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Integrated Archaeogeophysical Approach for the Study of a Medieval Monastic Settlement in Basilicata

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Abstract: The paper deals with the results of an archaeo-geophysical approach adopted for the study and the reconstruction of the architectural plan of the medieval monastery of San Pietro a Cellaria in Calvello (Basilicata, Southern Italy). The monastery is a remarkable witness to Benedectine architecture of the 12-13th century in Basilicata, built by monks of the Congregation of S. Maria di Pulsano, who were active mainly in southern Italy. The historical data and the diachronic architectural study, based on the analysis of building techniques, provide evidence for a long and intense history, during which the monastery underwent several architectural changes, including the demolition of buildings and the superposition of other constructional elements. The only preserved medieval remains are a church with a nave; the adjacent structures are more recent. This preliminary data prompted a research project to shed new light on the as yet unknown history of the medieval monastery. Specifically, a remote sensing approach around the monastery including aerial survey by unmanned aerial vehicle (UAV), ground-penetrating radar (GPR) and geomagnetic survey in gradiometric configuration (MAG), was adopted in order to verify the possible existence of buried masonry structures and other possible features of archaeological interest, including channels and aqueducts. The GPR time slices were constructed from closely spaced parallel profiles. The time slices, computed by averaging radar reflections over vertical time windows several nanoseconds thick, are used to map subsoil features associated with the structures, probably of anthropogenic origin. To facilitate the interpretation of the results, a three-dimensional image was constructed using closely spaced parallel profiles, which are linearly interpolated. The MAG survey was carried in gradiometer configuration, in order to study magnetic properties of the shallow subsoil. Ground-penetrating radar gives details about archaeological structures in a limited area where survey was possible, while gradiometer survey confirms GPR results and improves archaeological knowledge in the areas where GPR survey was impossible. This multi-sensor remote sensing program revealed a wide variety of archaeological features of interest, which may be targeted accurately with excavations in the future.

Keywords: Archaeo-geophysics; Magnetometry; GPR; Medieval archaeology; Calvello; Basilicata

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1 Introduction

Remote sensing and geophysical surveys are a critical component of research on historical landscapes and cultural heritage, providing a large amount of data that allow efficient mapping of buried elements of the built environment within large sample areas.

The integrated use of remote sensing and geophysics for archaeological applications has increasedin the last two decades due to the development of technology, the increased availability of user-friendly data processing software, and awareness by archaeologists of the benefits of such investigation methods for preventive archaeology (Leucci, 2002; Conyers 2004; Gaffney & Gater, 2003; Leucci, 2006; Leucci et al., 2007; Lasaponara et al., 2011; Masini et al. 2011; Calia et al., 2012; Leucci et al., 2012; Lasaponara & Masini, 2012; 2013).

However, despite all of this, the data acquired is not always fully exploited for a number of reasons, such as the difficulty of interpreting the results in order to provide information of archaeological interest. This problem is widely debated among scientists, geophysicists and archaeologists. To overcome this gap, the integrated use of different geophysical methods has proven to be the most successful approach for archaeological investigations (Chianese et al., 2004; Rizzo et al., 2005; 2010; Lasaponara & Masini, 2008).

This paper deals with the results of an archaeogeophysical approach adopted for the detection of archaeological features in order to improve our knowledge of a medieval monastic settlement: the monastery of St. Peter “a Cellaria,” located in the territory of Calvello, a village between Camastra and Agri valleys in Basilicata.

The settlement was built in the first half of the 12th century by the monks of the Congregation of S. Maria di Pulsano, founded by St. John of Matera in 1128 (Panarelli 1997). These monks followed the Rule of St. Benedict, as can be seen from the first documentary attestation dating back to 1147. They were devoted to the search for God and the radical rejection of the material life. They walked barefoot and lived on what they obtained by agricultural work. They did not eat meat and refrained from wine, milk and their derivatives. In the first decades of the congregation, these monks erected mainly hermitages and small cells, formed sometimes by a simple cave or solitary dwellings on inaccessible cliffs and inaccessible. We do not know about the features of the first architectural nucleus of the monastery of St. Peter “a Cellaria”.

Currently, the monastery of St. Peter consists of a church and two buildings, leaning against the perimeter walls of the nave to the north and south, where some rooms for collective use were located. Remains of walls and traces of foundation suggest the existence of other buildings, probably cells (hence the name “Cellaria”), along the edge of the plateau to the west and north of the existing monastery (Masini, 1997).

