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THREE-DIMENSIONAL ELECTRICAL RESISTIVITY TOMOGRAPHY FOR THE EXPLORATION OF THE PREHISTORIC DEPOSITS OF FUMANE CAVE (VERONA, ITALY)

Abstract - Obradović M., Abu-Zeid N., Peresani M. & Santarato G., 2015 - Three-dimensional electrical resistivity tomography for the exploration of the prehistoric deposits of Fumane Cave (Verona, Italy).

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The study is focused on implementation of Electrical Resistivity Tomography (ERT) for the investigation of early prehistoric sites taking up the archaeological site of Fumane Cave, located in Verona province in northern Italy as an example. To our knowledge, employment of geophysical techniques have been rarely incorporated into research activities of early prehistoric sites, mostly, due to their nature and almost complete absence of architectural remains that can result in geophysical anomalies from surface measurements The primary goals of the study are to determine: the geometry of the buried topography, the creation of three-dimensional model of the subsurface, shedding insight on the nature of the sedimentary infill that could better aid in understanding post-depositional processes involved in the creation of this important archaeological deposit. The study involved the use of two resistivity arrays to favor both the shallow resolution in the first 2-3 meters and to get information about the total depth of the deposit. Two and three dimensional inversion models provided suggestive resistivity images that resulted in detailed information about deposit's texture spatial characteristics indicating areas of low resistivity values where potential archeological materials may be found. Moreover, the maximum depth of the deposits is believed to be around 4/5 m based on the Pole-Pole resistivity images. The achieved findings shall guide future archaeological campaigns that are done on regular yearly basis by the archaeological researchers of the University of Ferrara.

Key words - Archaeology , Paleolithic, Fumane Cave, 3D Electrical Resistivity Tomography.

Riassunto - Obradović M., Abu-Zeid N., Peresani M. & Santarato G., 2015 - Esplorazione del deposito preistorico della Grotta di Fumane mediante l'impiego della tomografia della resistività elettrica in 3D.

La presente nota è incentrata sull'uso della tomografia della resistività elettrica (ERT) per indagare il sottosuolo di siti preistorici, considerando come caso di studio l'insediamento della grotta di Fumane (provincia Verona, Italia settentrionale). A nostra conoscenza, raramente metodi geofisici sono stati inseriti nell'attività di ricerca di siti preistorici antichi, soprattutto per la loro natura e per la completa assenza di resti architettonici, che possano dar luogo ad anomalie ottenute da indagini geofisiche di superficie. Gli scopi primari del lavoro consistono nel determinare la geometria della topografia sepolta, creando un modello tridimensionale del sottosuolo, e nel gettare luce sulla litologia del materiale di riempimento, che potrebbe aiutare una migliore comprensione nei processi post-deposizionali implicati nella creazione di questo importante sito archeologico a livello europeo. Lo studio ha utilizzato due tipi di quadripoli di misura, per ottenere il massimo della risoluzione nei primi 2-3 m ed un'informazione sullo spessore totale del deposito. Modelli di resistività bi- e tri-dimensionali forniscono suggestive immagini della distribuzione della resistività elettrica, con ciò producendo un'informazione dettagliata circa la distribuzione spaziale delle caratteristiche tessiturali del deposito, in particolare indicando volumi di bassa resistività, dove potenzialmente possono essere presenti materiali archeologici. Inoltre, lo spessore massimo del deposito è stato quantificato in circa 4-5 m. I risultati raggiunti guideranno le future campagne di scavo archeologico, condotte con una regolare cadenza annuale dagli archeologi dell'Università di Ferrara.

Parole chiave - Archeologia, Paleolitico, Grotta di Fumane, Tomografia della Resistività Elettrica in 3D.

