination. Since this time, the Cathedral has dominated the skyline of Tarragona and probably concealing in the subsoil some of the answers we need to recognize and understand the historical evolution of the city (Muñoz 2001). Therefore, as the latest archaeological researches assumed that there are remains of older buildings under the mediaeval cathedral, related to the Roman emperor, a geophysical survey was planned—also taking into account the potential interest of the remains.

The objective of the survey was to obtain a first picture of the archaeological remains existing in the subsoil without disturbing both the religious cult and the cultural visits to the temple. Thus, the subsurface of the cathedral could host the remains of religious buildings prior to construction of the Cathedral, which may be related to the Roman temple and to the Visigoth church. Given the importance of these remains and in order to provide continuity to archaeological work of the Directive Plan of the Cathedral of Tarragona, the Archbishopric and the Catalan Institute of Classical Archaeology have identified a need for the establishment of a geophysical survey in order to make a first determination of the existence of these archaeological structures in the subsurface of the Cathedral without interfering with the cults and visits to the church (Fig. 2).

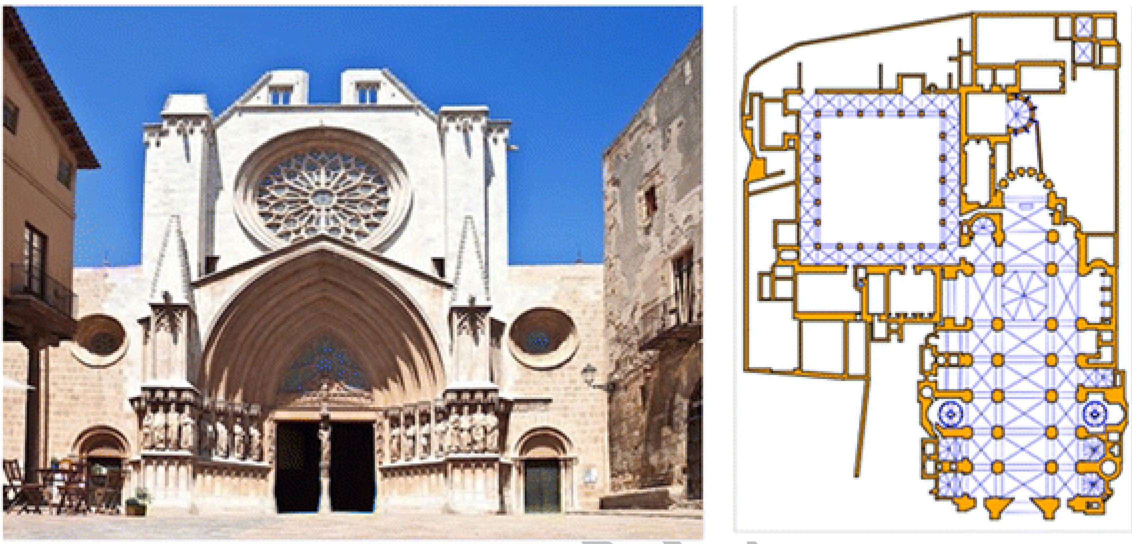

Figure 2. Main facade of the Gothic Cathedral of Tarragona (left side) and map of the cathedral including the cloister located at the left upper part (right side)

3 Geophysical Surveys

Taking into account preceding experiences in other similar surveys two complementary geophysical methods were planned: electrical resistivity tomography (ERT) and Ground Probing Radar (GPR).

3.1 ERT

The ERT method aimed to characterize the geometrical characteristics of the structures of the subsoil as a function of the electrical resistivity of the materials existing in the subsurface, which in turn depends on the porosity, clay content and water content. In archaeology and cultural heritage applications, ERT surveys have been successfully applied with different aims, such as the characterization of tumulus (Griffiths and Barker 1994; Wake et al. 2012), the location of buried voids, walls and foundations of monuments (Capizzi et al. 2007; Tsokas et al. 2011; Tsourlos and Tsokas 2011), the study of the geological or geomorphological assets of archaeological and monumental sites (Bottari et al. 2018; Ercoli et al. 2012; Capizzi and Martorana 2014). Its use has been frequently reported for the structural assessment and restoration of historic buildings built on older structures (Capizzi et al. 2012; Di Maio et al. 2012; Tsokas et al. 2008).

For this study, the ERT method was carried out performing both 2D and 3D analyses. In both cases, the practice for data acquisition was to apply a DC electrical current by means of two electrodes and to measure the electrical potential generated over two other electrodes placed along profiles (2D-ERT) or regular grids (3D-ERT) spaced 1 m apart over the pavement (Cosentino et al. 2009). 22 two-dimensional profiles and 4 three-dimensional grids were acquired (Fig. 3a).