It is not possible to accurately date the construction phases of the monastery from documents. But the analysis of building techniques and a few artistic elements allow us to draw a line of the evolution of the building, divided into two main phases: first a medieval one (12-14th century), and the second one between the 17th and 18th centuries.

In order to shed new light on the so far unknown history of the medieval monastery, a multi remote sensing approach, including aerial survey by UAV, GPR and Geomagnetic techniques, was adopted. The goal was to identify everything which could help to ascertain the possible distribution of landscape space (street patterns, site orientations, etc).

Only a portion of site could be investigated with GPR due to the soil conditions (for most part cultivated), while magnetic gradiometry was employed in the rest of the area, partially overlapping with the GPR (Fig. 1).The choice to use these two geophysical methods was due to the widespread use of them in archaeology for the investigation of large areas (Piro et al. 2003; Chianese et al., 2004; Rizzo et al., 2005; De Domenico et al., 2006; Nuzzo et al., 2009; Rizzo et al. 2010; Leucci et al., 2013; Leucci et al, 2014).

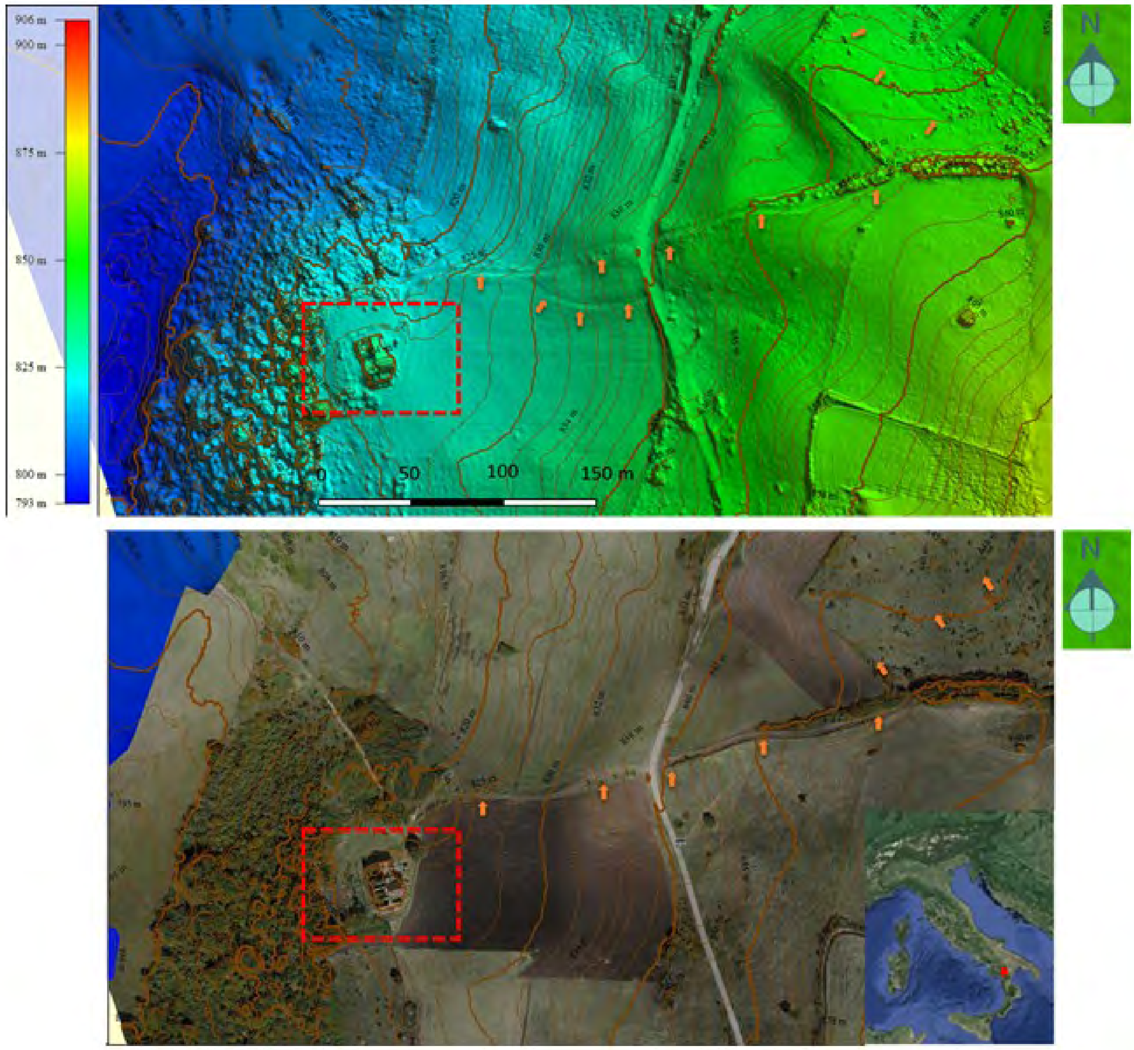

Figure 1. Digital Surface Model and orthophoto provided by the processing of images taken from drone. The orange arrows denote the presence of some features of possible cultural interest such as old roads and field divisions. The dashed rectangular box indicates the investigated area. Lower right: Location of Calvello.

2 UAV based survey

2.1 Aircraft Characteristics, Flight and Image Acquisition Parameters

The survey of the area was performed by processing images taken from a UAV. The aircraft used was a “motor glider” that is launched by hand and can land on any terrain. This latter feature is particularly useful if no space is available for landing and take-off, as in the case of the site under investigation. It is made of polypropylene foam with an electric motor, with a power of about 100 W. The images were taken by a compact photographic camera CANON PowerShot A2300 at 16M pixels resolution.

The remote control is via radio in the 2.4 GHz band commonly used for model airplanes. The aircraft is equipped with “single board computer” with the flight software Arduplane, with a series of sensors in MEMS technology (Micro Electro-Mechanical Systems).

