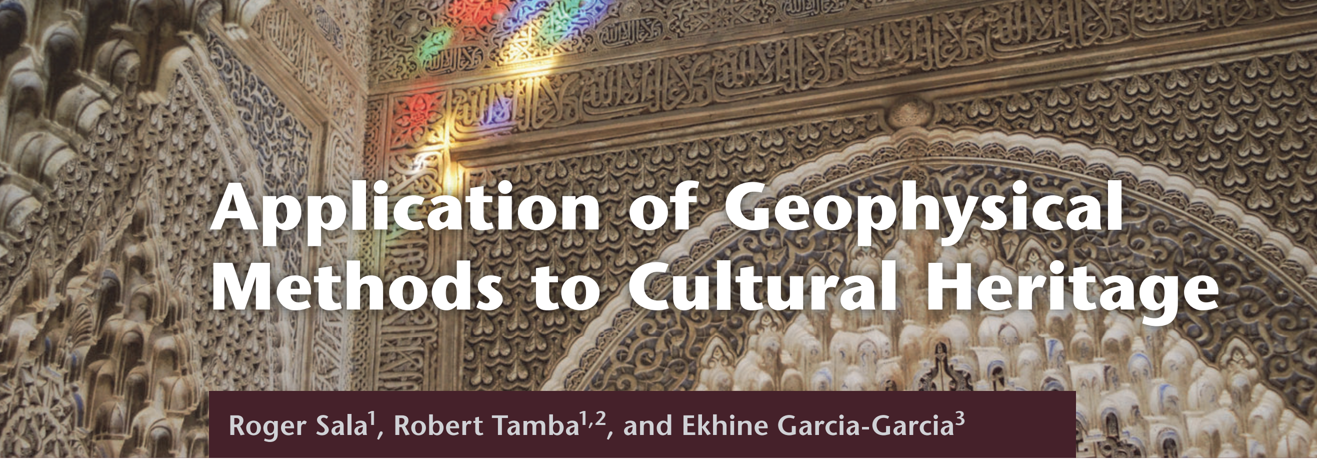
Application of Geophysical Methods to Cultural Heritage



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Archaeological geophysics is a vital part of exploring and documenting cultural heritage. Three of the most commonly used techniques are magnetometry, resistivity, and ground penetrating radar. These methods help archaeological geophysicists to unravel the complexity of many archaeological sites, including urban ones, old buildings, and built structures of cultural importance. However, local factors, such as constraints on time, local environment, pre-existing available information, and budgets, all contribute to a given site requiring unique geophysical surveying strategies. Four Spanish-based, but generally applicable, case studies will illustrate key geophysical strategy types for particular local archaeological conditions.

Keywords: geophysics, archaeology, cultural heritage, magnetometry, resistivity survey, ground penetrating radar

INTRODUCTION

Archaeological geophysics is a multidisciplinary field, requiring knowledge both of archaeology and of the Earth sciences. Archaeologists use geophysical techniques to either find or define the remains of past civilizations that occur near the surface within the top few meters of soil. In most cases, remains lie in a complex and heterogeneous environment: as such, geophysical results can be difficult to interpret.

Archaeological geophysics uses different methods of imagery that can be applied to the ground surface and buried structures or to built heritage (visible constructions of cultural importance such as buildings, roads, bridges, pillars, altarpieces, and statues). The main objective is to reveal hidden information in a non-destructive way. In terms of image acquisition and processing, this field can be compared to other image-based disciplines such as medical imagery. There are two particularly important imaging parameters: (1) the sensitivity of the sensors or their capacity to detect small variations; (2) the spatial resolution of the image or the size of the pixel used during image acquisition. Over the last few decades, both parameters have undergone significant improvements (Gaffney 2008). Archaeological geophysicists are now able to produce high fidelity images of the subsurface. However, even with the highest-level technology, the results can lack meaning if the methods are not applied with an appropriate strategy and with clear objectives.

This paper discusses the different strategies that can be applied in archaeological geophysics in order to reveal archaeological or architectural information to specialists or multidisciplinary teams. It focuses on how the different available methods can be used alone or in combination to map, image or analyse elements of archaeological interest in a non-destructive way. After briefly describing the standard workflow of archaeological geophysics and the most commonly used methods, selected case studies will illustrate how to strategically use geophysical methods to solve particular, locally encountered, problems.

THE WORKFLOW OF ARCHAEOLOGICAL GEOPHYSICS

The complete workflow of archaeological geophysics can be divided into three phases: (1) *field work*: design of the project, fieldwork methodology, and data acquisition; (2) *data transformation*: processing, integration, and interpretation of the data; and (3) *finalization*: disseminating and archiving the results.

