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Recent advances in the integrated geophysical exploration of buried archaeological targets

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Summary. — We propose the integration of magnetic, electromagnetic (ground-penetrating radar, GPR) and seismic methods to study the inner structure of prehistoric funerary mounds. The combination of techniques allows high-resolution imaging and detection of buried targets and characterization of subsurface materials based on magnetic susceptibility, dielectric permittivity, conductivity and seismic velocity/attenuation. The 2012 archaeo-geophysical expedition to Scythian necropoleis in Kazakhstan allowed advancement of the integrated procedure through optimization of the individual techniques. We improve the results of seismic tomography inversion through an ART algorithm with a relaxation parameter which is progressively reduced during the iterative reconstruction process. We use instantaneous attributes and spectral decomposition to improve the interpretation of GPR reflection data. The results obtained from the 2012 dataset allow detailed reconstruction of the inner structure of three kurgans (*i.e.* funerary mounds) with maximum 7 m central elevation. In particular, localized anomalies related to metallic targets smaller than the GPR and seismic resolution limits are identified from magnetic data after high pass filtering; GPR data allow imaging of inner stratigraphy up to a maximum depth of about 250 cm; seismic tomography maps large traveltime anomalies probably related to funerary chambers at the base of the mound.

PACS `93.85.-q` – Instruments and techniques for geophysical research: Exploration geophysics.
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PACS `93.85.Jk` – Magnetic and electrical methods.
PACS `93.85.Rt` – Seismic methods.

1. – Introduction

The archaeological excavation of a funerary mound is a challenging and demanding task, which implies the application of a layer-stripping technique to the reconstruction of the inner stratigraphy. Time and costs of such procedure can be greatly reduced by the preliminary non-invasive identification of favourable sectors, *i.e.* zones of the mound where the probability of buried targets (in particular funerary chambers) is maximum.

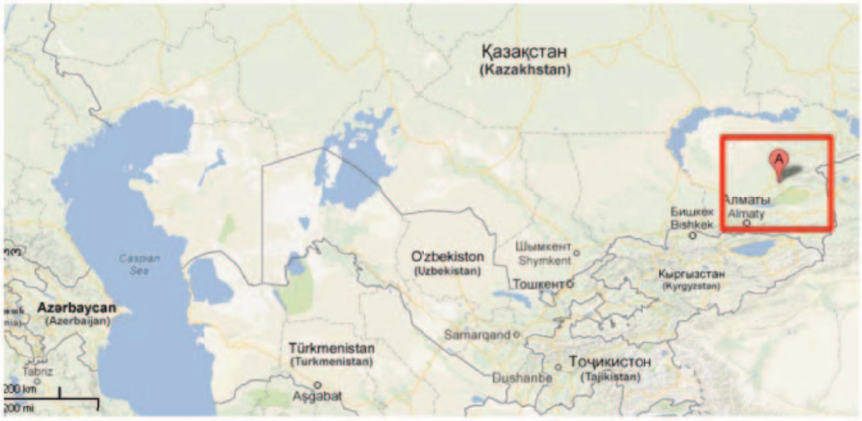

Fig. 1. – Location map of the test site: a Scythian necropolis in the Almaty region (Kazakhstan).