The system is equipped with three-axis accelerometer and gyroscope for attitude control, a sensor integrated barometric precision for control of the altitude, and a GPS receiver for navigation. A telemetry system operating at 433 MHz allows the operator to follow the various stages of flight. The photographic camera is equipped with dedicated firmware that ensures optimal arrangement of the acquisition parameters of the images such as time of exposure, focus and level of sensitivity of the CCD (Charge Coupled Device). The images were taken with a field of view of about 60° x 46° by flying the aircraft for parallel lines spaced about 30 m at an altitude of 130 m. With an average time of release of 4 s, traveling at a nominal speed of 36 Km / h, the single images have been taken with an overlap of about 73% along the direction of flight and 27% in the transverse direction of flight.

2.2 Processing Steps

The image processing was done using open source software.

The first step was to search for specific points that show features invariant to the scale factor by Scale Invariant Feature Transform (SIFT) method (Lowe 1999).

The second step provided the geometry of the scene (that is the 3D reconstruction of the points identified by SIFT) by applying the Sparse Bundle Adjustment method (Lourakis and Agyros 2009).

Then, by means of a Patch-based Multi-View Stereo algorithm, a dense point cloud of the entire area was created. In practice, the algorithm uses pairs of images appropriately chosen to perform the processing, in a manner similar to stereophotogrammetry, for the construction of "depth maps". Finally, a DSM (Digital Surface Model) was obtained from the points cloud and used to project all of the images into a single orthophoto. Since all processing steps were carried out in a domain with an arbitrary scale, the final results have been geocoded by selecting a number of points, recognizable in the scene, whose geographic coordinates have been acquired by total station.

The DSM and orthophoto have been used for georeferencing and 3D visualization of the geophysical maps, facilitating their utility for archaeological interpretation. The acquisition period and surface characteristics of the area, plowed a few weeks before the flight, were not ideal for the archaeological detection of the crop marks, however. Only some relief, relating to past field divisions, and roads could be observed. Unfortunately, they are outside of the area under geophysical investigation (see figure 1).

3 Archaeo-geophysical Surveys

The magnetic gradiometry prospection was conducted in three areas (M1, M2 and M3 in Fig.2) located to the north, west and east of the monastery. The area labeled M1 was also investigated using GPR. The archaeo-geophysical investigations were primarily aimed at identifying anomalies in the immediate vicinity of the monastery relating to the presence of underground wall structures (M1 and M2 areas). A further objective was the acquisition of information about any other buried archaeological structures, since the monastery is located in an area with a long human presence, as demonstrated by a reconnaissance conducted on the east side of the medieval artifact.

