High-resolution Geophysics in Imaging and Characterization of Buried Cultural Heritage

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Abstract. Resolution is a crucial parameter in pre-excavation surveys of archaeological sites. Geophysical methods based on Laplace (gravity, magnetics), diffusion (e.g. low-frequency electromagnetics) and wave equations (i.e. seismics and ground-penetrating radar GPR) are often applied in this sequence to attain increasing detail about subsurface characteristics (i.e. shape and location of subsurface volumes) and physical properties. We apply potential (magnetic gradiometry) and wave-equation based (i.e. seismics and GPR), combined with dedicated data-processing and analysis techniques based on instantaneous attributes, to the study of different archaeological sites, namely: an area characterized by scattered remains of unknown shape and dimension, a prehistoric grave, buried walls and foundations, a funerary tumulus. The depth range of interest is between 80 and 500 cm. Magnetic gradiometry, filtered to remove long wavelength anomalies and to focus the analysis on a +/- 5 nT range, allows clear identification of buried brick-walls, with unavoidable uncertainty concerning the depth of the targets. Detailed 2-D and 3-D subsurface models come from the GPR results, where imaging of the buried structures can be combined with assessment of physical properties that affect wave velocity and attenuation. The combination of magnetic and radar methods in sequence is an effective strategy for high-resolution pre-excavation surveys: magnetic measurements allow rapid identification of localized anomalies, GPR provides higher resolution in their imaging and characterization. The application of attribute analysis techniques to GPR data further enhances the performance of the method in target identification. Peculiar archaeological targets, such as e.g. burial mounds, eventually require the use of transmission seismic tomography to overcome the limits of potential and GPR methods. Examples from pre-historic graves show that

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1 Introduction

The enhancement of resolution is crucial in geophysical imaging and characterization of archaeological targets. The identification of buried cultural heritage, based on amplitude and geometry indicators obtained from geophysical data, requires details that help in filtering false targets and in focusing on actual objectives of potential interest.

Several strategies are practiced and proposed in literature on such purpose. Among potential methods, magnetic ones are often successful and can be used during different excavation steps (Morariu et al., 1989; von der Osten-Woldenburg et al., 2002; Becker and Fassbinder, 2001). The implicit limit of any potential method is that infinite different subsurface configurations are solution of the Dirichlet problem for the underlying Laplace's equation. Shallow targets with quantities of ferrous materials or ferrimagnetic minerals produce strong magnetic anomalies. Among them, maghemite is mainly related to natural or man-made fires (Le Borgne, 1960) while fossils of magnetic soil bacteria influence the content of in situ formed magnetite (Fassbinder et al., 1990). Targets with such characteristics often allow detailed mapping of the anomalies of interest. Electromagnetic induction techniques (Bevan, 1983; Dalan, 1991; Fröhlich Gugler and Gex, 1996) measure variations of conductivity. Such methods allow relatively rapid investigations of large areas but the resolution level is rather low. Moreover, background conductivity can be considered a function of topography, but is calculated from empirical relations, which are valid in specific conditions (Monier-Williams et al., 1990).

As for seismic techniques, reflection methods are seldom used, due to the limited depht of the targets and to the blind shallow layer that prevents from imaging targets in the depth range of primary interest for archaeological applications. Nonetheless, seismic refraction (Tsokas et al., 1995), crosshole seismic tomography (Louis, 2001) and transmission seismic tomography (Xu and Stewart, 2002) can provide useful information in a limited range of target/subsurface conditions, such as, e.g., pyramids and burial mounds (see also Forte and Pipan, 2008).

Ground-penetrating radar (GPR) is being extensively used in archaeological prospection for pre-excavation and non-destructive studies (Brooke and Maillol, 2007; Whiting et al., 2001; Perez Gracia et al., 2000). In this work we integrate magnetic gradiometry, seismic tomography and GPR, coupled with radar trace attribute analysis, to obtain enhanced resolution at all depth levels.

We apply the integrated techniques to three sites of the roman period and to two areas with buried prehistoric remains. High resolution images and attribute volumes show that sub-metric resolution is attainable through the proposed methods.