At the same time, burial mounds are an ideal laboratory to test integrated geophysical techniques for the high-resolution study of buried archaeological targets. The first studies based on single techniques, such as seismic refraction [1], magnetic measurements [2] or seismic tomography [3] evidenced the resolution and characterization limits that individual geophysical methods can not overcome. Recent works combine magnetic, GPR, seismic and low-frequency EM (see, *e.g.*, [4,5]) and successfully achieve higher resolution, improved characterization of materials and more detailed mapping of inner stratigraphy and features of archaeological interest. This study further exploits the convexity of the mounds to jointly apply reflection and transmission wave propagation based methods, *i.e.* GPR and seismic tomography, integrated by magnetic measurements to identify localized anomalies associated with buried metallic objects. The latter technique is particularly useful in the identification of small targets that can not be resolved by wave methods. The test site is located in the Almaty region of SE- Kazakhstan (see fig. 1 for location). It was surveyed in the framework of the 2012 archaeo-geophysical expedition to Scythian necropoleis, jointly organized by Centro Studi e Ricerche Ligabue (Venice, Italy) and University of Trieste (Italy). The target of the 2012 expedition were four necropoleis: we obtained high-resolution GPR and tomographic data, complemented by magnetic anomaly maps, that allow the interpretation of inner stratigraphy and the identification of targets of potential archaeological interest. The methodological advancement of the present work is related to optimization of the individual techniques in the data acquisition and processing/inversion phase. In particular, finely sampled data acquisition grids and high angular coverages were used in the acquisition phase, an optimized ART algorithm in tomographic inversion of transmission seismic data, attributes and multi-attributes cross-interpretation in the interpretation of GPR data. The results confirm the effectiveness of an integrated approach to burial mound geophysical studies and, in particular, highlight the complementary roles of GPR and seismic tomography in unravelling the shallow and peripheral stratigraphy and the deep and central structure of the mounds, respectively. Seismic tomography plays a crucial role in the identification of burial chambers.

The geophysical results of the 2012 geophysical surveys will be validated by excavations to be performed starting from 2014.

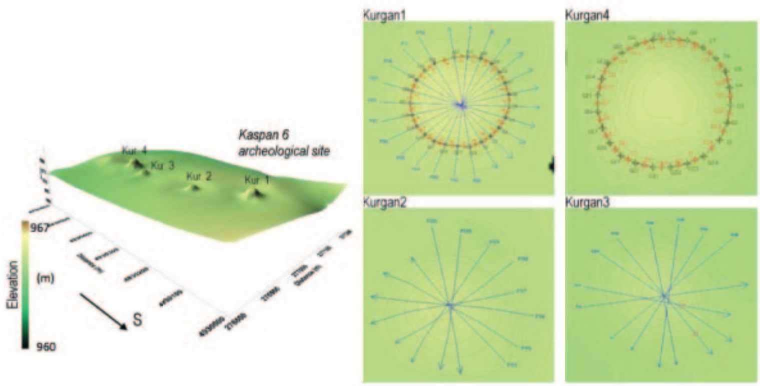

Fig. 2. – Example of 3D digital elevation model and topographic maps of the kourgans at the Kaspan 6 archaeological site. Positions of seismic sensors and sources and of GPR profiles are superimposed on the topographic maps.

2. – Methods

Kourgans (*i.e.* Scythian burial mounds) have an approximately conical shape and are normally built over one or mores funerary chambers, located at or below ground level. The position of the burial chamber is variable (*i.e.* not always central or corresponding to the projection of the most elevated part of the tumulus) as well as the dimensions of the mounds, which can be more than 100 m in diameter and 15 m of elevation for the monumental tombs, but are more commonly in the range of 5–40 m in diameter and 1–7 m elevation. Figure 2 shows the Digital Elevation Model (DEM) and the topographic maps of the kourgans surveyed at one of the four archaeological sites visited by the 2012 expedition.

Our study is based on the integration of magnetic gradiometry, multi-fold (MF) ground-penetrating radar and seismic transmission tomography. 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.*, [6]). 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. The formal equivalence of elastic and electromagnetic wave propagation in horizontally layered media established by Ursin [7] allows analysis and data processing by means of exploration seismology techniques. In particular, we applied static, dynamic, spherical divergence and attenuation corrections, predictive deconvolution, band-pass filtering and FK migration (see, *e.g.*, [8] for details). The instantaneous attributes (Energy and reflection strength) of the radar trace were calculated by Wavelet Transform techniques [9], which are less sensitive to noise.