3.1 The Magnetic Gradiometry Data Acquisition and Analysis

The objective of the MAG survey is to detect, by means of surface measurements, variations in the magnetic properties, or magnetization, of the subsurface. These variations in subsurface magnetization are related to archaeological buried remains (walls, tombs, floors, etc.) and a geological structure, such as a pegmatite vein or basaltic dike in granite, a fault in bedrock, or hydrothermal alteration. They can also be related to human disturbance of soil, from the presence of magnetic objects in the subsurface. The anomalous values define the spatial variations in the field that can be measured on the surface, and constitute magnetic anomalies. Mapping magnetic anomalies on the surface allows to infer the presence or absence of magnetic material in the subsurface. The magnetic gradient allows the differentiation between deeply buried objects versus those that are shallows. A gradiometer typically uses two sensors to measure the gradient in the magnetic field.

Figure 2. The areas investigated by GPR (M'1) and magnetometry (M1, M2 and M3). Upper right and lower right: images of georadar and magnetic data acquisition, respectively.

The MAG data were acquired using a Geometrics G-858 caesium vapour gradiometer along parallel lines spaced 1 m apart. Data were acquired in continuous mode with a sampling interval of 0.2 seconds. As a gradiometer (dual sensor), the sensors for the G-858 were spaced vertically 0.8 m apart with the lowest sensor being approximately 0.5 m from the ground surface. In addition, the sensors were oriented vertically. A data-logger and a control console, which was mounted in front of the driver, were used to control the data collection. Data were recorded to an accuracy of 0.002 nano-Teslas (nT).

All MAG acquired data were pre-processed with the use of bandpass filters with values between -30nT/m + 30nT/m, which represents a range in which those values associated with archaeologically significant magnetic alignments usually fall. In this phase, in addition, it was necessary to eliminate events, referred to as spikes, that are attributable to the presence of alignments due to anthropogenic settlement. In the next step, all the data were interpolated through a grid of data using both the system Base Map of Surfer8 scaled between -20nT/m and + 20nT/m. Figure 3 shows the maps overlapped on the orthophoto of the areas M1 (11 x 25 m), M2 (15 x 12 m) and M3 (30 x 40 m). The results show weak anomalies (dashed dark line) in area M3, related to the presence of a buried structure. The presence of a water bath downstream of the anomaly suggests that these anomalies could be related to water channels (C). In area M1 some aligned anomalies (labeled M) are visible and should be associated with the buried walls, which are clearly visible by GPR surveys.

3.2 GPR Data Acquisition and Analysis

The GPR survey was carried out with a georadar Hi Mod using both the 200 and 600 MHz (centre frequency) antennae manufactured by Ingegneria Dei Sistemi (IDS). In order to obtain a 3D model of the subsurface, one should make an adequate field acquisition consisting of a grid of GPR lines. Thus, the surveyed area was a rectangle of 12x32 m^2. The distance between the parallel GPR lines was 0.5 m. This area overlapped the area labeled M1, which was also surveyed with the magnetic method (Fig. 1). The quality of the raw