2 Methods

A geophysical exploration protocol for archaeological applications can be developed starting from reconnaissance work performed with magnetic methods followed by higher resolution surveys, such as ground-penetrating radar. Primary objectives in the study of archaeological sites are identification of targets of potential interest and study of the stratigraphy of the site to reconstruct its history. The integration of different techniques helps in overcoming the limits of each method and in extending the analysis to different physical properties of the materials. In this work we use magnetic gradiometry, multifold (MF) ground-penetrating radar and seismic transmission tomography to study different archaeological targets buried in soils with different characteristics. We perform magnetic surveys with a cesium magnetic gradiometer (SMARTMAG model SM4-G), with a sensitivity of 0.01 nT and an operating range from 15000 to 100000 nT. Measurements are performed with two sensor located at 30 and 130 cm above ground level, with 2 cm - 25 cm inline - crossline sampling interval. Data processing includes background field removal and a band-pass filter to remove incoherent noise and enhance localized magnetic anomalies. Ground-penetrating radar (GPR) is a pulsed electromagnetic technique designed to detect dielectric discontinuities buried beneath the earth's surface (see e.g. Daniels, 2004). The basic system is composed of a couple of transmit and receive antennas, which are used to propagate wide-band electromagnetic radiation and to detect the backscattering from targets. Arrival time and amplitude of the backscattered radiation are exploited to image dielectric discontinuities. Ursin (1983) proposed a unified treatment of elastic and electromagnetic (EM) wave propagation in horizontally layered media and such formal equivalence allowed sharing procedures for analysis and data processing that are used in exploration seismology. In reflection seismics and GPR, an irregular topography produces variations in traveltime, which are due to the differences in elevation of the source and receiver and need to be corrected, both in single- and multi-fold datasets, with a positive or negative time compensation (static correction) depending on the topography and the position of a reference plane (datum). Further dynamic corrections are performed on multi-fold data after velocity and CMP gather analysis.

A Groundtracer GPR system equipped with 300 and 500 MHz central-frequency antennas was used to acquire single- and multi-fold (average 1200% fold) data. Minimum and maximum offset were set according to preliminary tests and range between 60 and 240 cm. The basic GPR processing sequence included de-wow, background removal, amplitude analysis and corrections, spectral analysis, time-varying band pass filter and predictive deconvolution with operator length = 30 ns and prediction distance = 4 ns. The instantaneous attributes (Energy and reflection strength) of the radar trace were calculated by Wavelet Transform techniques (Guangyou and Pipan, 2003), which are less sensitive to noise .

2-D seismic tomography at constant elevation planes was performed on a prehistoric tumulus. A simple transmission scheme was implemented to obtain angular coverage and minimum data acquisition/inversion effort. The only constraint in data acquisition geometry is to keep constant the elevation of sources and geophones. Angular sampling interval and number and spacing of the selected elevation levels affect the resolution attainable. By adding sources and receivers around the mound at small angular interval we obtain information from most of the model function's cells, while closely spaced elevation levels allow more detailed tracking of traveltime/attenuation variations as a function of depth (see e.g. Tien-when and Inderwiesen, 1994). Tomographic inversion starts from traveltime/amplitude picking for traces all source-receivers pairs and is based on an initial velocity/attenuation model. Data analysis and previous stratigraphic and geological information, if available, typically drive the initial model definition. The model is then updated after comparison of the observed traveltime with those calculated from the model (see e.g. Tien-when and Inderwiesen, 1994).

3 Results

An example of magnetic gradiometry results is shown in Fig.1. Magnetic data come from the Flambruzzo (NE Italy) area and clearly show the location of buried remains of orthogonal roman walls, and a furnace of the same period. The magnetic anomalies shows small variations (in the range of ±12nT from average magnetic field) that exhibit geometric coherence and are actually related to buried remains of brickwalls.

