Exploring the paleolithic cave of Fumane (Italy): Geophysical methods as planning tool for archaeology

Nasser Abu Zeid, Samuel Bignardi,Giovanni Santarato and Marco Peresani, University of Ferrara, Italy*

Summary

Geophysical techniques are seldom used for the investigation of paleolithic archeological sites, mostly due to their sedimentary nature and the almost complete absence of architectural remains that can result in clear geophysical anomalies. The Fumane cave (Italy) is considered one of the most important sites in Europe. Recent investigations and studies carried out by the archaeological group of the Dep. Of Humanities (University of Ferrara) with the enrollment of the Department of Engineering of the same University allowed for the reconstruction of the 3D model of the Fumane Cave. This offered an opportunity for the applied geophysics group of the same university to assess the capability of Electrical Resistivity Tomography to retrieve subsurface information of archaeological interest. As primary goals, the study aimed at the creation of a three-dimensional resistivity model of the subsurface, to infer the nature of the sedimentary infill, so enabling a better understanding of the depositional processes involved in the formation of this important archaeological deposit and at the same time, for planning long-term field-investigations and to locate areas interesting for excavation. Moreover a Ground penetrating radar and a Nakamura survey were attempted in an integrate approach to test whether the combined methodologies could provide further insight about the subsurface. With respect to previous work, we present new and improved results both on ERT, GPR and HVSR. In particular, the HVSR test was accomplished to gain information about the maximum thickness of the deposit and to see if other impedance contrast discontinuities are present as was anticipated by previous archaeological studies.

Introduction

Ground surface geophysical prospection methods have been used extensively in archaeology for non-invasive exploration of shallow-depth targets. Different techniques are of course sensible to different physical properties so that, when used together in an integrated geophysical survey, they allow reaching a deeper insight about position and extension of anomalous bodies present in the subsurface.

In a previous study (Obradovic et al. 2015) presented 2D Electrical Resistivity Tomography (ERT) results of this paleolithic deposit (Paresani et al., 2008; Peresani, 2012).

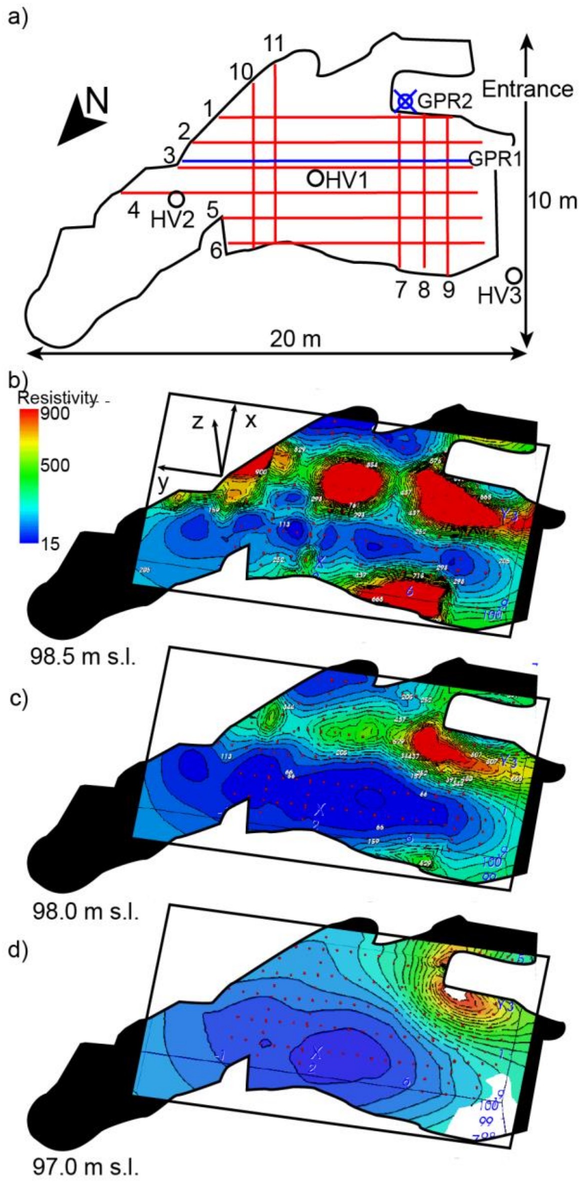

Figure 1: selected 3D resistivity slices of the 3D ERT inversion model. Blu: low resistivity volumes associated with fine grained sediments. Red: high resistivity volumes associated with troughs filled with drained coarse-grained sediemnts.