The successful outcome of any exploration campaign requires (1) the systematic collection of all previously available archaeological, historical, and environmental information, which is crucial to the selection of the most appropriate techniques and optimization of the measurement strategy (Sala et al. 2012); (2) the use of a geographic information system (GIS) environment to cross-link the measurements obtained by different techniques and to make them easily available to other researchers, including archaeologists and managers involved with assessing the historical value of the site (Neubauer 2004); and (3) the proper archiving and dissemination of the measured data, which is important for any future reprocessing of the data and the scientific impact of the information obtained.

Standards and guidelines give a broad perspective on the complete workflow and on the best practice of archaeological geophysics. The main standards currently available are the ones established by English Heritage (Schmidt 2013). These have inspired other standardization projects, such as the European guidelines offered by the Europae Archaeologiae Consilium (the European Archaeological Council, or EAC) (Schmidt et al. 2015).

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A BRIEF DESCRIPTION OF THREE GEOPHYSICAL METHODS USED IN ARCHAEOLOGY

Any geophysical method that can provide information on near-surface properties can be applied, in theory, to archaeology and built heritage. Geophysical methods can be subdivided into passive methods, where a property is directly measured, and active methods, where the property values are inferred after being subject to a stimulus. The most commonly used geophysical methods in archaeology are magnetic surveys, resistivity (electric) surveys, and ground penetrating radar (GPR) (Gaffney and Gaffney 2011). The main characteristics and archaeological applications of each method are briefly described below. The characteristics of the three methods are compared in Table 1.

Magnetic Survey

Magnetic surveying is a passive method and is considered to be the fastest of the three geophysical methods reviewed here. The property measured is the intensity of the Earth's magnetic field, and the main goal is to map the local magnetic contributions to the total magnetic field. The different magnetic contributions fall into two groups: (1) induced magnetism, i.e. caused by the presence of a body with magnetic properties in a magnetic field such as Earth's magnetic field, which generates an induced magnetic field, and (2) permanent or remanent magnetism, i.e. inherent to the material (Schmidt 2007). The magnitude of the magnetic field in the induced category tends to be much lower than for the permanent or remanent category.

Magnetic surveys are very good for the description of soil disruptions such as might have occurred in ditches (Křivánek 2006), pits (Marshall 1999), or trenches (Masters and Stichelbaut 2009); for detecting temperature-induced alterations, as caused by fires or hot sources such as kilns (Linford and Canti 2001); and for detecting the scattered remains of iron-containing materials (Vernon et al. 2002). Magnetic surveys can also be used for the description of building remains and the interpretation of urban outlines of archaeological sites (Benech 2007), though the results will be more dependent on the contrast between the soil and the building material. Because of the speed of such surveying, it is often used as an exploratory tool to delimit areas of interest.

The main limitation of magnetic surveys is that magnetic data are strongly affected by uneven ground surfaces, metallic structures and superficial contamination, which can mask features of archaeological interest.

Resistivity Survey

Resistivity surveying is an active method in which an electric current is injected, via electrodes, into the soil and the resultant difference in potential between two points is measured. Resistivity represents the capacity of the explored media to resist the current being injected. The separation between electrodes influences the volume of terrain affected by the current and determines the depth of investigation beneath the ground surface. The main physical properties that can influence resistivity measurements are the amount of water in the soil, which varies with porosity and saturation, and its salinity (Samouëlian et al. 2005). Resistivity surveys require a good contact between the sensor and the (soil) media, which can be difficult in dry conditions.

Two acquisition modes exist. In the first one, referred to as the extensive mode (i.e. cartographic mode), the distance between the electrodes is fixed and the apparatus is moved in order to perform measurements for a fixed depth of investigation. In reality, several depths can be measured simultaneously (Walker 2000). In the second one, known as the pseudo-section mode (or tomographic mode), the location of the apparatus and measurement is fixed and the distance between electrodes is increased progressively, allowing measurements to correspond to different depths. A vertical section or "pseudo-section" of the soil is created by repeating vertical soundings along a profile.

The extensive mode is usually applied when needing to describe construction features (Neubauer and Eder-Hinterleitner 1997) or roads and paths (Tsokas et al. 2009). The potential of multilevel, high-resolution resistivity mapping is very well illustrated in a research project that investigated the changing designs of a Victorian municipal park (Parkyn 2010). The pseudo-section mode is used when a larger depth of investigation is needed or if the site presents a complex topography. Typical applications would be the detection of cavities or the exploration of tumuli (Papadapoulos et al. 2010).

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) is an active method based on the emission and re-collection of an electromagnetic signal. It gives nearly continuous, but indirect, information on depth. The re-collected signal is measured in terms of magnitude (strength), phase (polarity), and times of wave arrival (Leckebusch 2003; Annan 2009). The main properties of interest of the explored media are the dielectric permittivity (ε) and the electrical conductivity (σ), which are strongly related to the moisture content (Pettinelli et al. 2014).