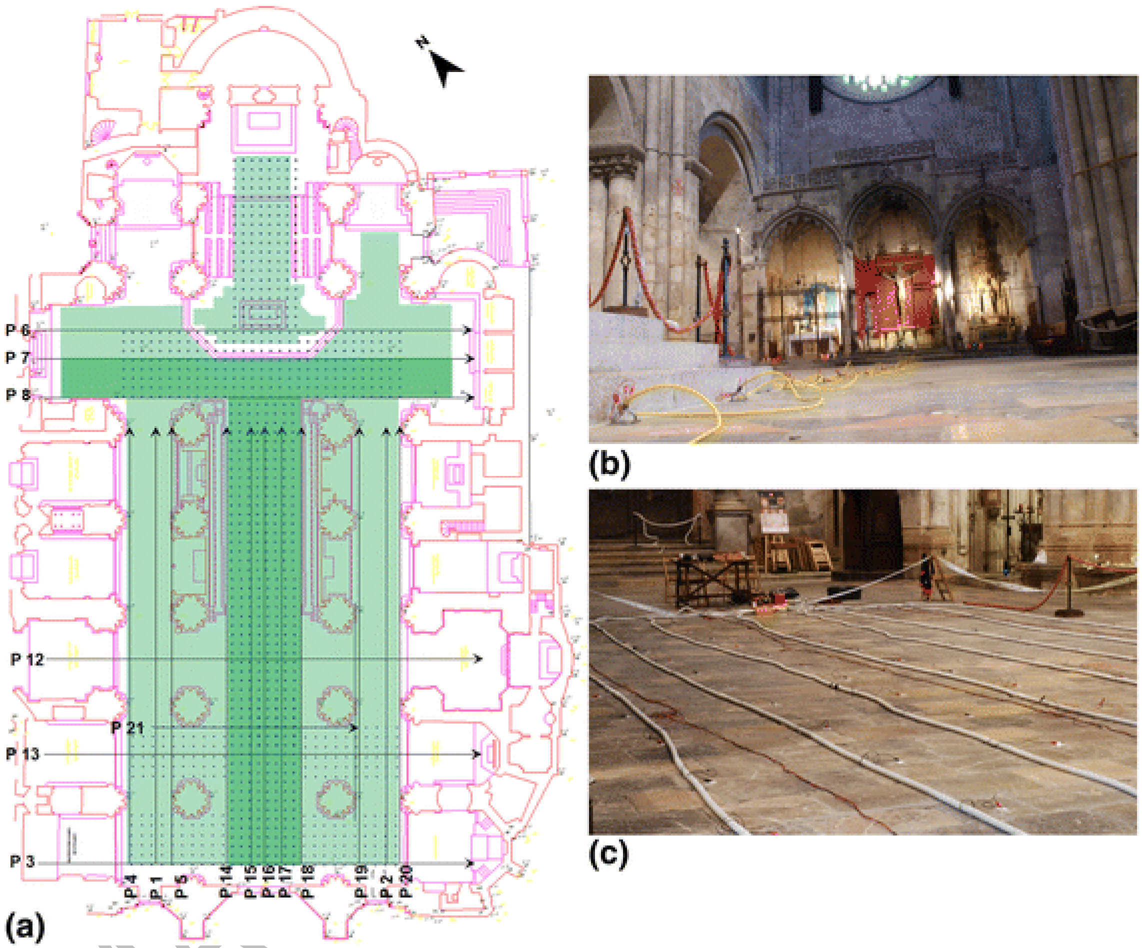

Figure 3. Map of the cathedral with location of the survey and ERT acquisition approaches. a black lines: 2D ERT profiles. Blue crosses: electrodes of the 3D ERT investigation. Light and dark green areas: Surface surveyed by GPR with 270 MHz centre-frequency antenna. Dark green area: Surface surveyed by GPR with only 100 MHz centre-frequency antenna. b Flat electrodes for 2D-ERT. c Foam Ag/AgCl electrodes for 3D-ERT

When in presence of lapideous tiles in the ground surfaces the use of metal spikes is unappropriated, because of both their invasiveness and the difficulty of injecting current and measuring potential. In these cases, the contact resistance between electrodes and ground floor can be much greater than the resistance of the subsurface. A suitable solution can be to insert current electrodes into small perforations on the surface in order to bypass the stone slab. Further solutions consist of using other types of electrodes. Current electrodes made by aluminium foil covered with soil soaked with salt water has been successfully used (Ward

1990). Flat-base electrodes have been used in stone surfaces or paved ground when stake electrodes cannot be inserted (Athanasiou et al. 2007; Tsokas et al. 2008; Cardarelli and Di Filippo 2009; Capizzi et al. 2012). In these cases, an electrically conductive gel is added between the electrodes and the surface to achieve a galvanic contact.

2D profiles were recorded both in transversal and longitudinal orientation, using a mixed Wenner–Schlumberger array of 48 electrodes, 1 m spaced (except for one profile, 0.5 m spaced). About seven thousand apparent resistivity values were acquired using an Iris Syscal Plus resistivity-metre with 48 channels, in a time of about 18 h. In order to avoid damage to the church floor, stainless steel flat-base electrodes were used (Fig. 3b), similar to those used by Athanasiou et al. (2007), while to decrease the contact resistances a conductive gel was placed between the metallic electrodes and the soil pavement; with this strategy, the contact resistances were set below 10 kΩ.

3D ERT was acquired using the Maximum Yield Grid (MYG) array (Fiandaca et al. 2010). This methodology has been developed with the aim of reducing the number of electrodes of the acquisition grid used for current injection, maintaining the resolution power of any other equivalent classical methodology. The approach of the MYG methodology is similar, in a 3D context, to the 2D Linear Grid Array (Martorana et al. 2009), and of the Multiple Gradient Array (Dahlin and Zhou 2006; Martorana et al. 2017). Small steel nails (diameter = 2 mm and length = 60 mm) were used for current injections, while for potential measurements, foam Ag/AgCl electrodes (Fig. 3c), typically applied for electrocardiogram (ECG) clinical tests, were used. The same choice for the electrodes has produced excellent results in previous electrical resistivity surveys carried out with the MYG array (Cosentino et al. 2009; Fiandaca et al. 2010).

In MYG methodology, only some electrodes (about 1/15 of the total) are used as current electrodes, greatly reducing measuring time. For each current electrode pair, the potential measurements are contemporary acquired by selecting those MN dipoles of foam Ag/AgCl electrodes, approximately aligned with the directions of electrical field in a homogeneous environment (Fig. 4). In this way, the measurement sequence is optimized to improve resolution and to reduce noise.

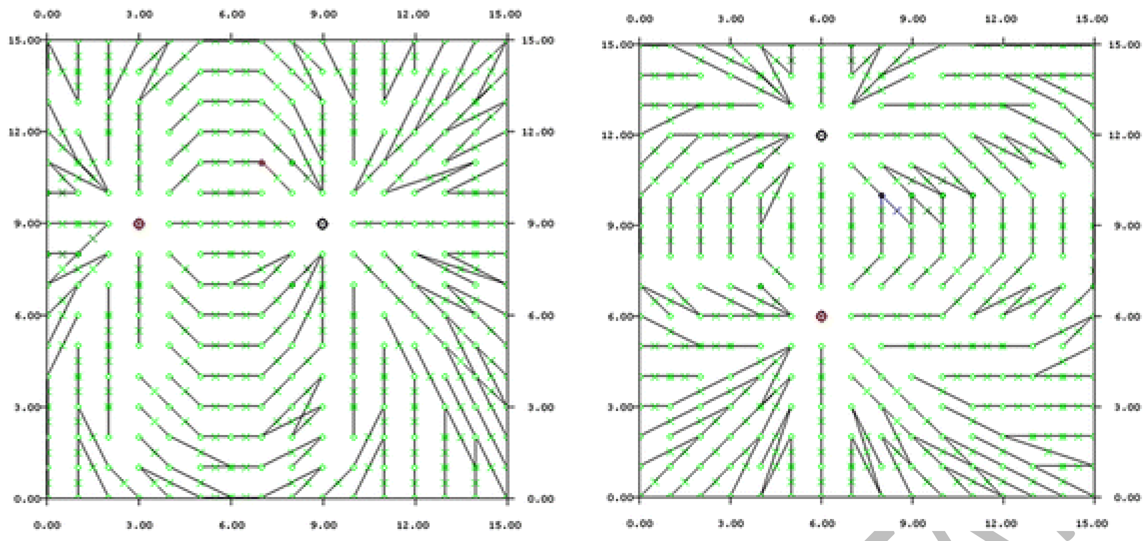

Figure 4. MYG array: two examples of choice of potential dipoles for a 16 × 16 grid. Green circles are the potential electrodes; red and black circles are the current electrodes; black segments represent the potential dipoles, approximately aligned with the electrical field of a homogeneous subsurface

Compared to the 2D case, however, the arrangement of the current electrodes for improving the resolution of the array is much more complex: in fact, the multiplicity of arrangements is much higher than that along a profile. The MYG array has an important characteristic of intrinsic “robustness”: in fact, the choice of different current dipoles, while conditioning the resolution, is not particularly critical in terms of stability of the results. Moreover, if the coverage of the current dipoles is properly homogeneous, the spatial resolution is generally acceptable (Fiandaca et al. 2010).

For the MYG array with an acquisition grid composed of N electrodes, each current input is associated to N-2 apparent resistivity measurements. In a 16 × 16 mesh, however, a good overall resolution can be obtained using 20–25 distinct current dipoles, for a total of about 5000–6000 apparent resistivity measurements. On the other hand, using the linear dipole–dipole array on the same mesh with a maximum order n = 13 (the highest allowed for 16 aligned electrodes), just over 4400 measurements can be carried out, but with a much larger survey time.