They showed that the methodology is of high value to search for sediment accumulations of different textures. Further they showed that resonance peaks obtained by Horizontal over Vertical Signal Ratio (HVSR: Nakamura, 1989, 2000) can be observed and empirically correlated to possible presence of subsurface acoustic impedance contrasts. In this work the ERT data was further elaborated so attaining a 3D resistivity model. Further, Ground Penetrating Radar (GPR) results are shown for the very first time. While GPR tests were carried out at specific locations to support the ERT model, some HVSR measurements were undertaken to possibly obtain information about the maximum depth of the deposit. While in previous work (Obradovic et al., 2015) HVSR curves were only qualitatively discussed, here a shear wave velocity model is obtained by inversion. This integrated geophysical survey was undertaken in order to achieve a better understanding of the evolution of this cave, as well as to detect hidden sedimentary structures of interest. The purpose of such investigation is mainly to give indications to be used for planning the archaeological fieldwork

The achieved result paves the strategy for the developments of a virtual archiving system were to collect all the available and future knowledge of this important site. Such a system should be of major help to researchers for planning the archaeological fieldwork and may constitute the first step towards enhancing its visibility to the broader public.

Methods

The geophysical survey was conducted mainly by means of the ERT, while a GPR and a HVSR survey were performed to investigate other physical properties to put light on the nature of observed resistivity anomalies.

While GPR is commonly used in archaeology, its application in paleolithic caves is very rare, perhaps because of the absence of those targets that are quite easily detected in archaeological sites. Further, despite the fact that HVSR is seldom used in such a context, successful applications of the method in archaeology exist (Abu Zeid et al. 2016, 2017), so that we decided to investigate the use of these techniques to cross-check and possibly integrate ERT results, therefore producing more reliable result. The ERT has the power to reconstruct the vertical and horizontal electrical stratigraphy (i.e. resistivity), while the HVSR spectral ratio helps in inferring the presence of lithological discontinuities characterized by different seismic velocities. The use of the HVSR method aimed to infer the depth to the hard bedrock and to identify possible shallow elastic reflectors hence extending the investigation depth of the ERT survey, confined to the shallowest 3-4 m, to the whole thickness of the deposit, estimated around 5-6 m. Finally, GPR was used mainly to investigate the presence of reflectors due to ancient rock falls, buried boulders or other more regular geometries.

The proposed integrated methodology is intended to achieve the following objectives in the long-term period: 1) to execute a high resolution ERT survey to investigate the shallowest part of the deposit and obtain more insight on its geometry and texture distribution; 2) to localize zones of greatest archaeological interest and to identify possible voids and/or channels; 3) to use microtremors to infer discontinuities of acoustic impedance present within and/or at the base of the deposit; 4) to generate an high resolution and geo-referenced three-dimensional model of the subsurface of the cave to be combined with previously acquired 3D laser scanner and photogrammetry data in a whole 3D model of the cave (Bolognesi et al., 2015). In this way, a great visual and communicative impact is achieved on a wide professional and non-professional public.

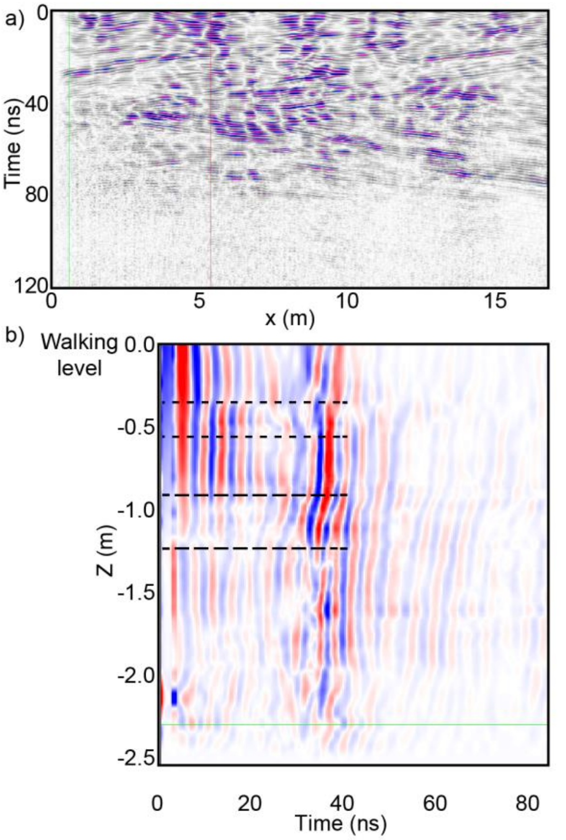

Figure 2: Two selected radargrams. Radargram a) was recorded along the line GPR1 (figure 1) on the top of the deposit with a 400 MHz antenna. Real amplitude is shown. Radargram b) highlighted as GPR2 was recorded vertically, along the deposit wall of figure 3c using a 200 MHz antenna. Total energy view is shown.