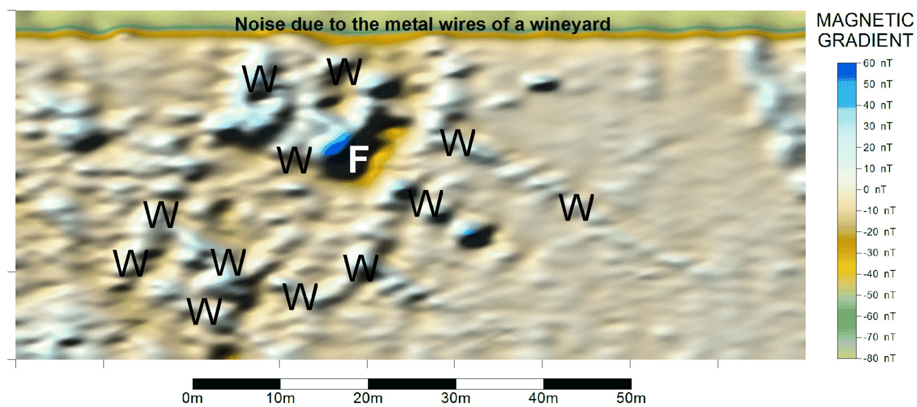

Fig. 1. Magnetic processed data obtained with a gradiometric device. The most negative zone is related to the metallic wires of a wineyard. Small elongated anomalies clearly image several buried roman wall (W) remains. The dipole *F* can be interpreted as a roman brick-kiln.

Imaging of the prehistoric grave in Fig.2 is the result of 32 multi-fold GPR profiles combined in a 3-D volume. The grave is in limestone and the sub-horizontal reflectors in the left part of the GPR section (Fig.2A) are the stratigraphic joints imaged by GPR. Point *L* marks the position of limestone outcropping at the surface. A layer of fine grained sediments, several meters thick, is located to the right of point *L*.

The remains of a ring-shaped Romanic baptistery, 10 m wide approximately, are imaged by multi-fold GPR in Fig.3. The site is in NE-Italy (S.Giovanni di Duino, Trieste) and the existence and location of the baptistery was unknown. The remains are totally buried and no surface evidences are observed in the area. Boundaries of the baptistery (red circles in figure) and internal structures are clearly imaged by the GPR data. The 3-D GPR volume covers only part of the buried remains due to logistic constraints. The value of resolution in geophysical surveying for archaeology is further illustrated by the example in Fig.4. This is a typical exploration case, where no previous information is available and site characteristics are totally unknown. The site is located in the industrial zone of Padua (NE-Italy) and the study area is a parking lot. The *CR* zone in Fig.4B is the high-amplitude response from concrete plates with internal rebars, that produce strong ringing effects in the record. Targets of potential interest range from small size objects (*S* in Fig.4A) to a large structure, 3 m wide approximately, inidcated by the white arrows in Figs. 4A,B,C. The borders of such buried feature are imaged with decimetric detail. The final example of high-resolution geophysical surveying of archaeological sites comes from a prehistoric tumulus in NE-Italy (Barazzetto, Udine).

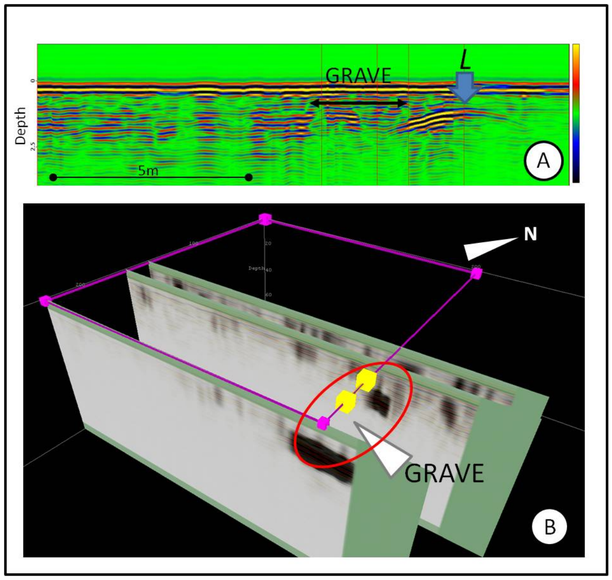

Fig. 2. Imaging of a prehistoric grave on the island of Malta. A) Example of 300MHz GPR profile intersecting the grave. *L* highlights the limit of the limestone, which extends from the beginning of the profile up to this point. B) 3D volume obtained combining all the 32 profiles acquired. The grave is clearly imaged by the *Energy* attribute.