Four rectangular grids were disposed on the floor of the cathedral (Fig. 3a). The main grid includes 512 electrodes, disposed in 8 × 64 mesh, and covered most of the central nave. The other three grids, each comprising 256 electrodes and disposed 8 × 32 meshes, were arranged orthogonally to the main grid to cover the floor in the area adjacent to the main entrance and the transept in front of the altar. All electrodes were spaced by 1 m.

Overall 1280 electrodes were used as potential ones, while only 82 electrodes were used to inject current. The MYG array allowed the use of only 340 different current dipoles to collect more than 80.000 apparent resistivity measurements, with significant time saving in the acquisition. The large amount of data, produced by multielectrode systems, required automated data handling and processing. After the removal of the outliers (about 10.000 data), all the remaining measurements were simultaneously inverted for each of the four grids.

The MRS-256 system (GF Instruments, Brno) has been used for 3D-ERT measurements. This system comprises a module for current transmission and a module for multichannel potential measurements. These parts are connected and synchronized with a laptop computer that manages the measurement sequence. The potential module is connected to potential electrodes through multichannel cables and allows up to 256 simultaneous measurements. In the MRS-256 system, the input impedance is 10 G ohm for each channel: in this way, errors due to high contact resistances, typical when in presence of lapideous surfaces, are minimized. At least, four replicates for each resistance measurement were carried out. An electromotive force of 560 V was generally applied between current electrodes, allowing a good signal-to-noise ratio. In some cases, lower voltages were applied in the field (typically 140 or 280 V) when the potentials at the measuring electrodes imposed by the current flow exceeded the measure range.

The software used for ERT inversions was RES2DINV and RES3DINV (Geotomo Software). The large amount of data produced by multielectrode systems requires automated data handling and processing. An appropriate filtering on 3D-ERT data was needed in order to identify and eliminate the outliers. The inversion method is based on the smoothness-constrained least-squares method. In this method, the subsurface is divided into cells of fixed dimensions for which the resistivities are adjusted iteratively until an acceptable agreement between the input data and the model responses is achieved, based on a nonlinear optimization technique by least-squares fitting (Loke and Barker 1996). During the inversion process, the root-mean-square value of the difference between experimental data and the updated model response is used as a criterion to assess the convergence. The robust least-squares method was selected because it assumes that the subsurface consists of a few homogeneous regions with a sharp interface between them. Such an inversion scheme is the logical choice where the subsurface comprises units with sharp boundaries in order to determine both layer boundary locations and layer resistivities accurately. Indeed, it produces models by minimizing the absolute value of data misfit, making it more efficient in removing noise compared to the other inversion methods. In all models, the same damping factor was used, with the initial and minimum values set to 0.15 and 0.03, respectively. After five iterations, the models reached the desired convergence limits lower than 2.0%, which are within the suggested value range of data misfit.

3.2 GPR

GPR technique (Davis and Annan 1989; Annan 2009) uses EM waves, generally in the frequency range of 10–3000 MHz, to detect hidden structures from reflections and amplitude variations produced by dielectric permittivity changes in the subsurface. In the GPR method, individual traces are used to produce reflection profiles. In recent years, the use of soil penetration radar (GPR) for archaeological interpretation has evolved from an interpretation of two-dimensional reflection profiles to a three-dimensional mapping to study larger areas of the subsoil (Conyers 2013, 2015; Goodman and Piro 2013). In archaeological application can be convenient a rearrangement of GPR data of a 3D dataset in time slices, i.e. horizontal maps of reflection anomalies at different reflection times (Goodman and Nishimura 1993), or isosurface rendering showing equal amplitude surfaces (Linford 2014).

The GPR survey used a Subsurface Interface Radar System (SIR 3000) manufactured by Geophysical Survey Systems, GSSI, with two shielded antennas with centre frequencies of 270 and 100 MHz. Most of the survey used the 270 MHz antenna, because the resolution obtained with the 100 MHz antenna was too low to be effective. Appropriate data processing stacking, filtering, migration and advanced visualization techniques were applied to help in understanding and interpreting GPR data. In addition, to obtain a significant "picture" of the underground electromagnetic discontinuities, both 3D data collection along closely spaced parallel survey lines, with sufficient spatial sampling to reduce aliasing problems, and time-consuming 3D data processing were required.

The surface of the temple was surveyed by a grid of profiles spaced 0.4 m apart and a horizontal resolution of 0.02 m (50 scans per metre in all the survey). Due to the need of having a greatest resolution on the central aisle, a perpendicular grid was traced in order to obtain records in both directions. In Fig. 3a, the portion of the plan with light green colour represents the investigated area with a 270 MHz antenna, while the darker green zone was studied with both 100 and 270 MHz antennae. Close parallel profiles allowed the assembly of GPR time slices, which made it easy to correlate anomalies recorded at the same time. This is one of the most useful data presentations for understanding the nature of subsurface structures over large areas at different depths (Goodman et al. 1995). Depths were calculated from an approximate velocity analysis based on the geometry of hyperbolae.

4 Geophysical Results

4.1 ERT Method

The subsurface images obtained from this geophysical survey give us an idea of the archaeological potentiality of the use of combined methodologies after adequate data processing.

The inverted cross sections of the twenty 2D-ERT profiles show very high electrical resistivity contrasts ranging between 20 and 5000 Ω m. According to the values of electrical resistivity, three layers can be clearly distinguished in most of the cross sections: an upper layer is 1.5 m thick and of low electrical resistivity (about 100 Ω m), an intermediate layer of very high resistivity which extends as a continuous slab up to almost 4 m of depth, and a bottom layer of again low resistivity values. An example of this distribution is shown in profiles of Fig. 5a, which highlights the existence of the high electrical resistivity layer both in longitudinal and transverse profiles. The abrupt change of electrical resistivities in the longitudinal profile after 14 m from its origin (close to the wall of the main façade of the cathedral) is interpreted as one of the boundaries of the foundations of the Roman temple (Fig. 5b). This interpretation is reinforced by the occurrence of this limit in all parallel longitudinal profiles acquired along the central nave of the cathedral. The low electrical resistivity values that appear at the beginning all the longitudinal 2D-ERT profiles can be associated with clay sediments.