The ERT survey comprised 11 profiles in total, one-meter spaced and covering the main excavated area (numbered lines in Figure 1). The electrode spacing was set to 0.5 m and data were collected using the ABEM SAS 4000 Multichannel georesistivity-meter. Profiles length was variable between 6.5 and 12 meters. Since we wanted to achieve the maximum quality result, the measurements were collected using both the Pole-Pole and Wenner-Schlumberger electrode configurations, to take advantage of the greater depth of investigation offered by the former, while retaining the enhanced resolving power of the second, especially in the shallowest 2 meters. Apparent resistivity data retained after preprocessing was inverted to obtain the best estimate of the true subsurface resistivity. To this end ERTLab 3D code was used. The code can handle rough topography so that the free surface represented by the two excavated sides of the deposit was handled by imposing suitable boundary conditions (Morelli and LaBrecque, 1996).

Concerning the passive seismic data, it was collected using a three component 2 Hz electromagnetic seismometer connected to a 24 bit seismograph (model Vibralog M.A.E. Italy). The equipment was positioned at three strategic points (Circles in Fig. 1a) with the seismometer oriented northward, which is also parallel to the cave walls. Seismic noise data were recorded continuously for one hour at 250 Hz sampling rate. The analysis performed using the HVSR method as implemented in the Geopsy (Di Giulio et al., 2006, Wathelet et al., 2008) was qualitatively discussed in (Obradovic et al., 2015) In this context, HVSR curves were inverted using OpenHVSR (Bignardi et al., 2016).

Finally, Radar scans were acquired using a 200 MHz antenna connected to the acquisition unit model RIS PLUS by IDS S.p.A. (Pisa, Italy). As the surface of the archaeological site could not be walked, acquisition took place by manually moving the antenna over the surface of the deposit.

Results

In Figure 1b-c slices at significant levels of the 3D ERT model are shown. The shallowest shows few anomalies with high spatial resistivity variations, especially along the eastern portion of the cave. The features of main interest are the zones with resistivity values lower than 100 Ohm.m (ERT lines 1 to 4 in Figure 1a), which extend to a depth of about 3 to 4 meters below the walking surface. Such zones are most probably the richest ones in fine-grained materials. Being fine-grained materials usually rich in term of remains, these areas are the best candidates for future excavations. On the contrary, ERT- lines 2 and 3 show the presence of very high homogenous resistivity volumes that can be associated to medium large blocks, probably detached from the ceiling, or alternatively, to dense accumulation of frost shattered stones. Medium and high resistivity volumes predominate the subsurface of the southern part of the deposit at the cave entrance where sediments are expected to be less humid and are also expected to contain more frost-shattered stones of medium-large size.