Table 1 COMPARISON OF THREE COMMON GEOPHYSICAL METHODS USED IN ARCHAEOLOGICAL APPLICATIONS.

Method	**Magnetic**	**Resistivity (Electric)**	**Ground Penetrating Radar (GPR)**
Main Characteristics			
Key Feature	Fast	Stable	3-D
Measured Property	Magnetization	Resistivity	Dielectric permittivity
Main Applications	Thermal alteration; soil disruptions	Maps: constructive structures, roads and paths; pseudo-sections: large and deep structures	Constructive structures, cavities
Ranking of the factors influencing the design of a project (+++ = very important; + = least important)			
Ground Conditions	+++	+	+++
Processing	+	++	+++
Water Content	+	+++	+++
Cost	+	+++	+++

At low frequencies (10–100 MHz), the GPR method is mainly used for geological or hydrological characterization, as well as for detecting large deep cavities. At medium frequencies (200–600 MHz), the GPR method is usually used to describe construction features because it can give a high-fidelity image of the targets (Verdonck et al. 2012). The nearly continuous depth information enables a 3-D visualization of the features imaged, and it can be used to identify several periods of occupation. Built heritage projects often require high frequency antennas (600 MHz–2 GHz) to map a building's internal structure (Goodman and Piro 2013) or for a diagnosis of the state of preservation (Binda et al. 2005).

Ground surface irregularities or obstacles can have a great impact on the quality of GPR data. Furthermore, water and clay contents are also important because they may drastically attenuate (reduce) the signal and limit the depth of investigation. In general, a GPR signal is complex and requires thorough processing, which increases the cost of this technique.

CASE STUDIES: ADAPTIVE GEOPHYSICAL STRATEGIES

Each of the three geophysical methods discussed above has a specific use and range of applications, and no single method can provide all the information needed to describe a complex archaeological site. The main question should then be, "What physical properties show a measurable contrast between the archaeological features and the background?" In this context, special attention should be given to the individualized strategy adopted to address the specific archaeological objectives.

The four main strategies for the application of the three geophysical methods described above can be classified as follows:

1. Exploration strategy: a first, fast and low-cost method applied to large areas in order to delimit smaller areas of interest. These areas of interest are then explored with a second method to obtain a higher-fidelity image of the identified features.

2. Focus strategy: methods are chosen based on specific archaeological objectives for the qualitative information they can give on any detected features.

3. Indoor-urban strategy: methods may be severely limited in their use due to hard ground surfaces, metal elements, and/or modern infrastructures.

4. Built heritage strategy: in built heritage, any strategy must adapt to the geometry of the objects being characterized. The objects of study are visible structures such as the facades of a building. They require extensive high-resolution surveys to describe their internal structure.

In the end, any proposed strategy should be chosen in order to answer the archaeological questions in the most efficient way given the external constraints identified during the initial characterization of the project.

The four strategy types above will now be illustrated through the use of case studies.

Case Study Illustrating the Exploration Strategy: the El Pueyo de Belchite site (Spain)

For some projects there is little available information on the archaeological context or budgets are limited. In these cases, an exploration phase with a fast type of measurement can be used to identify the areas of interest where a complementary higher resolution survey can be applied subsequently.

The site of El Pueyo de Belchite (Aragon, Spain) is currently occupied by the Sanctuary of Nuestra Señora del Pueyo. In more ancient times, it was occupied by the Romans, as evidenced by structures visible at the surface (Rodríguez and Diez de Pinos 2014). Based on the analysis of the superficial structures, an archaeological survey was planned to delimit and characterize the Roman settlement.

A magnetic survey was conducted initially, and, based on its results, two excavation trenches were planned. To complement the description of the excavated buildings, a high-resolution GPR survey was performed, which covered the area between the two trenches.

The main results of the magnetic survey are given in Figure 1. Figure 1A shows the response of the magnetic gradiometer and Figure 1B shows the magnetic map interpretation. The wide and positively contrasted linear anomalies (visible in the white part of the colour scale) were interpreted as buried streets. The linear anomalies (streets) define the urban mesh of the site. The negatively contrasted linear features (visible as the black part of the colour scale) were interpreted as walls or some other type of built structure. The irregularity of the magnetic intensities could be explained by factors such as variable depth, local environment, or the state of preservation. Intense focus anomalies were also visible, and they are associated with metals (in blue), possibly from recent contamination, and to combustion (in red). Some areas show continuous highly positive values with a clear geometry. These might correspond to accumulated highly magnetized archaeological sediments in the inner part of buildings or to pavements or floors that are still in a good state of preservation. Figure 1C shows the GPR results for different depths of investigation and the survey interpretation. The GPR results are presented in relation to the results of the archaeological excavation trenches and show the inner distribution of an urban "domus", or house.