The area is now partly covered by a church and the study is therefore performed by integrating measurements done around (seismic tomography) and above (multi-fold GPR) the elevated zone. GPR and seismic data, even if sensitive to different physical properties of the materials, converge in highlighting a somewhat elliptic buried target (in map view, Fig.6A,B) at an average 1.5 m depth from present topographic surface, with a slightly upward convex boundary marked by the yellow reflector in Fig.5B. Based on the integrated interpretation performed with the archaeological experts and on the results obtained from previous surveys on similar tombs, such feature likely corresponds to the central part of the tumulus. The strength of the GPR reflection is probably due to the stones laid to cover the funerary chamber.

4 Conclusions

The application of integrated geophysical methods and advanced signal analysis (attributes of radar trace) indicate that resolution can be enhanced within the physical limits of the methods and improved subsurface images can be produced in archaeo-geophysical surveys to attain higher levels of confidence in identification and characterization of targets of potential interest. Improved focussing of magnetic data analysis can be achieved by filtering the background field and by visualizing the short wavelength variations that are related to shallow targets. The magnetic method has well

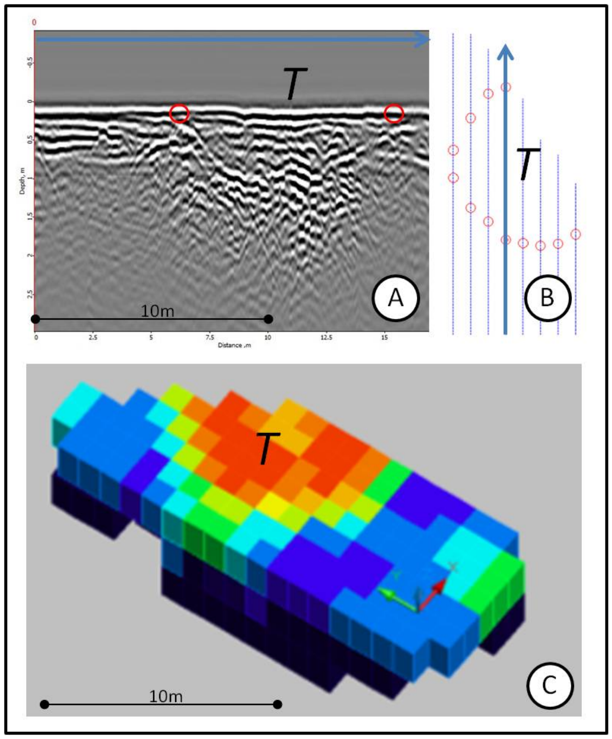

Fig. 3. 2D and 3D subsurface reconstruction of the remains of an unknown Romanic baptistery. A) 2D processed 300MHz GPR profile; B) schematic map of the GPR profiles with the border of the discovered structure highlighted by red circles. The location of the profile in A) is specify by the azur arrow; C) volumetric analysis of the Reflection strength calculated on all the processed profiles. *T* capital letter marks the centre of the baptistery.

established characteristics of low-cost and high efficiency, which are combined with good performance in archaeological surveys even in the case of low-constrast targets. It is therefore best suited for reconnaissance work as a preliminary step to design and complete further high-resolution data acquisition. An optimum sequence to achieve the maximum achievable resolution in non-invasive archaeological surveys should therefore include multiple steps, starting from the preliminary magnetic survey followed by wave-equation based methods, like GPR, to obtain images and estimates of physical properties in 3-D subsurface models. GPR imaging benefits from the application of multi-fold methods, which allow increment of SNR and selective analysis and removal of coherent events. Moreover, multi-fold methods are instrumental in velocity and attenuation analyses, which provide insight into the physical properties of the subsurface materials. The use of attributes of radar trace can further improve imaging and data interpretation in GPR: the sensitivity of attributes to different factors (amplitude, phase and their variations) allows improved focusing of the targets through the combined in-