Introduction

Ground surface geophysical prospection methods have been used extensively in archaeology for non-invasive investigation and identification of shallow depth targets relying on the physical property contrasts eventually existing between buried structures and the surrounding medium (Reynolds, 1997). The electrical resistivity method is one of the oldest and most frequently used geophysical method due to its relative simplicity, basic theoretical concepts and availability of friendly field instrumentation. Significant technological improvements of field instrumentation and computer software had as a result that 2D and 3D surveys are routinely applied and that there are even interest in developing 4D surveys (Papadopulous *et al.*, 2006; Loke *et al.*, 2013). In electrical resistivity method, direct current or low-frequency alternating current is injected into the soil and the developed artificial potential difference is measured between a different couple of electrodes. Variations in resistance to current flow, at depth, causes variations in the potential difference measurements, which provide the information on subsurface structure and gives an idea about the materials (Burger *et al.*, 2006). Since the late 1950's electrical resistivity method has been widely employed in archaeological sites and was successfully used for detection of large features such as masonry walls, stone foundations, ditches or mounds. Electrical resistivity surveys are also sensitive to variations of moisture, so they can often easily differentiate between excavated and unexcavated soil. As a results, most of the successful electrical resistivity surveys counts for late prehistoric, early historic or historic sites (Clark, 1990; Thacker *et al.*, 2002; Gaffney & Gatter, 2010; Papadopulous *et al.*, 2010), and much less for early prehistoric sites due to the poor nature of their archaeological remains, absence of permanent structures, very complex stratigraphy and thin layering. Nevertheless, a number of studies has been conducted over the years with noticeable results and invaluable information concerning the site geology, formation processes and buried topography (Ellwood *et al.*, 1993; Beck & Weinstein-Evron, 1997; Thacker *et al.*, 2002; Compare *et al.*, 2009; Valois *et al.*, 2010; Ortega *et al.*, 2010; Orlando, 2013). In the present work, the proposed methodology is intended to achieve the following objectives: 1) Execution of an high resolution geoelectrical resistivity survey to investigate the shallower part of the deposit and to offer more insight on its probable thickness; 2) To map the area of the greatest archaeological interest and to identify possible presence of voids and channels not yet discovered; 3) Generation of high resolution and georeferenced three-dimensional model of the cave by means of 3D laser scanner and photogrammetry, which can be easily updated, integrated with results of geophysical survey, shared and presented to the wider professional and non-professional public with great visual impact (see Bolognese *et al.* in this volume). The selected test site (Fumane Cave, Fig. 1) represents a middle to late prehistoric site, located to the north of Verona city, Northern Italy, along the southern margin of the Alps.

Archaeological and geological setting

Fumane cave is situated in a small tributary valley and is a part of a fossil karst system formed during the Neogene in the Ooliti di San Vigilio carbonaceous sandstone (Peresani *et al.*, 2011). From the main shelter zone other three tunnels are excavated in micritic bank and only partially explored. These are marked as A, B and C (Fig. 1). The main shelter zone is protected by sandstone rocks, which are unstable due to the fractures that are almost parallel to the cave walls and rising 20m in height. The intense fissuring suggests that the cave entrance was originally positioned few meters towards south (i.e. outside the present-day entrance) which was progressively reduced due to multiple collapses whose traces are still