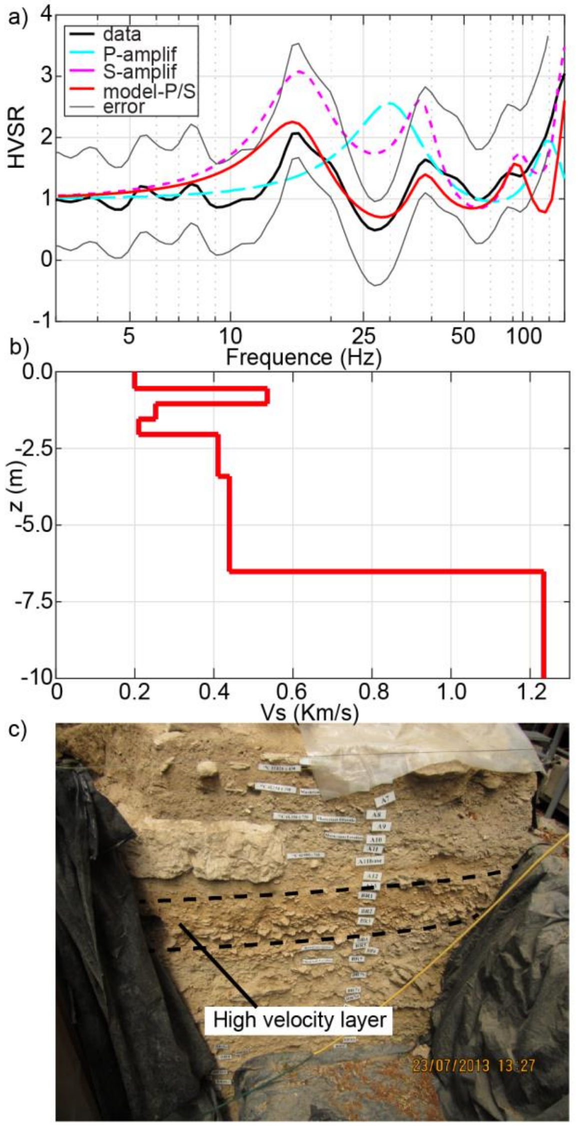

Figure 3: a) Result of HVSR inversion. Fitting between data and the synthetic HVSR. P and S waves amplifications are represented with dashed lines. B) best estimate subsurface model. Depth of deposit is found nearly at the depth of 6 m. An high Vs layer is present, nearly 1 m deep, most probably corresponding to the stratigraphic units highligted in figure c). c) An image of the deposit wall showing closely packed thin stratigraphic units.

A relatively shallow anomaly, around 40 cm deep, can be observed in profile no. 3 with regular geometry, which almost certainly can be associated to an old test pit whose traces are still visible today in the cave-mouth. GPR scans were able to highlight features in accordance with the ERT result. Figure 2a shows real amplitude view of radar section performed using a 400 MHz antenna along the major ERT anomalies (GPR1 in Figure 1). Grouped reflections may be observed. Further, Figure 2b shows a total energy view of radar section acquired vertically along the excavated wall of the deposit using a 200 MHz antenna. The radar signature corresponding to the fast seismic layer highlighted by HVSR can be observed.

The ERT result, as it was expected, did not give any indication neither about the maximum thickness of the deposit nor its basal morphology. Therefore, we tested the capability of HVSR to obtain an estimate of the whole thickness of the deposits. Figure 3 show the inversion result of the HVSR data acquired at the center of the cave. The outcome both in the data space (i.e. the fit of the curve) and in the parameter space (the shear wave velocity “Vs” profile) are shown in figure 3a and 3b respectively. Two major impedance contrasts can be observed at roughly 2.5 and 7 meters respectively. Further the inversion routine highlighted a layer of high Vs values located roughly at 1 meter beneath the surface which seemed to coincide with the coarse-grained stratigraphic units visible in figure 3c.

Of course, since available modelling routines assume a subsurface simplified as a stack of infinite parallel layers, which is an acceptable approximation only when lateral variations are much greater than the wavelengths into play, to achieve a good fit of the curve was particularly challenging. In particular 3D effects are expected to be not negligible in this complex geometry (Guéguen et al. 2007). Therefore, inversion was not able to retrieve the correct amplitude of the HVSR curves. Fortunately, in such a kind of inversions, amplitude is not as an important parameter as the frequency position of peaks, which despite of the unmet modeling assumptions was correctly retrieved. The best estimate Vs profile is shown in figure 2b. The retrieved velocity profile for the HVSR measurement point in the vicinity of the cave entrance (i.e. 5 meters below, at the base of the excavated portion of sediments) provided a Vs model in accordance to those retrieved from measurements performed at the top of the paleolithic deposit. Further, it can be inferred that the sediments become thinner towards the inner part of the cave.

Conclusions

Prehistoric sites have been greatly ignored by the wider geophysical community due to the nature and fragility of archaeological material and the almost complete absence of permanent structures. The presence of numerous, thin and closely packed occupation layers containing archaeological remains generally of tiny dimension that would be destroyed by invasive investigations makes the contribution of integrated geophysical methods significant. Features present on the site such as simple hearts and areas associated with the exploitation of large mammals and stone knapping, implicate that the site was periodically occupied by humans which left traces that could be detected only using very high resolution geophysical methods such as for example high frequency GPR (> 900 MHZ) to be executed before and during each excavation campaign. Of course this approach has a very short depth of investigation and is unpractical for many aspects. Nevertheless, geophysical methods still retain some value even at lower resolution. The present investigation proved successful in the description of subsurface morphology and possibly in the nature and thickness of sedimentary infill, delineating potential areas of archaeological interest in a completely non-invasive way. This work leads to methodological insights about how to improve both efficiency and effectiveness of future archaeological campaigns, especially suitable for the Palaeolithic age, enabling a better and successfully focused management of the available funds.