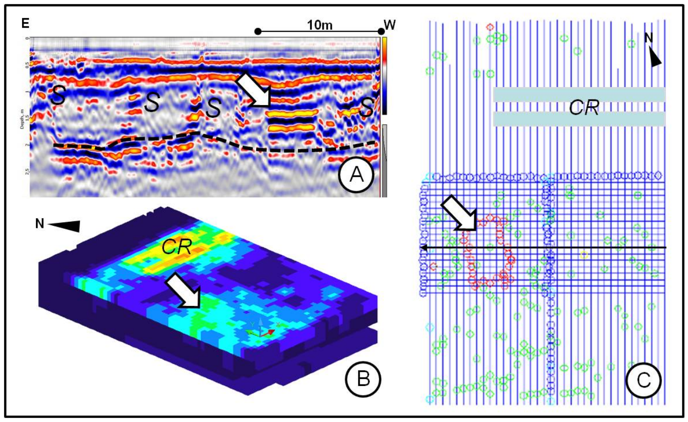

Fig. 4. GPR results obtained in a possible archaeological area close to Padua. A) Example of a 500MHz full processed (depth migrated) profile; B) Reflection strength calculated within the depth interval 1-1.5m; C) Map summarizing the survey results. S: Small objects; white arrows: main subsurface structure; CR: Concrete plates on the surface with internal rebars. Circles on c) describe de position of different targets: limits of the main structure in red, buried pipes in blue, small objects in green.

terpretation of processed data and attribute volumes. Wave-equation based tomographic applications, such as e.g. transmission seismic tomography, offer promising solutions but are limited to a subset of targets, namely elevated ones, such as pyramids, mounds, tumuli. They are nonetheless best suited for an integrated application, together with magnetometry and GPR, in case of study of such class of targets. As for technical data acquisition issues, conditions met in the proposed case studies and in a wide range of target/soil combinations indicate that the frequency range between 200 and 500 MHz is adequate for most applications of GPR to archaeological studies. Future developments should explore the possible application and integration with the proposed methods of ultra high-resolution shallow multi-component reflection seismics, by exploiting low energy sources that are suitable for use at archaeological sites.

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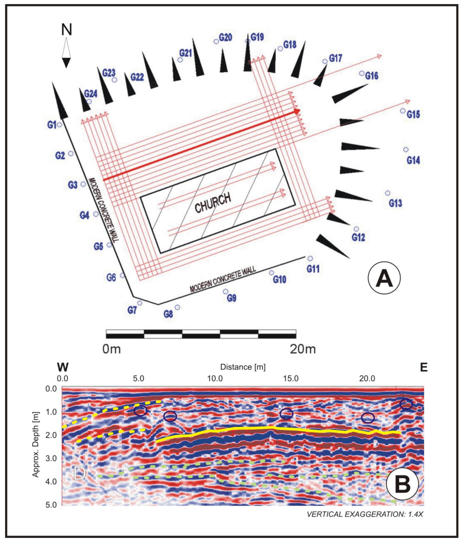

Fig. 5. GPR and seismic tomography on a prehistoric tumulus. A) location map with superimposed the GPR profiles (in red) and the geophones (in blue) positions; B) Example of a 300MHz preocessed and interpreted GPR profile. Yellow continuous line follows the top of a high reflective horizon; yellow and green dotted lines highlights low amplitude reflection respectively above and below the previous surface. Blue circles show small diffractions.

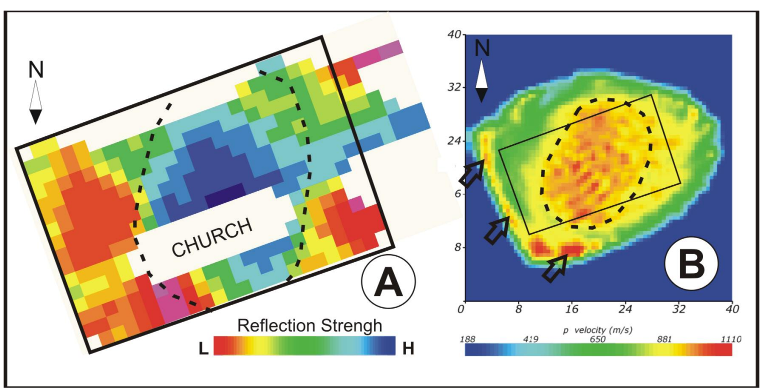

Fig. 6. Integration of GPR (A) and seismic (B) results on the same area of fig. 5. A) reflection strength calculated along a 1.5m GPR depth slice; B) Seismic tomography inversion results. The area highlighted by the dotted lines represents the same structure on both geophysical methods. The rectangle on B) marks the extension of the area plotted in A). The arrows indicate the effect of the modern wall shown on fig.5A.

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