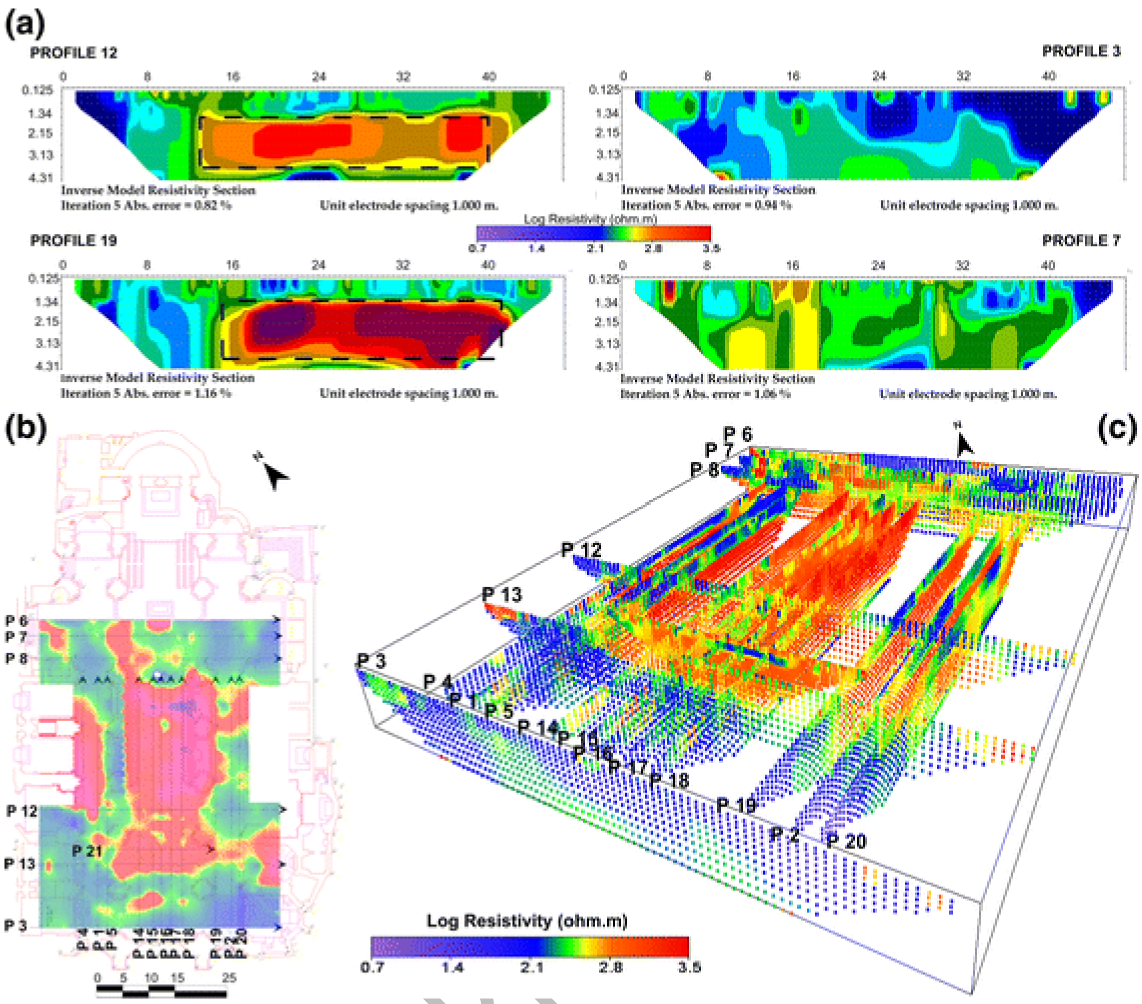

Figure 5. Results obtained from 2D-ERT array. a Four examples of 2D-ERT inverted cross sections of profiles 12, 19, 3 and 7 (for location see Fig. 3a). b Horizontal depth-slice of electrical resistivity changes at − 2.5 m below the surface from 2D-ERT data. c Three-dimensional distribution of electrical resistivities from 2D inversions

A 3D resistivity model has been created by inverting the four datasets acquired with the MYG methodology (Fig. 6). This model extends throughout the central aisle, for much of the area adjacent to the main entrance and the zone of the transept in front of the altar. In the central aisle, the survey depth reaches about 10 m. The results of the 3D-ERT inversion confirm those obtained from the 2D-ERT. The comparison between some 2D sections made in the central aisle and the corresponding vertical sections extracted from the 3D-ERT demonstrates that all the main anomalies shown by the 2D imaging are equally visible in the 3D model. In all sections, an elongated resistive zone is clearly visible. It extends from depths of about 0.5 m to about 3 m. The electrical resistivity values of this structure generally range between 1000 and 1500 Ω m, although in some areas at depths lower than 2.5 m it can reach 5000 Ω m. At depths greater than 4 m, the resistivity becomes much lower (between 50 and 200 Ω m). The high resistivity anomaly is visible in all sections carried out in parallel direction to the main aisle of the church and laterally extends from x = 14 m to the end of the sections.

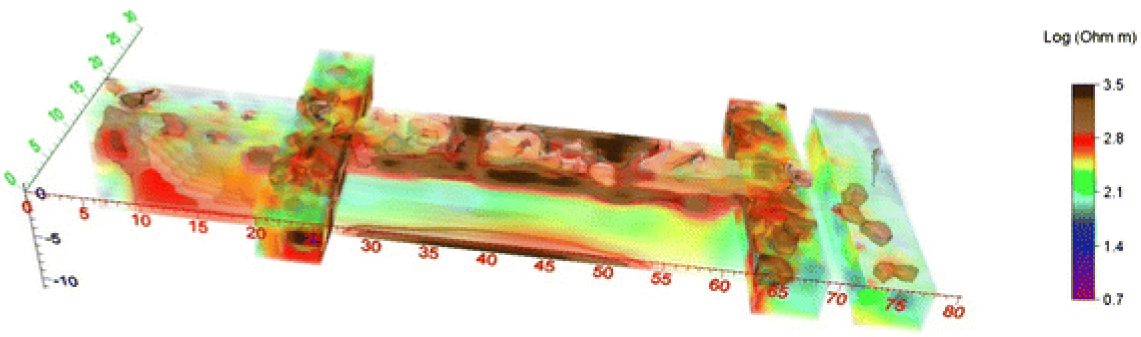

Figure 6. 3D model obtained from the inversion of full 3D-ERT data

Observing the distribution of high resistivity anomalies through horizontal slices at different depths (Fig. 7), the lateral limits of the supposed basement of the Roman Temple are clearly visible up to z = 3 m. Below this depth, the base rests on rocks which resistivity ranges from 50–100 Ω m below the right aisle, to 400–500 Ω m below the left aisle.