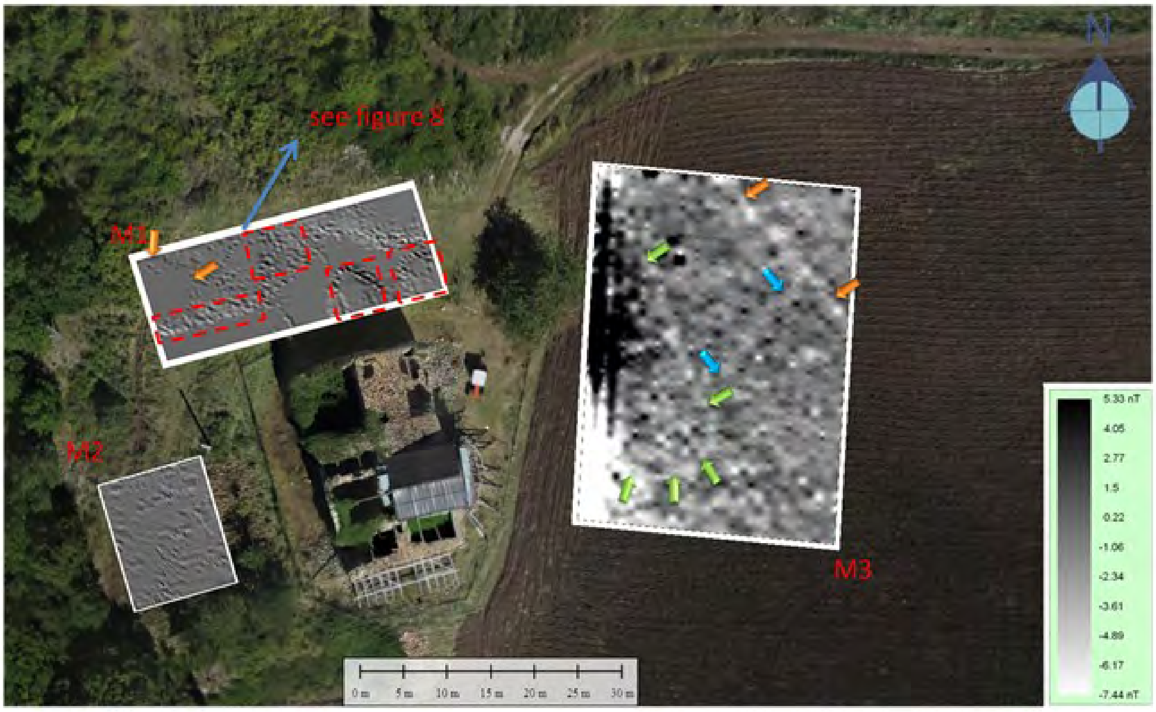

Figure 3. Gradiometric maps of the surveyed areas.

data required appropriate processing for easier interpretation. The data were processed using standard two-dimensional processing techniques by means of the GPR-Slice Version 7.0 software (Goodman, 2013). Processing steps can be summarised as follows:

1. amplitude normalisation; consisting of the de-clipping of saturated (and thus clipped) traces by means of a polynomial interpolation procedure;
2. background removal; the filter is a simple arithmetic process that sums all the amplitudes of reflections that were recorded at the same time along a profile and divides by the number of traces summed. The resulting composite digital wave, which is an average of all background noise, is then subtracted from the data set (Conyers and Goodman, 1997);
3. Kirchhoff 2D-velocity migration (Ylmaz, 1987); a time migration of a two-dimensional profile on the basis of a 2D-velocity distribution is performed. The goal of the migration is to trace back the reflection and diffraction energy to their "source". The Kirchhoff 2D-velocity migration is done in the x-t range; this means that a weighted summation for each point of the profile over a calculated hyperbola of preset bandwidth is performed. The bandwidth means the number of traces (parameter summation width) summated.

There was good penetration of the electromagnetic energy (about 40 ns corresponding to a depth of about 1.8 m if the mean electromagnetic wave velocity value of 0.09 m/ns is used) in the survey area. This was due to the physical characteristics of the subsurface, which dissipated the electromagnetic energy very little.

The EM wave velocity can be determined from the reflection profiles acquired in continuous mode, using the characteristic hyperbolic shape of reflection from a point source (diffraction hyperbola) (Conyers and Goodman, 1997). This is a very common method for the EM velocity estimation and based on the phenomenon that a small object (the dimensions of the object are smaller than the wavelength of the EM wave introduced in the ground) reflects EM waves in almost every direction (Fruhwirth and Schmoller, 1996).

Most of the observed anomalies are confined from about 15 ns to about 40 ns; this is also the case in all the other profiles acquired in the area. The shape and alignment of the anomalies found in the survey area (labelled M in Fig.3) suggest that they are related to the probable presence of archaeological structures (such ''walls'').

The distribution plan of reflection amplitudes was obtained by the creation of horizontal time slices within specific time intervals. These are maps on which the reflection amplitudes have been projected at a specified time (or depth), with a selected time interval (Conyers, 2006). In a graphic method developed by Goodman et al. (2006), termed '*overlay analysis*', the strongest and weakest reflectors at the depth of each slice are assigned specific colours. This technique allows the linkage of structures buried at different depths. Time-slice technique has been used to display the amplitude variations within consecutive time windows of width Δt=5 ns. The time slices show the normalized amplitude using a range defined by blue as zero and red as 1. In the slices ranging from 78 cm to 96 cm depth and 109 cm to 126 cm depth, relatively high-amplitude alignments (labelled M) are clearly visible (Fig. 5). These correspond to the anomalies labelled M in the radargram showed in figure 4.