The combination of an initial magnetic survey and a subsequent GPR survey in targeted areas was successful in achieving the archaeological objectives in an economically feasible manner. The main structure of the El Pueyo de Belichite site was thus described, and a detailed image of the construction features in a selected area was obtained.

Case Study Illustrating the Focus Strategy: Mapping Iron Age Storage Pits in the Surroundings of Ullastret (Spain)

A focused strategy is applied when the archaeological objective is to detect features that can be characterized by their physical properties, i.e. cavities, burnt areas, ditches or pits, metals or hydrologic processes.

The archaeological site of Ullastret (Catalonia, Spain) is a well-known urban, fortified settlement (oppidum) of the Iberian period. One of the archaeological sites (ULL-166) was located after a low-flight photographic reconaissance operation that spotted a group of circular anomalies in the vegetation. These were identified and interpreted as storage pits (Plana-Mallart and Prado 2012). After their use, the storage pits were usually filled with surface sediments and waste materials (ashes, pottery, food wastes). These fillings are rich in archaeological information and represent an important target in archaeological research. Furthermore, the fillings are in general, more magnetic than the media in which they were placed, which makes the magnetic survey an ideal tool to local them. The objective of this case study was to complement the information derived from the aerial photographs with a geophysical survey and to describe the concentration of late Iron Age storage pits.

The results of the magnetic survey are presented in Figure 2. Three groups of positive circular features were identified, resulting in a total of 50 features, most of which could be associated with storage pits. The intensity and geometry of these features show some variations, which could be related to different preservation states or to different dimensions and depths of the pits. The magnetic survey also detected other features that added interest to the site. Two groups of high-contrast focal anomalies were identified in the northern part of the survey area. They showed high-magnetic values with a negative peak north and a positive peak south. Such features are often associated with thermal alteration, so the interpretation is that of possible ancient kilns. At the eastern limit of the survey area, there are two linear anomalies of weaker positive values and two other extensive anomalies. These latter anomalies were interpreted as two small ditches, possibly related to building remains.

Thus, applying the focused approach meant that the archaeological objective, which was to map the storage pits was achieved. Nevertheless, the site seems to be more complex than a simple array of storage pits. Other anomalies could be interpreted as possible buildings and remains related to production activities in the same area. However, only archaeological excavation can determine whether all the detected features belong to the same period.

Case Study Illustrating the Indoor Urban Strategy: Mapping Medieval Defensive Walls (Figueres, Spain)

Indoor applications of geophysical mapping techniques are part of urban archaeology. The environment and the stratigraphy involved are complex and there are interruptions in potential data caused by the presence of modern facilities and electromagnetic interferences. In most cases, the space to be surveyed is limited, which in turn limits the context of the results and of their interpretation. In this type of scenario, the main tool of archaeological geophysics is GPR. This technique offers 3-D information that can be visualized in a sequence of horizontal cuts. Such specificity enables an independent observation of several periods of occupation. And as a subset of indoor applications, religious complexes have their own characteristics. Many religious