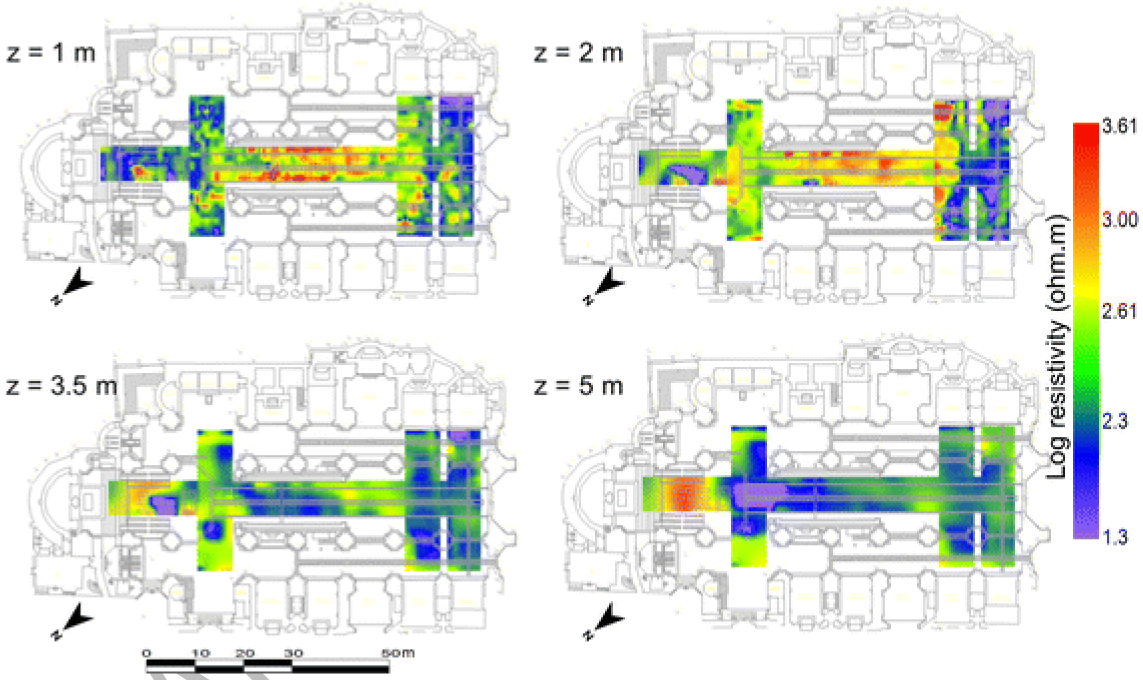

Figure 7. Horizontal depth-slides of 3D ERT inverse model

4.2 GPR Method

GPR analysis showed the existence of an archaeological stratigraphy. Data analysis suggested depth alterations or differences between the central and the lateral aisles, as well as between the central aisle and the main entrance to the mediaeval temple (Fig. 8). A general characteristic of all the surveyed area is the good penetration of the electromagnetic energy, 100 ns corresponding to a depth of about 4.0 m when a mean velocity value of 0.08 m/ns is used. This is essentially due to the physical characteristics of the materials used for the construction of the temple (limestone), which have high resistivity values and therefore dissipate the EM energy only slightly. In spite of the clarity of some of the described structures, it must be pointed out that their vertical projections are irregular. This would indicate a reuse of preexisting elements for the erection of the building and an irregular condition of preservation.

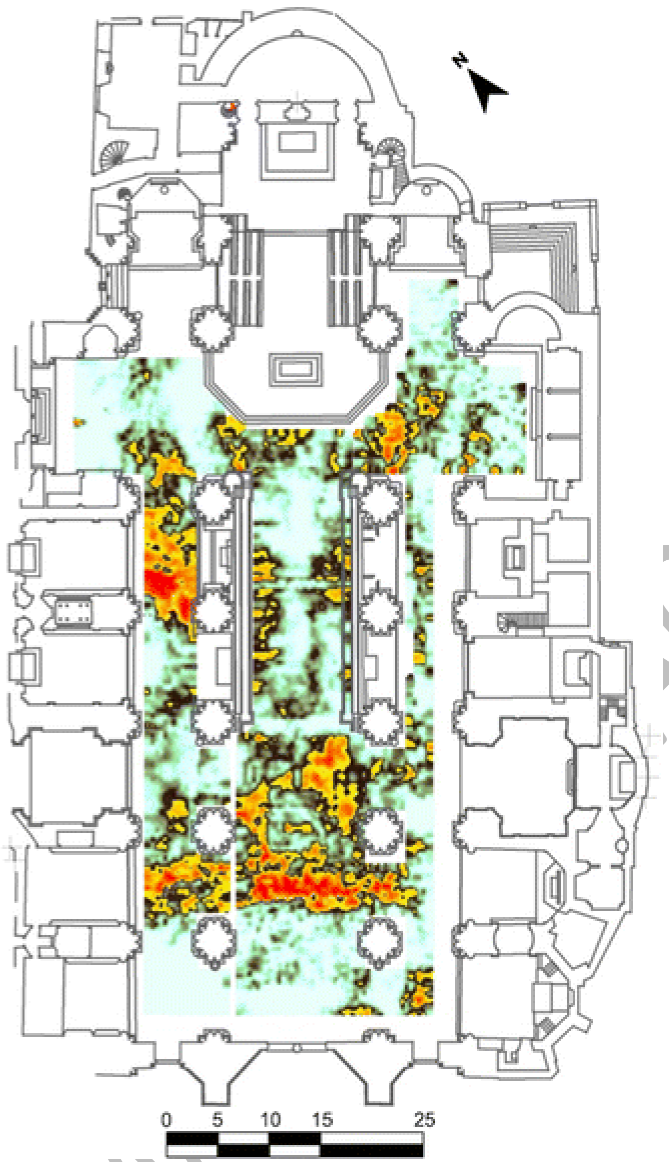

Figure 8. Time slice at a depth about 1.0–1.2 m (23.9–28.8 ns) derived from GPR signals recorded with the 270 MHz antena

In addition, a detailed GPR survey has been carried out in the area around the altar with the same 270 MHz antenna. The result of the treatment of the amplitudes and the construction of corresponding time-slice sections has made it possible to identify clearly individual anomalies, which by their size, shape and distribution are interpreted as tombs (Fig. 9).

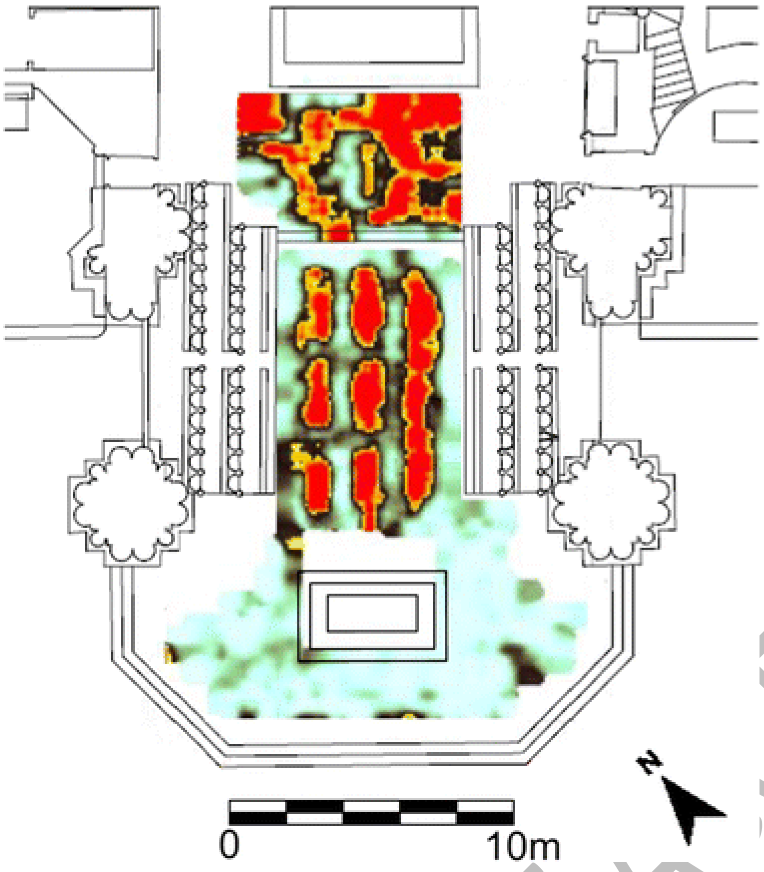

Figure 9. Time slice at a depth about 0.3–0.5 m (8–12 ns) derived from GPR signals recorded with the 270 MHz antenna around the altar showing the anomalies interpreted as tombs

5 Archaeological Results

The archaeological interpretation of the geophysical evidence started after all data was handled and plotted. One of the first points examined was a very high electrical resistivity anomaly (more than 2000 Ω m) detected in some of the transversal ERT profiles, which was interpreted as corresponding to a cavity filled with air. The archaeological investigation of the subsurface at this point revealed the existence a sewer probably built by the Romans to drain water from the vast square that constituted the Imperial Forum (Fig. 10).