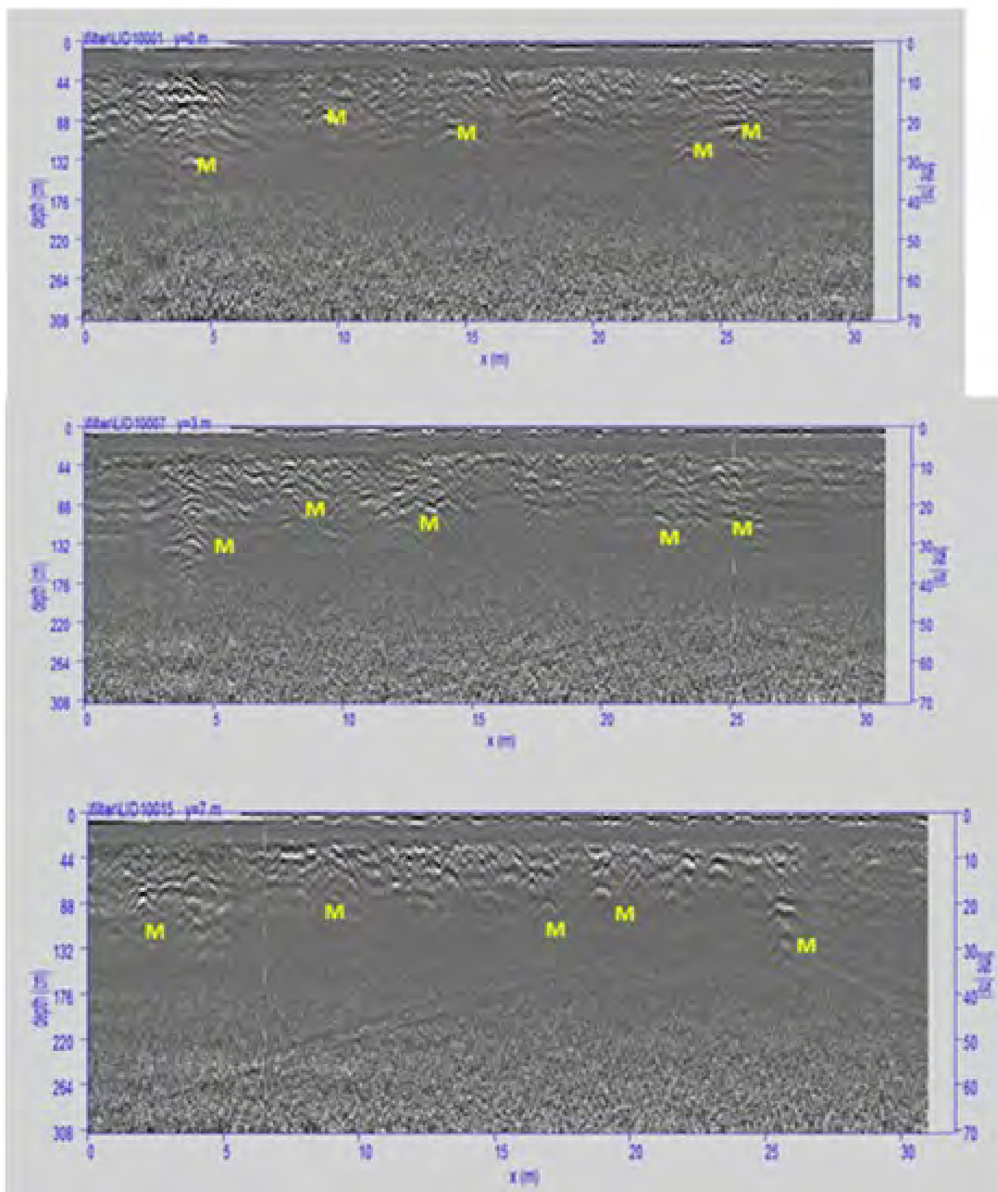

Figure 4. Processed radar sections relating to the profiles labeled 1, 7 and 15: M indicates reflection from walls.

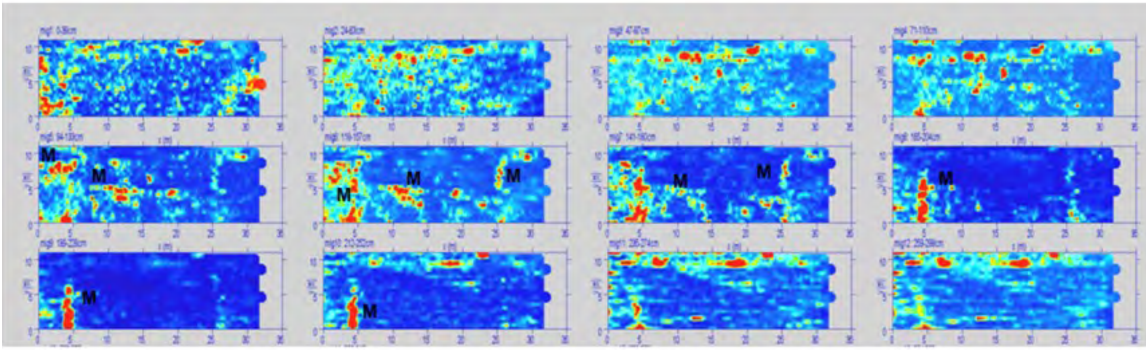

Figure 5. Time slices: M indicates alignments relating to walls.