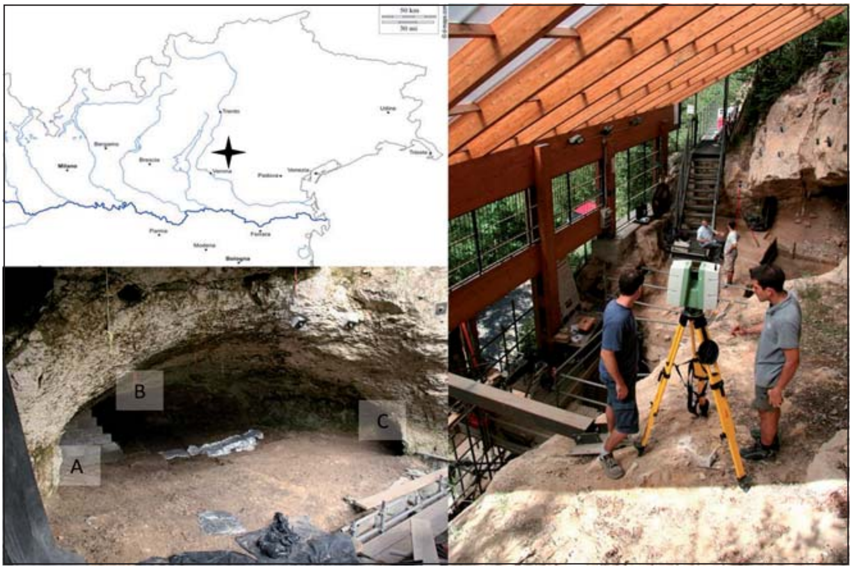

Fig. 1 - The location of Fumane Cave and two photographs showing the cave entrance, where the ERT survey was carried out, and an instant of laser scanner data collection. Note the complex nature of the cave entrance. A, B, C: partially explored other tunnels.

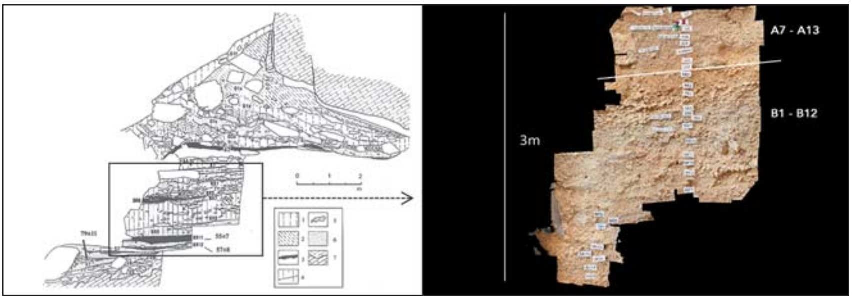

Fig. 2 - Left: Stratigraphic sequence of Fumane Cave reported for the main sagittal section reported from the outside the cave with the main lithological features of the most significant units within the **D**, **A**, **BR** and **S** complexes: 1) rendzina, upper soil; 2) slope deposits with boulders; 3) living floors, with high concentration of organic matter or charcoal; 4) loess and sandy loess; 5) $CaCO_3$ cemented layers; 6) sandy deposits; 7) un-weathered and weathered bedrock (after Peresani *et al.* 2008b). Right: Three-dimensional model of the main stratigraphic sequence showing micro units A7-A13 and B1-B12.

visible in the main stratigraphy sequence. Even if the Fumane Cave has been known since the 19th century, it was excavated for the first time in 1964 and again in 1982 and 1988. Since then systematic archaeological excavations have been performed exposing numerous Middle to Upper Paleolithic layers, including multiple Mousterian and Aurignacian living floors in addition to some traces left by the Gravettian populations (Peresani *et al.*, 2008a, 2012, 2013, Jèquier, 2014). The site contains 12m high, very well preserved stratigraphic sequence divided in four major macro units and numerous micro-units, defined on the basis of the lithological features and archaeological evidence (Fig. 2). The basal macro unit ***S*** is composed of several tabular layers formed from the run-off of residual dolomitic sands, some partially weathered boulders and human living floors. The overlaying macro unit ***BR***, shows clear lithological change with the noticeable decrease of dolomitic sands and predominance of Aeolian dust associated with breccia and the stone layers formed as a result of intense frost shattering. Apart from micro-unit BR11 where the thick Mousterian living floor containing high concentration of archaeological material has been unearthed, this macro unit offers humble archaeological evidence consisting of few lithic artefacts, faunal remains and hearts. More intense human presence has been documented in unit ***A*** which includes several horizontal layers from A13 to A1, mainly, composed of residual sands produced by the frost heaving (A13-A12) action, cryo-clastic breccia and aeolian dust (A11-A1) with varying content of organic material locally affected by faunal bioturbation (Peresani *et al.*, 2008). Mousterian living floors have been documented in units A11-A5, Uluzzian in units A4 and A3 and Proto-Aurignacian in units A2 and A1. Frost-thawing breccia, colluvial sands and aeolian matrix (A13-A3) gradually replaces stones from the inner to outer zone of the cavity, where it becomes almost exclusive. The macro unit ***D*** occurs at the top of the sequence characterized by mainly coarse material result of numerous landslides and re-worked sediments. Human occupation has been confirmed for the lowermost units D3d, D3b and D3a, assigned to the Aurignacian and becomes sporadic in unit D1d where some Gravettian artefacts have been discovered. This unit has been excavated during the early campaigns and cannot be seen today. The part of a sequence still visible today and therefore the object of the geophysical investigation, includes portions of the macro unit ***A***(A7-A12) and units ***BR*** and ***S*** (Fig. 2).