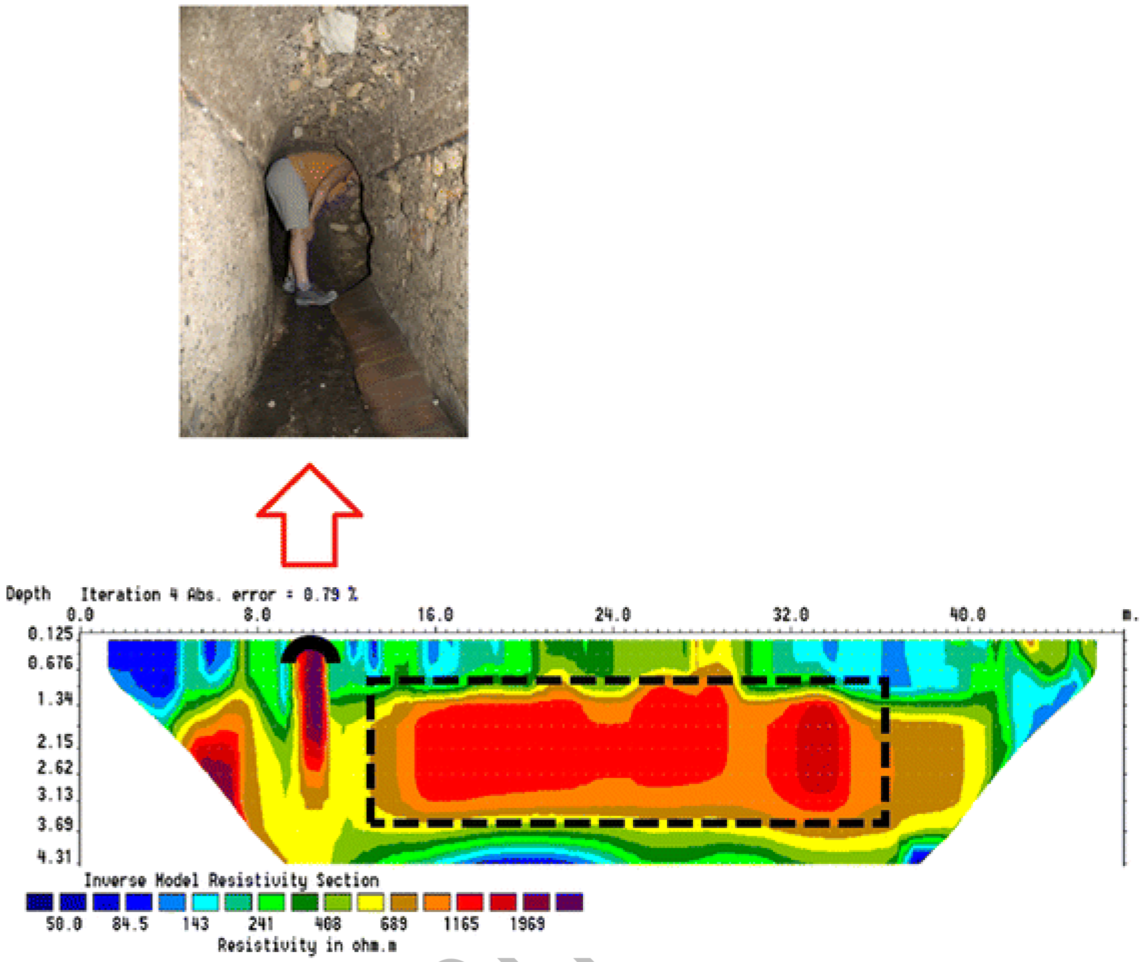

Figure 10. 2D-ERT transversal cross section showing the high resistivity anomaly coincident to the Roman sewer and the high resistivity slab interpreted as the foundation of the Roman Temple

Two selected archaeological digs were successively planned and executed with the aim to confirm the geophysical evidence. The first one, covering 30 m2, was sided in the longitudinal axis of the Cathedral, just on the southern boundary of the prominent electrical resistivity anomaly, with the aim of verifying its source. The second archaeological excavation covering a surface of 55 m2 following the same longitudinal axis of the seat; this time next to the presbytery with the intention to meet the remains of the foundations of the Roman temple.

The archaeological excavations confirmed the origin of the geophysical anomalies. In particular, the existence of the great platform of opus caementicium interpreted as the basement of the Roman temple in honour to the Emperor Augustus, and remains of mediaeval walls probably corresponding to religious buildings of the Visigoth period, before the construction of the Romanesque Cathedral (Fig. 11a).

Figure 11. a Archaeological dig revealing the foundations of the Roman Temple and walls of Mediaeval buildings (left). b Borehole machine drilling inside the cathedral (right)

As the archaeological excavations could not follow the penetration in the subsurface due to the hardness of a slab of concrete, the use of a geotechnical drilling machine was planned to traverse the structure (Fig. 11b). Two boreholes (SR1 and SR2) were drilled inside the first archaeological excavation one of them over the concrete slab. The first borehole (SR1) was placed closer to the main entrance of the Cathedral above the low resistivity zone interpreted as clay sediments out of the concrete slab, and the second one (SR2) was placed over the high resistivity slab interpreted as the basement of the Temple.

Borehole SR1 started at − 0.9 m below the ground surface and drilled clayey unconsolidated sediments until a depth of − 5.1 m where a limestone substrate was detected. Borehole SR2 started at—1.2 m below the ground surface over the concrete slab and drilled 2.3 m of opus caementicium concrete reaching below first a clay layer and after the limestone substrate. The correlation between the longitudinal 2D-ERT cross section, and the logs obtained from the boreholes confirmed the archaeological interpretation and the finding of the foundations of the Roman temple (Fig. 12).

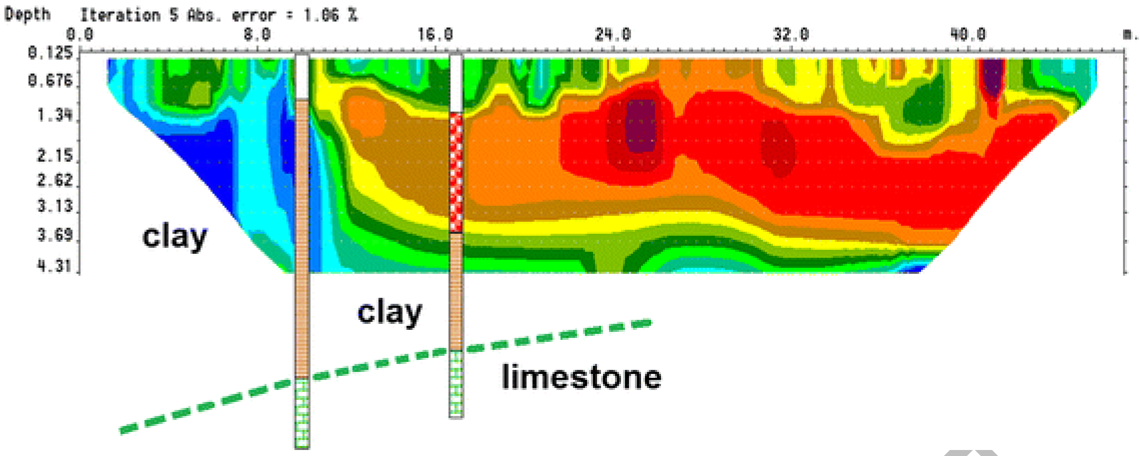

Figure 12. Correlation between a longitudinal 2D-ERT cross section recorded at the centre nave of the cathedral and the results of two boreholes (SR1 and SR2). Note that below the concrete slab, a clayey layer exists, confirming the low resistivity layer depicted in the 2D-ERT cross section

6 Discussion

The noticeable geophysical anomaly that extends through the central nave of the Cathedral of Tarragona has been interpreted as the foundation slab of the Roman Temple. Therefore, the precise location of August Temple, a cause of debate since the 16th century, is definitively confirmed.