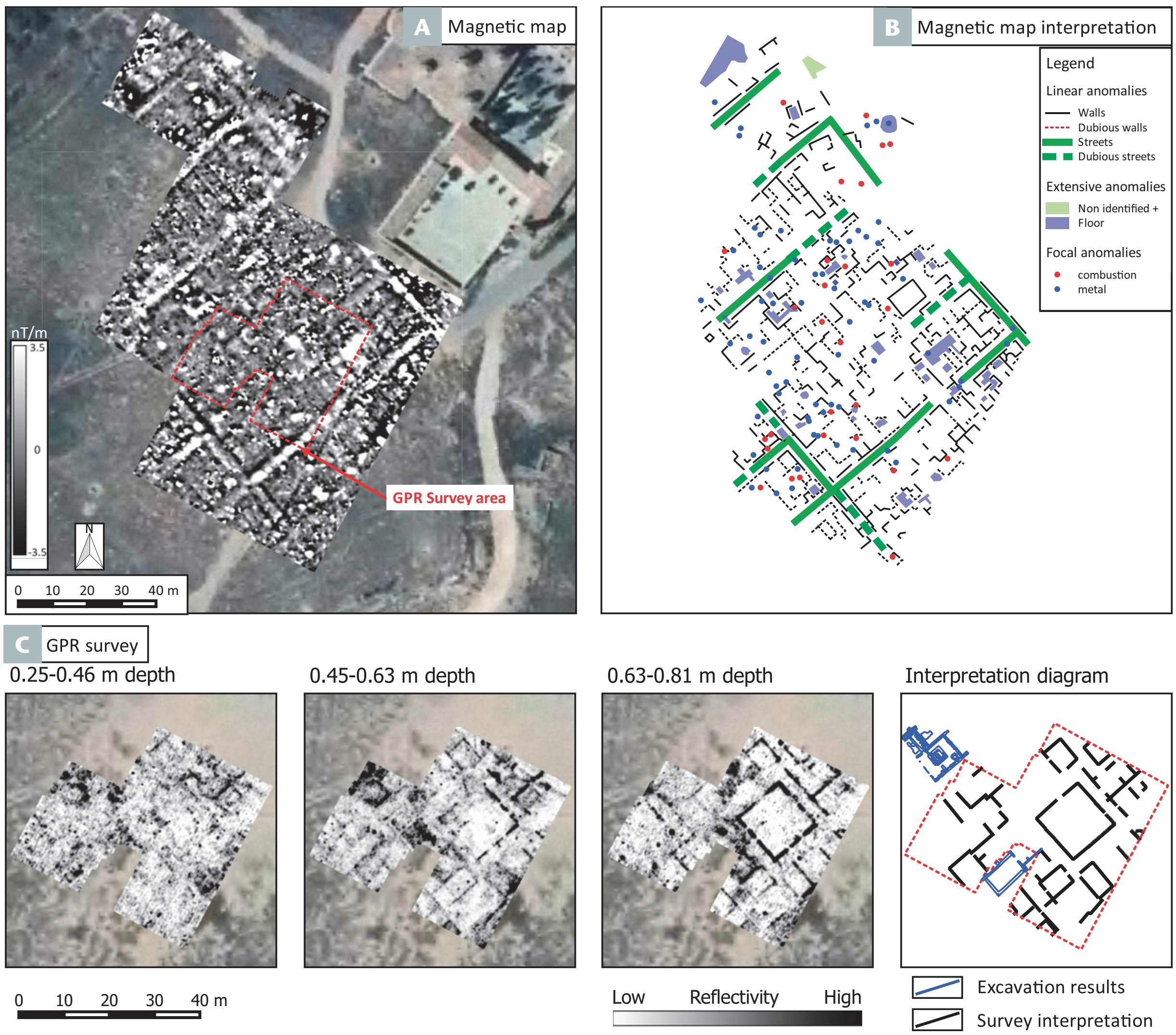

Figure 1 Geophysical surveys of the Roman settlement at El Pueyo de Belchite (Aragon, Spain). (**A**) Magnetic survey map. Positive and negative magnetic gradiometer responses are indicated by the colour scale at the lower left of the image. The ground penetrating radar (GPR) survey area (see part C) is outlined in red. (**B**) Interpretation of the magnetic map shown. The green lines represent the urban mesh of the settlement. The details of a block were produced by GPR and are shown in C. (**C**) The first three images from the left are the results of the GPR surveys at different depths. The interpretation of the GPR surveys is shown in the last image (far right). Black lines indicate walls of houses/structures. Blue lines indicate physical excavation results. Aerial photograph: Instituto Geográfico Nacional (www.ign.es); Geophysical results: SOT Archaeological Prospection; Excvation results: Pedro Rodríguez Simón.