The deposit of Fumane Cave also documents main climatic events and environmental changes occurred in the region of Valpolicella for the last 90,000 years. These changes have conditioned post-depositional processes and human occupation. The paleo-ecological changes have been documented by the presence of so-called paleo-ecological proxies such as charcoal of certain threes, micromammals, ungulates, birds and caprids hunted during the different stages revealing the passages from cold-arid to more temperate-humid climate.

Data acquisition and interpretation

Field equipment for a typical electrical resistivity survey consists of an ammeter, a voltmeter, a power source, electrodes and connecting wires. In order to measure the resistance of the investigated body, a current is injected between two electrodes inserted into the ground, named accordingly current electrodes. Alongside two current electrodes, two potential electrodes are inserted into the ground in order to measure the potential difference between these two points. This is carried out because the current electrodes have a finite and unknown contact resistance with the earth, and although contact resistance also occur at the second set of electrodes, the values are usually considerably smaller that the input impedance within the voltmeter and therefore do not affect its reading (Gaffney & Gater, 2003). The four electrodes can be configured in many ways or arrays according to the survey objectives, however, dimensionality of the problem at hand and hypothesized resistivity contrasts have to be carefully explored in order to gain the inspired goals. Today only some of the possible configurations are commonly used in archaeology including Wenner, Schlumberger, Pole-Dipole, Twin probe (i.e. Pole-Pole) and Dipole-Dipole. The depth of the investigation is a fraction of the current dipole length (1/4-1/6)xL.

The survey grid used in our work included a total of 11 profiles, placed on every meter and covering the main excavation area following the orientation NE-SW (ERT1-6) and SE-NW (ERT 7-11) (Fig. 3). The unit resistance data were collected using the ABEM SAS 4000 Terrameter Georesistivity meter (Sweden). The longest profile is 12m long, while the shortest is 6,5m long. In order to meet the goals of the survey, the measurements were collected using the Wenner-Schlumberger and Pole-Pole arrays. Wenner-Schlumberger (WSC) is a combined array arranged in line of electrodes with constant spacing, with a better lateral resolution and 15% more increased depth of investigation than Wenner array. On the other hand, Pole-Pole (PP) array has been widely used in archaeology due to its best signal/noise ratio, great depth of investigation (0.86xL) and best lateral resolution. The Pole-Pole array is characterized with the two separate (AM-BN) pairs of probes in which the distance between needs to be at least 30 times the inner-electrode spacing (meaning that for the inner-electrode spacing of 0.50m, remote pair of electrodes should be 15m away from the