Table I. – *Data acquisition parameters (GPR and seismic tomography).*

GPR	
Central frequency	250–500 MHz
Sampling frequency	2.5–5.0 GHz
Record length	180 ns
Sampling interval	5 cm
Seismic tomography	
Seismic source	6 kg sledge hammer on steel plate
Geophones	40 Hz natural frequency
Angular sampling	7.5°
Sampling frequency	1.2 kHz
Record length	0.2 s

A RAMAC GPR system equipped with 250 and 500 MHz central-frequency antennas was used to acquire single- and multi-fold data. 60 and 240 cm minimum and maximum offsets were selected on the basis of preliminary tests. Transmission 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 the elevation of sources and geophones constant. A 7.5° angular sampling interval was selected to improve the results of tomographic inversion. An ART reconstruction scheme was adapted and optimized by including a relaxation parameter progressively reducing with the number of iterations (see, *e.g.*, [10]).

Table I reports data acquisition parameters for the GPR and seismic tomography measurements. Tests performed with different sledge hammers and steel plates allowed to choose a combination that produced a spectral peak in excess of 140 Hz. Five preliminary hammer blows were used at each source location to ensure consistent source-ground coupling. The resulting source signature was highly repetitive.

3. – Results

The test site is characterized by low magnetic, electromagnetic and seismic noise levels, due to its remote location in an unspoiled environment. The GPR datasets are characterized by an average Signal-to-Noise ratio around 9.3 dB.

An example of magnetic gradiometry results obtained at the Kaspan 6 test site is shown in fig. 3. A strong anomaly clearly shows the location of a buried target characterized by large magnetization. The GPR profile across the mound (fig. 4) highlights shallow, dipping reflections up to an approximate 150 cm depth that are associated with the thin layers (average thickness around 25 cm) put down during construction. A series of diffractions at the base of the imaged reflectors indicates the presence of coarser materials, characterized by granularity comparable to the radar wavelength and therefore probably in the boulder size range. A weak diffraction in the central, most elevated position (see ellipse in fig. 4) is produced by a localized buried target at shallow depth (less than 50 cm). The depth estimate of the magnetic anomaly source, based on the slope of the magnetic gradient, is compatible with such depth value and the weak diffraction is therefore probably associated with a shallow buried target with high magnetization.

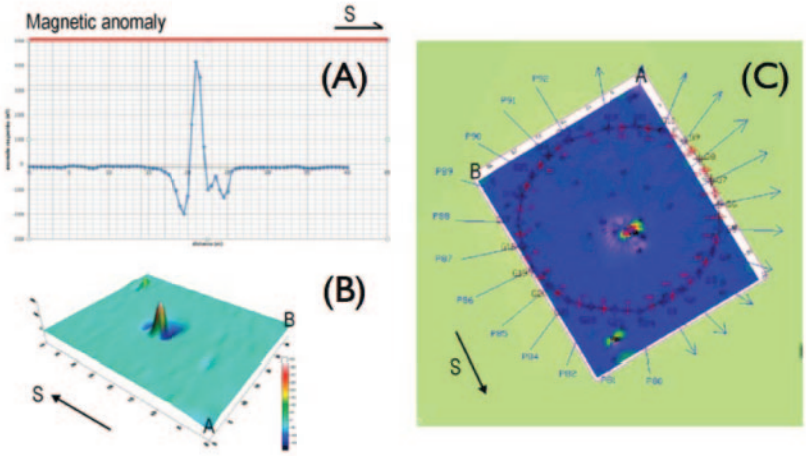

Fig. 3. – Example of magnetic results at the Kaspan 6 test site: (A) Magnetic profile across the mound; (B) 3D view of magnetic anomaly; (C) Magnetic anomaly map with superimposed location of GPR profiles and seismic source/sensor locations.

The proposed integration of GPR and seismic tomography methods is illustrated by the results obtained at the Kaspan 6 test site, from a 30 m diameter kourgan. The GPR data successfully image reflectors up to an approximate 300 cm depth (fig. 5A,B). The line drawing produced by the GPR interpretation (fig. 5C) highlights a rather regular layering, approximately parallel to the topographic surface and sparse diffractions likely associated to isolated stones (boulders, see above). Two clear interruptions of the reflectors (1,2) show up at locations 10 and 24 m from the profile's starting point. They are indicated by dotted lines and show an increasing dip, from subvertical at the surface to approximately 35° in the deeper segment. Their location is symmetric with respect to the apex of the tumulus and the relative displacement of the reflectors on the two sides indicates a lowering of the central part of the mound. The two interruptions therefore behave