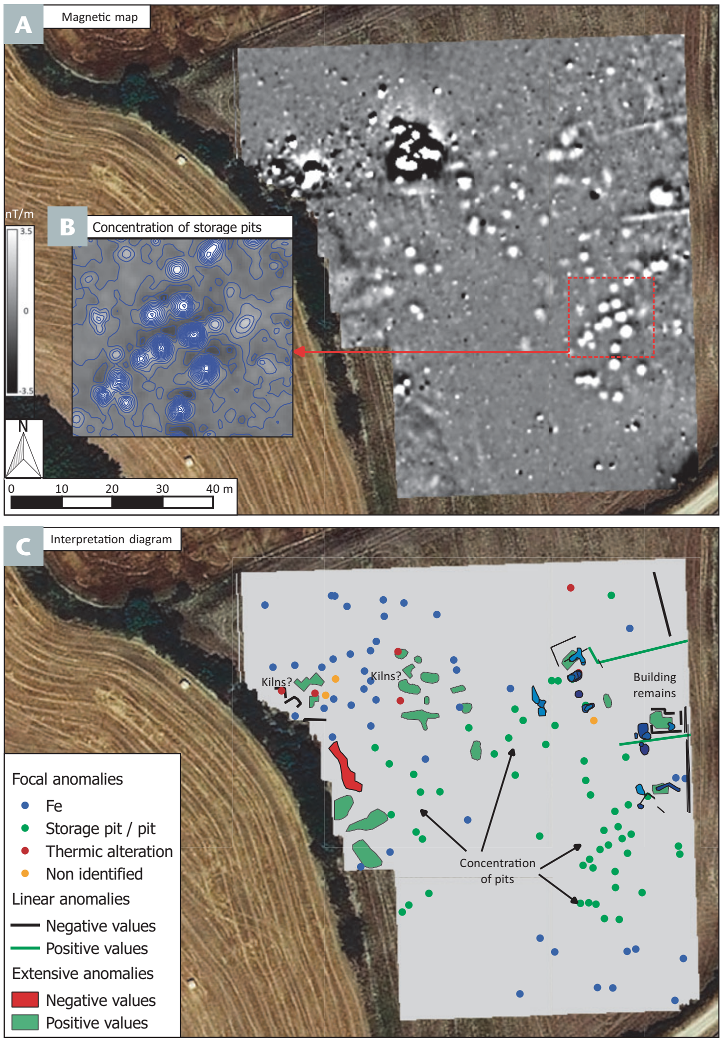

FIGURE 2 Geophysical survey of archaeological site ULL-166 near the Iberian fortified settlement of Ullastret (Catalonia, Spain). (**A**) Magnetic survey map. Positive and negative magnetic gradiometer responses are indicated by the colour scale at the left of the image. Positive (white) circular features are associated with storage pits. (**B**) Contour map showing the intensity and geometry of the storage pits located in the red outlined box of part A. (**C**) Interpretation of the magnetic survey. This site shows evidence of storage pits, kilns, and building remains. AERIAL PHOTOGRAPH: INSTITUT CARTOGRÀFIC I GEOLÒGIC DE CATALUNYA (WWW.ICGC.CAT); GEOPHYSICAL RESULTS: SOT ARCHAEOLOGICAL PROSPECTION.

complexes originated during medieval times, and they have evolved over the centuries, as evidenced by multiple building phases.

The case study presented here had as its main objective the mapping of the ninth century medieval defensive walls of the city of Figueres in Catalonia (Spain). A preliminary study of historical documents and maps provided a possible outline of the walls (Puig Griessenberger 2013). One of the targets of this study was the neo-classical church of Sant Pere. The available documentation located a possible segment of the enclosure that was in contact with the medieval phase of the church.

An extensive GPR survey was planned in order to map the remains of the defensive walls and the proximal church. Because of the expected difficulty of mapping the archaeological remains of multiple construction phases in a limited area, the survey resolution was set to obtain a good spatial definition of the detected targets so that archaeologists could interpret these in the context of previous historical research.

The results of the GPR survey for the Figueres site are presented in FIGURE 3. FIGURE 3A shows the GPR survey image of the medieval phase of the church. FIGURE 3B is the interpretation diagram, with the identified features classified by depth. The superficial layers from the surface down to 0.60 m below ground were associated with the gothic phase of the church. The deeper layers show the medieval foundations mixed with later burial chambers. However, the results did not show any element that could be interpreted as remains of the ninth century enclosure of the city. One explanation is that the medieval church was larger than was initially thought; therefore, the enclosure walls could be outside the survey area. Nevertheless, the GPR survey helped document the early phases of the church of Sant Pere.

Case Study Illustrating the Built Heritage Strategy: Pillar Restoration in the Sant Pau Historic Complex (Barcelona, Spain)

Considering the value of built heritage (i.e. historic buildings, bridges, pillars, altarpieces, etc.), restoration specialists and architects are increasingly avoiding destructive