Being archaeological excavations destructive, it is of outmost importance to correctly document the location of each survey in order to faithfully reconstruct the subsurface geometries in later times. In this sense, the integration of geophysical maps with accurate 3D geometrical models allows to build high quality images capable of enhancing historical understanding and providing a powerful communication tool to attract a broad public, both professional and non-professional.

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Abu Zeid, N., E. Corradini, S. Bignardi, and G. Santarato, 2016, Unusual geophysical techniques in archaeology — HVSR and induced polarization, a case history: NSAG-2016, 22nd European Meeting of Environmental and Engineering Geophysics, https://doi.org/10.3997/2214-4609.201602027.

Abu Zeid, N., E. Corradini, S. Bignardi, V. Nizzo, and G. Santarato, 2017, The passive seismic technique 'HVSR' as a reconnaissance tool for mapping paleo-soils: The case of the Pilastri archaeological site, northern Italy: Archaeological Prospection, https://doi.org/10.1002/arp.1568.

Bignardi, S, A. Mantovani, and N. Abu Zeid, 2016, OpenHVSR: imaging the subsurface 2D/3D elastic properties through multiple HVSR modeling and inversion: Computers & Geosciences, **93**, 103-113, https://doi.org/10.1016/j.cageo.2016.05.009.

Bolognesi M., M. Obradovic, N. Abu-Zeid, M. Peresani, A. Furini, P. Russo, and G. Santarato, 2015, Integrazione di rilievi laserscan e fotogrammetrici con metodologie geofisiche applicata ad una cavità pleistocenica con stratificazione archeologica: Accademia Roveretana degli Agiati, a. 265, 2015, ser. IX, vol. **V**, B: 21–30.

Di Giulio, G., C. Cornou, M. Ohrnberger, M. Wathelet, and A. Rovelli, 2006, Deriving wavefield characteristics and shear-velocity profiles from two-dimensional small-aperture arrays analysis of ambient vibrations in a small-size alluvial basin, Colfiorito, Italy: Bulletin of the Seismological Society of America, **96**, 1915–1933, https://doi.org/10.1785/0120060119.

Guéguen, P., C. Cornou, S. Garambois, and J. Banton, 2007, On the limitation of the H/V spectral ratio using seismic noise as an exploration tool: Application to the Grenoble valley (France), a small apex ratio basin: Pure and Applied Geophysics, **164**, 115–134, https://doi.org/10.1007/s00024-006-0151-x.

Nakamura, Y., 1989, A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface: Quarterly Report of Railway Technical Research Institute, **30**, 25–33.

Nakamura, Y., 2000, Clear identification of fundamental idea of Nakamura's technique and its applications: Presented at the 12th World Conference on Earthquake Engineering, New Zealand.

Morelli, G., and D. J. LaBrecque, 1996, Advances in ERT inverse modeling: European Journal of Environmental and Engineering Geophysics, **1**, 171–177, http://dx.doi.org/10.4133/JEEG1.3.171.

Obradovic, M., N. Abu Zeid, S. Bignardi, M. Bolognesi, M. Peresani, P. Russo, and G. Santarato, 2015, High Resolution Geophysical and Topographical Surveys for the Characterisation of Fumane Cave Prehistoric Site, Italy: Near Surface Geoscience 2015: 21st European Meeting of Environmental and Engineering Geophysics, https://doi.org/10.3997/2214-4609.201413676.

Peresani, M., 2012, Fifty thousand years of flint knapping and tool shaping across the Mousterian and Uluzzian sequence of Fumane cave: Quaternary International, **247**, 125–150, https://doi.org/10.1016/j.quaint.2011.02.006.

Peresani, M., M. Cremaschi, F. Ferraro, Ch. Falguères, J. J. Bahain, G. Gruppioni, E. Sibilia, G. Quarta, L. Calcagnile, and J. M. Dolo, 2008, Age of the final middle palaeolithic and uluzzian levels at Fumane cave, northern Italy, using 14C, ESR, 234U/230Th and thermoluminescence methods: Journal of Archaeological Science, **35**, 2986–2996, https://doi.org/10.1016/j.jas.2008.06.013.

Wathelet, M., D. Jongmans, M. Ohrnberger, and S. Bonnefoy-Claudet, 2008, Array performances for ambient vibrations on a shallow structure and consequences over Vs inversion: Journal of Seismology, **12**, 1–19, https://doi.org/10.1007/s10950-007-9067-x.