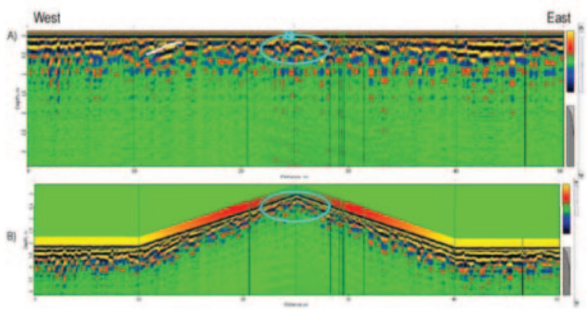

Fig. 4. – Example of 250 MHz GPR section across a 30 m wide kourgan: A) before B) after topographic correction. The central ellipse highligths the location of the probable source of the magnetic anomaly in fig. 3.

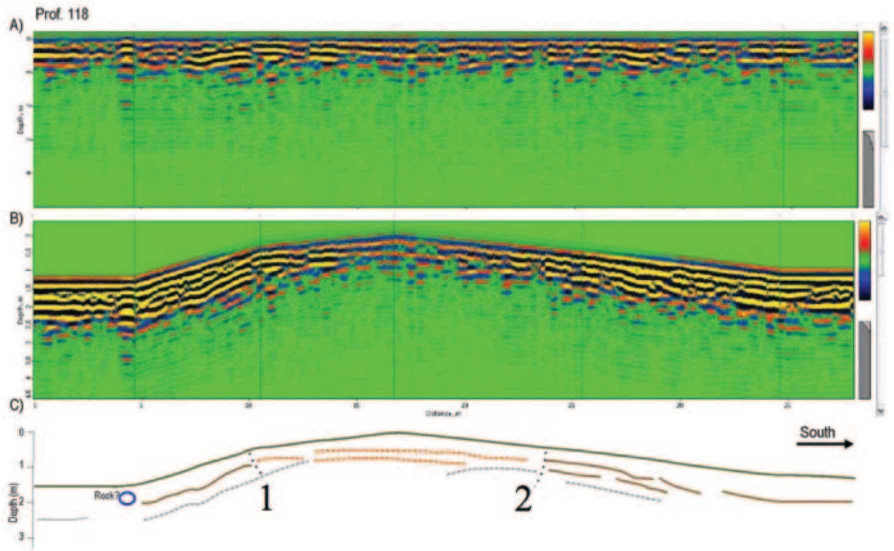

Fig. 5. – Example of 250 MHz GPR section across a 30 m wide kourgan: A) before B) after topographic correction C) line drawing of the interpreted GPR reflectors and targets. A collapse structure, possibly related to failure of the deep chamber roof, is bounded by two sub-vertical small faults at 10 m and 24 m (dotted, lines: see text for details).

as *normal faults* and are compatible with a moderate collapse of the central part of the kourgan. The burial chamber cannot be detected from GPR data analysis, due to the radar wave attenuation. Nonetheless, transmission seismic tomography successfully images traveltime anomalies that can be correlated with deeper features at the base of the mound. Figure 6 A,B shows a comparison of the results obtained by a SIRT and an optimized ART inversion of the data. The latter exhibits an improved resolution in the identification of the anomalies. The application of the ART algorithm to the kourgan of fig. 5 clearly shows a central area, with irregular geometry, characterized by strong traveltime anomalies. The limits of the area fall within the radius defined by the interruptions (1,2) of fig. 5 and are probably connected to the collapse of inner structures of the tumulus (as, *e.g.*, the roof of the funerary chambers) associated with the traveltime anomalies identified by seismic tomography.