Moreover the highest amplitudes were rendered into an isosurface (Conyers and Goodman, 1997; Conyers, 2004, 2012; Conyers et al., 2013). Three-dimensional amplitude isosurface rendering displays amplitudes of equal value in the GPR study volume. Shading is usually used to illuminate these surfaces, giving the appearance of real archaeological structures. In Fig. 6 the same data set is displayed with iso-amplitude surfaces using a threshold value of 65% of the maximum complex trace amplitude. A relatively strong continuous reflection is visible on the threshold volumes (between 0.8 and 1.8 m). This visualization technique put better in evidence the anomaly labelled M in Fig. 5.

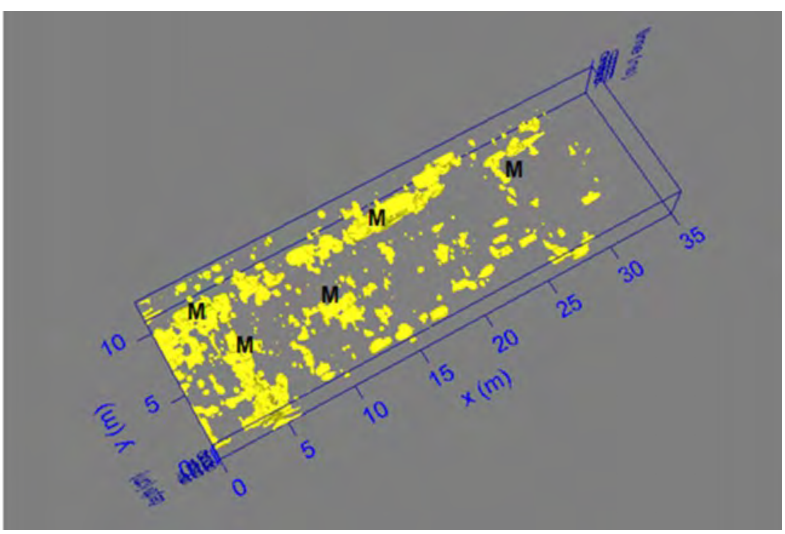

Figure 6. 3D amplitude iso-surface map.

Figure 7 shows two maps with GPR overlain on the planimetry of the surveyed area. Particularly interesting is the depth slice at 78-96 cm, which highlights anomalies (amplitude variations) oriented in the east-west direction, thus parallel to the north facade of the monastery. Other anomalies are oriented in the orthogonal direction, some of them appear at first glance aligned with the walls of the monastery. Most of these are visible up to about 1 meter deep. Our interpretation (Fig. 7, bottom right) shows a pattern of anomalies related to underground structures that suggest the presence of buildings partially aligned in continuity with the monastery, partly detached and seemingly unrelated to current monastery.

Finally, Figure 8 shows two georadar time slice at 63-80 and 94-111 cm depth and a geomagnetic map.

The comparative analysis of the three maps puts reveals a number of anomalies (indicated with letters a, b, c and d) visible from both georadar and magnetometry. In particular, the anomaly b, clearly related to buried walls, can be observed from both the magnetic and and georadar maps, whereas other anomalies are only visible from georadar and from magnetic maps and vice-versa.