Combining geophysical data and boreholes with the archaeological evidence, a rectangular platform of 27 × 39.75 m and around 2.30 m thick has been detected. The later limit of the foundation is most imprecise, maybe 7 m more in length, since it concludes below the current altar of the Cathedral. The approximate size achieved for the slab as foundation of the temple fits well within the models of octastyle temples, with an eight-columned frontage, as is represented on contemporary coins (Fig. 13). However, current archaeological research shows that the Roman temple construction was both historical and urban complex process (Macias et al. 2014; Peña et al. 2015). This nucleus rests upon a bed of compacted strata of clay, over rock. This massive base was probably covered by a second structure of stone, opus quadratum. The podium of the temple made in marble from Carrara quarry and the second base of stone were dismantled between five and sixth centuries AD. After being studied and documented, the remains were protected and covered again by the mediaeval pavement of the Cathedral.

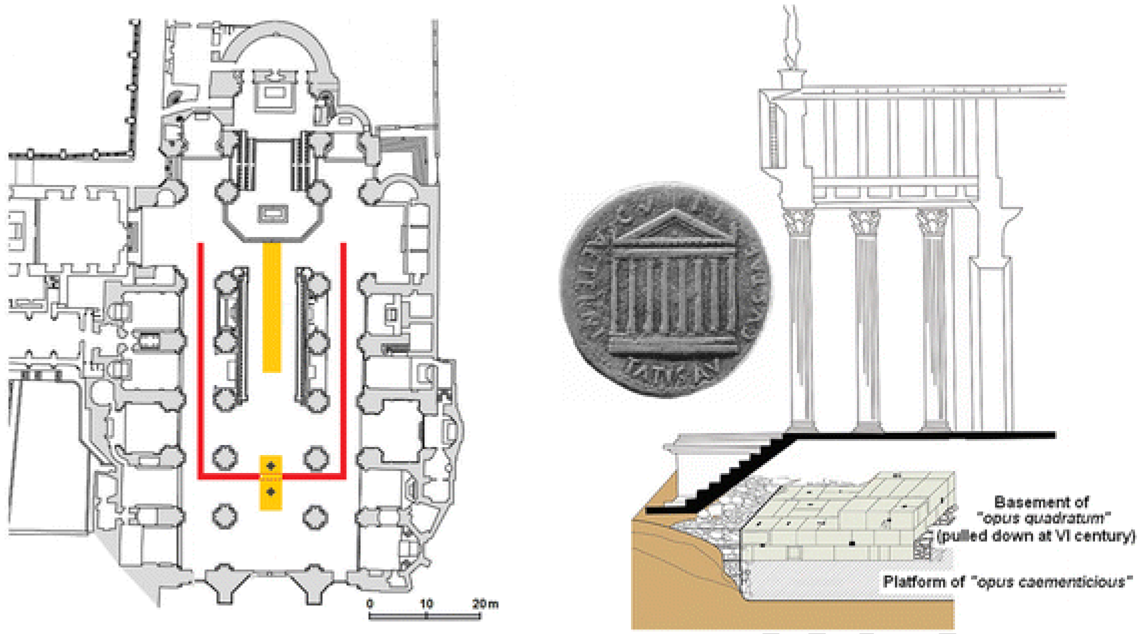

Figure 13. At left: Location of archaeological excavations (yellow areas), boreholes (black dots) and basement of the August's (red rectangle) in the central part of the Roman Forum and almost coincident with the central nave of the Cathedral. At right: Idealized image of the temple based on the archaeological results and the image of one side of a Roman coin

7 Conclusions

The identification of the location and size of the foundations of the Roman Temple of Augustus have been accomplished based on the comparative study between selective archaeological excavation and geophysical anomalies. The structure of the temple's basement has been revealed using both 2D and 3D electrical imaging technique as well as with the GPR survey. The models derived from the inversion of experimental data show the existence of a very high resistivity anomaly beneath the floor that extends up to 4 m. The horizontal limits of the high resistivity anomalies, probably correlated to the extension of the temple basement, are recognizable also in some of the GPR time slices.

The archaeological evidence from the selected excavations have confirmed the effectiveness of the different geophysical methods in mapping the archaeological features in Tarragona's Cathedral. The 2D and 3D models obtained under the Cathedral of Tarragona will play an important role in future archaeological investigations since they have furnished a synthetic view of the location and sizes of the most important structures in the area.

The results indicate that the use of flat-base electrodes—instead of standard spiked electrodes—is a very good alternative in sites where the floor surface cannot be bored. It provides the advantage of fully non-destructive application and the expansion of using geoelectrical methods in environments that otherwise we would never consider. The structure of the temple basement seems to be revealed both using 2D and 3D electrical imaging techniques. Moreover, the MYG array gave results in accordance with the classical Wenner–Schlumberger 2D array, but with greater time efficiency and the advantage, in terms of resolution, of a 3D investigation. Furthermore, the anomalous areas detected by the different geophysical techniques are very consistent.

Notes

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References

- Annan P (2009) Electromagnetic principles of ground penetrating radar. In: Jol HM (ed) Ground penetrating radar: theory and applications. Elsevier, New York, pp 3–40

- Aquilué X (2004) Arquitectura oficial. In: Dupré Reventós X (ed) Tarragona. Colonia Iulia Urbs Triumphalis Tarraco, Las capitales provinciales de Hispania 3. L'Erma di Bretschneider, Rome, pp 41–53

- Athanasiou E, Tsourlos P, Tsokas G, Papazachos C, Vargemezis G (2007) Nondestructive DC resistivity surveying using flat base electrodes. Near Surf Geophys 5:263–272

- Bottari C, Albano M, Capizzi P, D'Alessandro A, Doumaz F, Martorana R, Moro M, Saroli M (2018) Recognition of earthquake-induced damage in the Abakainon necropolis (NE Sicily): results from geomorphological, geophysical and numerical analyses. Pure Appl Geophys 175(1):133–148

- Capizzi P, Martorana R (2014) Integration of constrained electrical and seismic tomographies to study the landslide affecting the Cathedral of Agrigento. J Geophys Eng 11(4):045009

- Capizzi P, Cosentino PL, Fiandaca G, Martorana R, Messina P, Vassallo S (2007) Geophysical investigations at the Himera archaeological site, northern Sicily. Near Surf Geophys 5(6):417–426