4. – Conclusions

We optimized and tested an integrated magnetic, seismic and GPR procedure to image the subsurface structure of burial mounds. Enhancements in imaging and resolution are obtained through the following steps: reduction of sampling interval in data acquisition (5–2 cm linear in GPR and Magnetic; 7.5° angular in Seismic Tomography); application of an optimized ART algorithm in the tomographic inversion of seismic data and of a multi-attribute analysis in the interpretation of GPR data. The procedure was applied to Scythian funerary mounds in Kazakhstan and succeeded in imaging the shallow stratigraphy of the mounds, up to approximate maximum depths and resolutions of 250 cm and $0.05\,\mathrm{cm}^{-1}$, respectively.

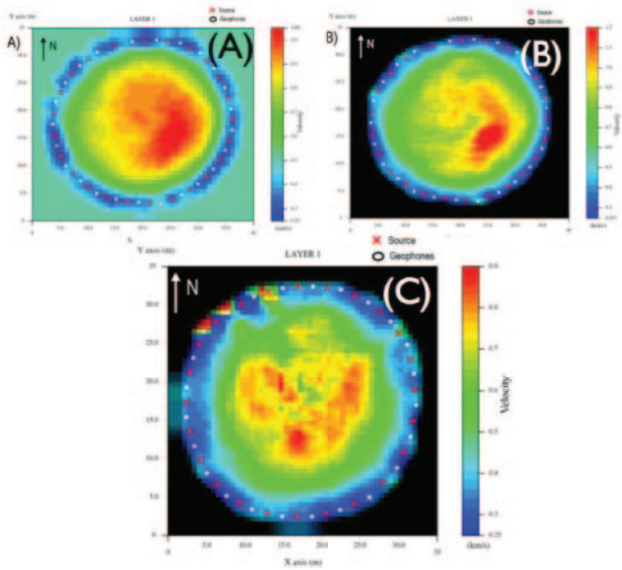

Fig. 6. – Example of seismic tomography results at base level (0 elevation from topographic surface) across selected kourgan at the test site: comparison between A) SIRT and B) optimized ART results C) results of ART tomographic inversion across the kourgan in fig. 5.

The surveyed kourgans are covered by a sandy loam: no sampling or preliminary excavations were made during the 2012 expedition and no sedimentological data are therefore available about the inner materials. Nonetheless, funerary mounds are normally built with the material available on site, which are layed in lenses corresponding to the average volume of the containers (cloth buckets) employed for the construction. We can therefore infer that the layers imaged by GPR are made of sediments comparable to the surface layer, with heterogeneities related to the variability of the weathered layer from which they come from.

The fraction of clay rich sediments and the presence of coarser materials (probably boulders or cobbles) in the shallow part of the mounds reduce the penetration of radar waves due to attenuation and scattering. The depth reached at the test sites is nonetheless adequate to image the shallow stratigraphy and to establish correlations with shallow localized magnetic anomalies.

The ART algorithm with a varying relaxation parameter, applied to traveltime transmission tomography, allows the identification strong anomalies at the ground level. Based on the results of previous tomographic studies of funerary mounds, such anomalies are most likely related to burial chambers, where strong and detectable contrasts in physical properties are observed at the contact between sediments and materials bounding the chamber (normally wood and stones).

The results obtained through extensive tests of the optimized procedure show that geophysical exploration can reconstruct structure and stratigraphy of funerary mounds on a large range of dimensions. We present examples of recent application to kourgans with a maximum 40 m diameter: processing of data from larger mounds is in progress and the preliminary results are promising. Small tombs (*i.e.* maximum elevation 3 m) can be completely surveyed by means of GPR and magnetic methods. The characteristics of the seismic source, with specific reference to bandwidth and spectral peak, deserve further testing comparative evaluation on mounds of different dimensions. The source used in the present tests (140 Hz spectral peak and approximately 180 Hz of bandwidth at half maximum power) allows satisfactory imaging of traveltime anomalies in the 30 to 50 m diameter range. The proposed technique can be applied at different stages of the archaeological excavation and can be adapted to mounds of different dimensions and characteristics. Further benefits of the method come from the possibility of imaging not only the original structure and stratigraphy of the tombs but also the effects of looting attempts (tunnels/shafts) and of successive uses of the mounds.

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