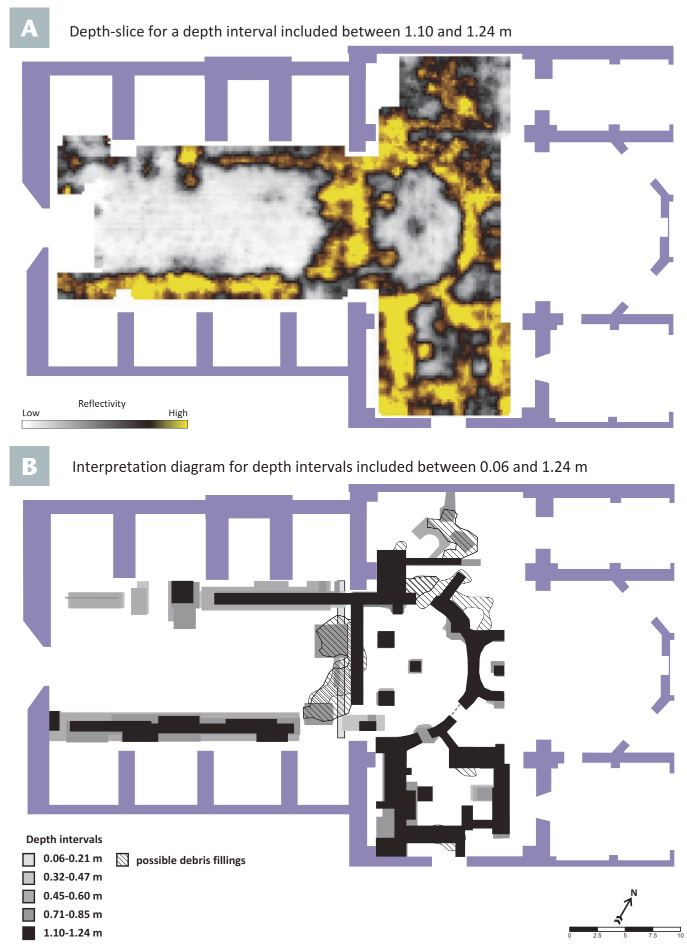

FIGURE 3 Ground penetrating radar (GPR) survey of the Sant Pere Church in the city of Figueres (Catalonia, Spain). (**A**) Depth-slice for a depth interval included between 1.10 and 1.24 m. Light blue lines represent the existing church walls. The survey map shows the reflectivity of the buried features. Low reflectivity areas (sediments) are shown in white and light grey. High reflectivity areas (walls, cavities, debris) are shown in black and yellow. The results show the medieval building phase of the church. (**B**) Interpretation of the GPR surveys by depth (0.06–1.24 m). The 0–0.6 m layers are associated with the gothic building phase of the church. The deeper levels show the medieval foundations mixed with burial chambers. CHURCH MAP: ADAPTED FROM THE RECONSTRUCTION MAP OF 1941–1948; GEOPHYSICAL RESULTS: SOT ARCHAEOLOGICAL PROSPECTION.

methods in their attempts to understand the structure of a building or to assess the conservation of specific construction elements. Many types of non-destructive methods are being used to plan and monitor restoration processes (Moropoulou et al. 2013). Ground penetrating radar is one of the non-destructive methods that can provide 3-D images and can detect areas with high moisture contents.

This case study concerns a restoration intervention in the pharmacy hall of the Sant Pau Historic Complex in Barcelona (Spain). Due to the change in the use of the old hospital building, a restoration process was started (González et al. 2011). Historic documentation showed that the centre of the pillars of the pharmacy hall contain iron pipes used to drain the roofs. The objective of the GPR surveys was to assess the degree of oxidation of the inner iron pipes and prove the relationship of this oxidation to external pillar cracking.

The geophysical survey was planned in order to cover all of the pillars in the hall (24 pillars divided in an upper and a lower section), and GPR data were collected in parallel horizontal profiles in order to have a view of the perpendicular inner iron pipes. The geometry of the profiles had to be adapted to the cylindrical shape of the pillars.

The results of the survey are illustrated in Figure 4 using two pillars of the pharmacy hall. Figure 4A shows the lower section of one of the pillars of the hall that presented external cracks. Figure 4B shows the strategy applied for the imaging of the pillars. They were imaged with vertical and horizontal sections created from the compilation of the acquired horizontal GPR profiles. In Figure 4C, the GPR results of the pillars are shown. The first pillar (on the left) was used as a reference because it showed a homogeneous GPR response, indicating no oxidation or decomposition of the pipes. The inhomogeneous GPR response on the second pillar (on the right) is an indication of oxidation of the iron pipes and degradation of the encasing brick work. The results revealed three important aspects of the inner state of the pillars. First, the iron pipe inside some of the pillars showed a discontinuity in its GPR response in vertical sections. Second, and in these discontinuity response cases, the horizontal sections showed a decrease in the reflection of the GPR signal and an apparent increase in the size of the iron pipes. Third, when discontinuity response cases are observed, they are coincident with pillars that have cracks on their surface, and these discontinuities are more frequent on the lower section of the pillars (i.e. the basement floor).

The conclusion of this study was that expansion of the inner iron pipe due to its oxidation was displacing the pillar bricks. The fact that this problem was more frequent in the basement floor pillars was interpreted as the result of a lack of isolation between the clayey soil and the bases of the pillars, causing increased moisture contents in the bricks that surround the pipes.