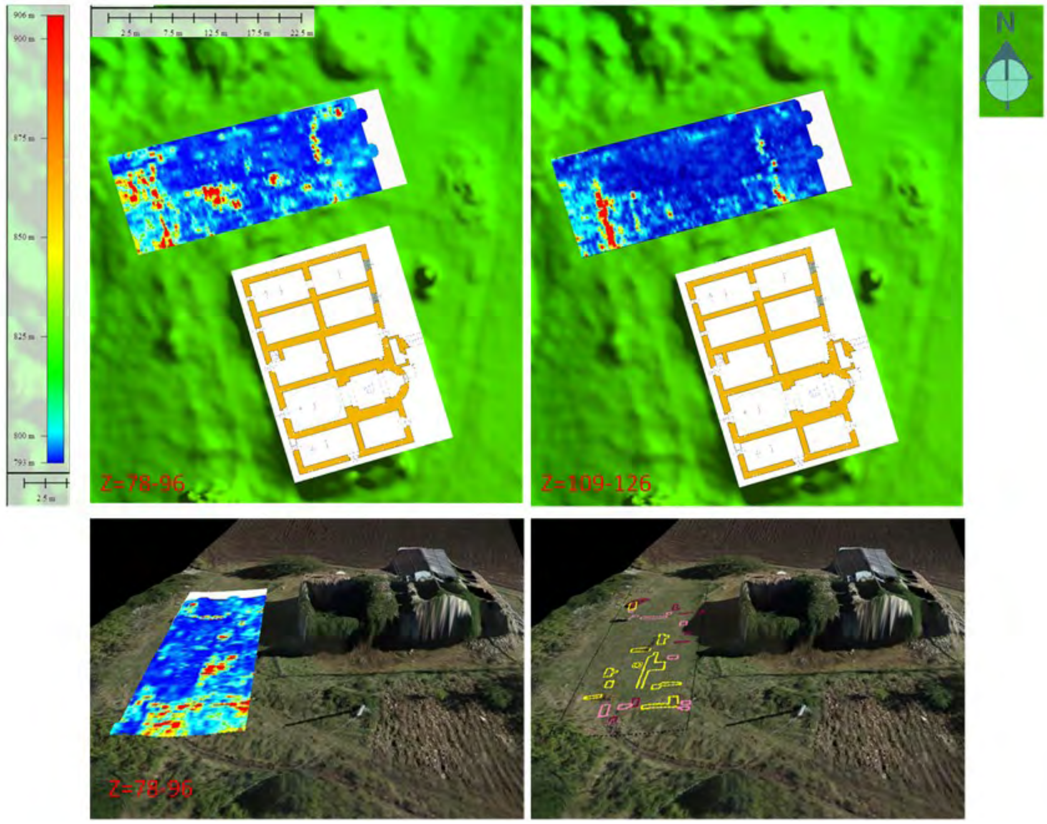

Figure 7. Depth slice overlain on the monastery maps.

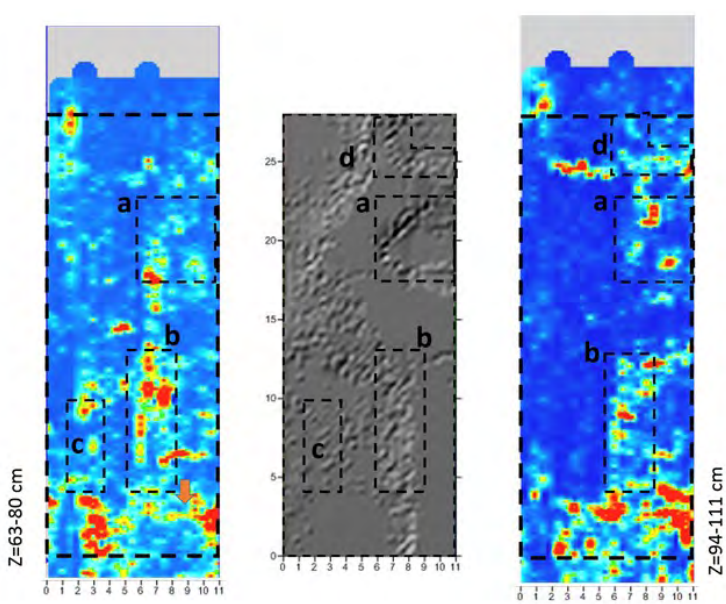

Figure 8. From left to right: georadar time slice at 63-80 cm depth, geomagnetic map and georadar time slice at 94-111 cm depth. The comparative analysis of the three maps shows a number of anomalies (indicated with letters a, b, c and d) visible from both georadar and magnetometry. In particular, the anomaly b, clearly relating to buried walls, can be observed from both the magnetic and and georadar maps, whereas other anomalies are only visible from georadar and from magnetic maps and viceversa.

4 Conclusions

In this first archaeo-geophysical campaign, ground-penetrating radar and magnetic gradiometry have proven valuable tools for understanding the development of structures around the monastery of St. Peter in Cellaria. Both magnetic gradiometry and GPR allowed us to identify salient aspects of the site, in an area where the architecture was virtually invisible and extensive horizontal excavations will not performed at this time.

Particularly important was the integration of geophysical prospecting with archaeological surveys, with the aim of better planning measurements and correct interpretations of results.

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