- Capizzi P, Martorana R, Messina P, Cosentino PL (2012) Geophysical and geotechnical investigations to support the restoration project of the Roman 'Villa del Casale', Piazza Armerina, Sicily, Italy. Near Surf Geophys 10(2):145–160

- Cardarelli E, Di Filippo G (2009) Integrated geophysical methods for the characterisation of an archaeological site (Massenzio Basilica—Roman forum, Rome, Italy). J Appl Geophys 68(4):508–521

- Carrara E, Carrozzo MT, Fedi M, Florio G, Negri S, Paoletti V, Paolillo G, Quarta T, Rapolla A, Roberti N (2001) Resistivity and radar surveys at the archaeological site of Ercolano. J Environ Eng Geophys 6(3):123–132

- Conyers LB (2013) Ground-penetrating radar for archaeology, 3rd edn. Rowman and Littlefield Publishers, Alta Mira Press, Lanham

- Conyers LB (2015) Analysis and interpretation of GPR datasets for integrated archaeological mapping. Near Surf Geophys 13(6):645–651

- Cosentino P, Capizzi P, Fiandaca G, Martorana R, Messina P (2009) Advances in microgeophysics for engineering and cultural heritage. J Earth Sci 20(3):626–639

- Casas A, Pinto V, Rivero L, Camerlink C, Dabas, M (1995) Urban Geophysics: The case of Cathedrals and other religious monuments. In: Proceedings of the XX European geophysical society general meeting, Hamburg (Germany)

- Dabas M, Stegeman C, Hesse A, Jolivet A, Mounir A, Casas A (1993) Prospection de la Cathédrale de Chartres. Bull Soc Arch d'Ellre el Loir 36:5–24

- Dabas M, Camerlynck C, Camps PFI (2000) Simultaneous use of electrostatic quadrupole and GPR in urban context: investigation of the basement of the Cathedral of Girona (Catalunya, Spain). Geophysics 65(2):526–532

- Dahlin T, Zhou B (2006) Multiple gradient array measurements for multi-channel 2D resistivity imaging. Near Surf Geophys 4(2):113–123

- Davis JL, Annan AP (1989) Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophys Prospect 37:531–551

- Di Maio R, Meola C, Grimaldi M, Pappalardo U (2012) New insights for conservation of Villa Imperiale (Pompeii, Italy) through nondestructive exploration. Int J Architect Herit 6(5):562–578

- Ercoli M, Pauselli C, Forte E, Di Matteo L, Mazzocca M, Frigeri A, Federico C (2012) A multidisciplinary geological and geophysical approach to define structural and hydrogeological implications of the Molinaccio spring (Spello, Italy). J Appl Geophys 77:72–82

- Fiandaca G, Martorana R, Messina P, Cosentino PL (2010) The MYG methodology to carry out 3D electrical resistivity tomography on media covered by vulnerable surfaces of artistic value. Il Nuovo Cimento B 125(5–6):711–718

- Figuerola J, Gavaldà J, Menchón J, Teixell I, Muñoz A, Macias JM (2002) La catedral de Tarragona: obres de restauració i treball arqueològic", VIIè Col·loqui Conservar i restaurar: arqueologia i arquitectura. Amics del Romànic. Lambard. Estudis d'Art Medieval XIV, Barcelona, pp 75–107

- Goodman D, Nishimura Y (1993) Ground radar view of Japanese burial mounds. Antiquity 67:349–354

- Goodman D, Piro S (2013) GPR remote sensing in archaeology, geotechnologies and the environment series, vol 9. Springer, New York

- Goodman D, Nishimura Y, Rogers JO (1995) GPR time-slices in archaeological prospection. Archaeol Prospect 2:85–89

- Griffiths DH, Barker RD (1994) Electrical imaging in archaeology. J Archaeol Sci 21(2):153–158

- Linford N (2014) Rapid processing of GPR time slices for data visualisation during field acquisition. In: Lambot S, Giannopoulos A, Pajewski L, André F, Slob E, Craeye C (eds) Proceedings of the 15th international conference on ground penetrating radar. Square Brussels Meeting Centre, pp 731–735

- Loke JH, Barker RO (1996) Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophys Prospect 44:131–152

- Macias JM, Menchón JJ, Muñoz A, Teixell I (2007) Excavaciones en la Catedral de Tarragona y su entorno: avances y retrocesos en la investigación sobre el culto Imperial. In: Culto Imperial: política y poder, Proceedings of the International Meeting (Mérida 2006), L'Erma di Bretschneider, Roma, pp 765–787

- Macias JM, Muñoz A, Peña A, Teixell I (2014) El templo de Augusto en Tarraco: últimas excavaciones y hallazgos. In: XVIII congreso internacional arqueología clásica centro y periferia en el mundo clásico. XVIII CIAC: Centro y periferia en el mundo clásico (Mérida 2013), Mérida, pp 1539–1543

- Martorana R, Fiandaca G, Casas A, Cosentino PL (2009) Comparative tests on different multi-electrode arrays using models in near-surface geophysics. J Geophys Eng 6(1):1–20

- Martorana R, Capizzi P, D'Alessandro A, Luzio D (2017) Comparison of different sets of array con-figurations for multichannel 2D ERT acquisition. J Appl Geophys 137:34–48

- Muñoz A (2001) El Cristianisme a l'Antiga Tarragona. Dels orígens a la incursió islàmica. In: Institut Superior de Ciències Religioses Sant Fructuós. Tarragona

- Negri S, Leucci G (2006) Geophysical investigation of the Temple of Apollo (Hierapolis, Turkey). J Archaeol Sci 33:1505–1513

- Peña A, Gorostidi D, Macias JM, Muñoz A, Rodà I, Teixell I (2015) Más datos sobre el templo del Divus Augustus de Tarraco: a propósito de una nueva inscripción. In: August i les províncies occidentals, 2n Congrés Internacional d'Arqueologia i Món Antic (2014), Tarragona, pp 181–189

- Pérez-Gracia V, Canas JA, Pujades L, Clapés J, Caselles O, García F, Osorio R (2000) GPR survey to confirm the location of ancient structures under the Valencian Cathedral (Spain). J Appl Geophys 43:167–174

- Tsokas GN, Tsourlos PI, Vargemezis G, Novack M (2008) Non-destructive electrical resistivity tomography for indoor investigation: the case of Kapnikarea church in Athens. Archaeol Prospect 15(1):47–61

- Tsokas GN, Tsourlos PI, Vargemezis GN, Pazaras NT (2011) Using surface and cross-hole resistivity tomography in an urban environment: an example of imaging the foundations of the ancient wall in Thessaloniki, North Greece. Phys Chem Earth 36(16):1310–1317

- Tsourlos PI, Tsokas GN (2011) Non-destructive electrical resistivity tomography survey at the south walls of the Acropolis of Athens. Archaeol Prospect 18(3):173–186

- Wake TA, Mojica AO, Davis MH, Campbell CJ, Mendizábal T (2012) Electrical resistivity surveying and pseudo-three-dimensional tomographic imaging at Sitio Drago, Bocas del Toro, Panama. Archaeol Prospect 19(1):49–58

- Ward SH (1990) Resistivity and induced polarization methods. In: Ward SH (ed) Geotechnical and environmental geophysics. Investigations in geophysics no 5. SEG, Waterville Valley, pp 147–190