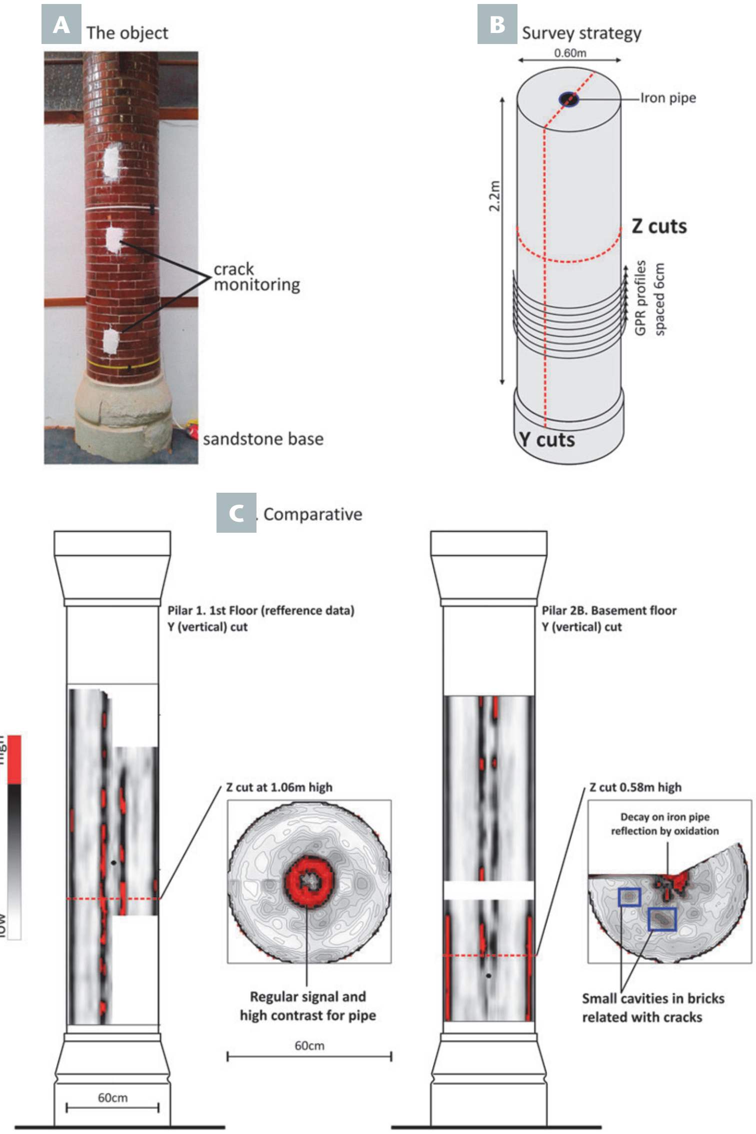

Figure 4 Ground penetrating radar (GPR) analysis of draining pillars. Pharmacy hall, Modernist Historic Complex of Sant Pau (Barcelona, Spain). (**A**) Photograph of one of the pillars of the pharmacy hall presenting external cracks. The columns have a brick exterior with a sandstone base. Iron pipes, used to drain water from the roof, are in the centre of the pillars. (**B**) Schematic illustrating the acquisition data (profiles) and the imaging of the results (Y and Z cuts) for analysis of the pillars. (**C**) Results of the analysis. On the left is the reference pillar showing relatively homogeneous GPR results in vertical and horizontal representations. Reflected energy scale shown to left. On the right is a pillar showing inhomogeneous GPR responses vertically and horizontally. These results are indicative of pipe degradation due to oxidation. Photograph, diagrams and geophysical results: SOT Archaeological Prospection.

CONCLUSIONS

Geophysical techniques are an invaluable tool to aid archaeological investigation. And these techniques are advancing all the time, which allows archaeological geophysicists to deploy them in an ever broader, and often more subtle, way to solve the many imaging problems that are associated with real archaeological research and with heritage conservation. The main geophysical tools used by archaeologists, and illustrated in this paper, are magnetometry, resistivity and ground penetrating radar. With appropriate strategies planned out, these three techniques can perform an astonishing array of tasks.

Although the selected case studies above are confined to Spanish archaeology, they illustrate the different strategies that can be applied to common problems pertaining to sites of different historical periods: the El Pueyo site example is representative of large-area surveys that must be carried out to prepare the way for subsequent, more targeted measurements; the Ullastret case illustrates the positive identification of a number of structures (pits, kilns) in response to very specific archaeological inquiries; the example of the city walls of Figueres is indicative of the problems encountered when surveying heavily stratified urban environments. Finally, the small-scale example of the GPR characterization of the Sant Pau pillars shows the potential of geophysical methods in architectural and built heritage investigation.

Many other complementary methods are also available for surveying beyond the three survey methods discussed here. These include electromagnetic induction (EMI), seismic tomography, thermography, micro-gravity, induced polarization, hyper-spectral imaging, and many more.

We hope that this short review conveys the idea that geophysical exploration at all scales, if adequately planned and performed, offers an array of tools that are invaluable for modern conservation and the historical evaluation of cultural heritage. In short, geophysical methods can make visible the cultural heritage hidden beneath the surface and help unfold the layers of history preserved at buried archaeological sites.

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