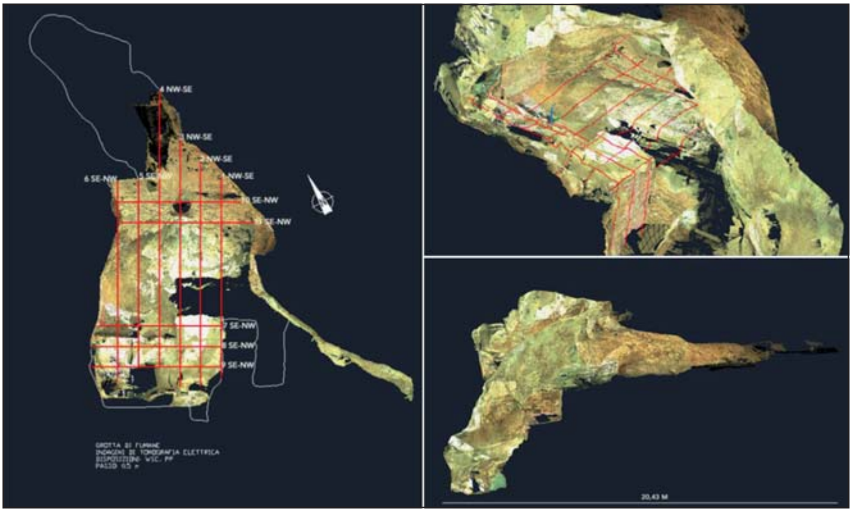

Fig. 3 - locations of ERT profiles (red lines) and the reconstructed topographic model of the Fumane Cave obtained using the Leica C10 scan station. The topographic model was reconstructed by merging data of 11 different scanning positions.

other current pole). In general the infinite electrode is placed at a 20 times the maximum inner electrode distance.

The data sets were processed in order to reconstruct the best subsurface resistivity distribution . All the raw data were inspected for extreme values caused by the poor contact between the electrodes and the ground. To this end, the Res2dinv/Res3dinv (Geotomosoft, 2013) and ERTLAB (MPT and Geostudi Astier, 2006) inversion codes were employed. The algorithms implements Occam's inversion style that adopt an efficient regularization approach to deal with the nonlinearity of apparent resistivity data inversion. Gauss-Newton optimization method is used to minimize or maximize some penalty on the model parameters, whilst demanding that the model fits the observed data to within some reasonable error between experimental and theoretically calculated apparent resistivity data based on the real distribution of resistivity model parameters. All codes can handle rough topography and allow for the addition of boundary conditions. In our case these are represented by the free surface contacts of two walls of the deposit

Most of the models resulted in RMS error less than 5% suggesting the high level of confidence and that the resulting profiles can be used to infer the subsurface characteristics of the investigated main living floor of the Fumane Cave. In the following we shall comment and discuss the obtained results.

The position and elevation of the electrodes were obtained in a precise way thanks to the first detailed three dimensional topographic model constructed following two different approaches: a laser scanner and photogrammetric surveys. With laser scanning technology it is possible to obtain a very high-resolution point cloud for the entire area, while photogrammetric technique will serve as a focus on specific areas of greatest interest in order to obtain better chromatic detail and more accurate geometry. Considering the complexity of the site and the presence of numerous occlusions that affected the visibility, it was necessary to perform multiple scans from different positions (11 in total), and then to merge them into a single three-dimensional, unique model (Fig. 3). This model represents the most accurate representation of the cave, which shall serve as a basis both for further geophysical data treatment and modelling and for the digital collocation of three stratigraphic sections that have been reconstructed using about 500 images acquired with a CANON EOS 7D camera, and then processed with modern "structure from motion" software PhotoScan (Agisoft, Russia). More details are found in the second paper included in this volume (Bolognesi *et al.*)

Results

Obtained two and three dimensional resistivity models are shown in Figs (4, 5, 6). The models show the resistivity distribution in the first 2/3 meters (for the Wenner-Schlumberger data set) while this depth increases to about 8 meters (for the Pole-Pole data set). These models were used to infer more information about the subsurface interpretation of the investigated stratigraphic sequence. The 3D resistivity model confirmed the presence of two different types of materials characterized by different proportions of fine-grained sediments (such as clayey) mixed with sands, fractured limestone and u-n-weathered limestone. Some portions of the deposit are likely to be saturated. Resistivity models confirms the absence of voids or human made structures. Most of the profiles demonstrate common information, however, while WSC derived resistivity models provide the more realistic and detailed images for the first 2-3m, the PP profiles offer the max reached depth of the investigation and information about the position and geometry of bedrock, its state of the alternation and the detection and distribution of sedimentary infill (Fig. 4).The obtained resistivity values ranged from 15 Ohm.m to 900 Ohm.m. First comparison between 2D resistivity sections elaborated using RES-2DINV software and the 3D model obtained using ERTlab software,

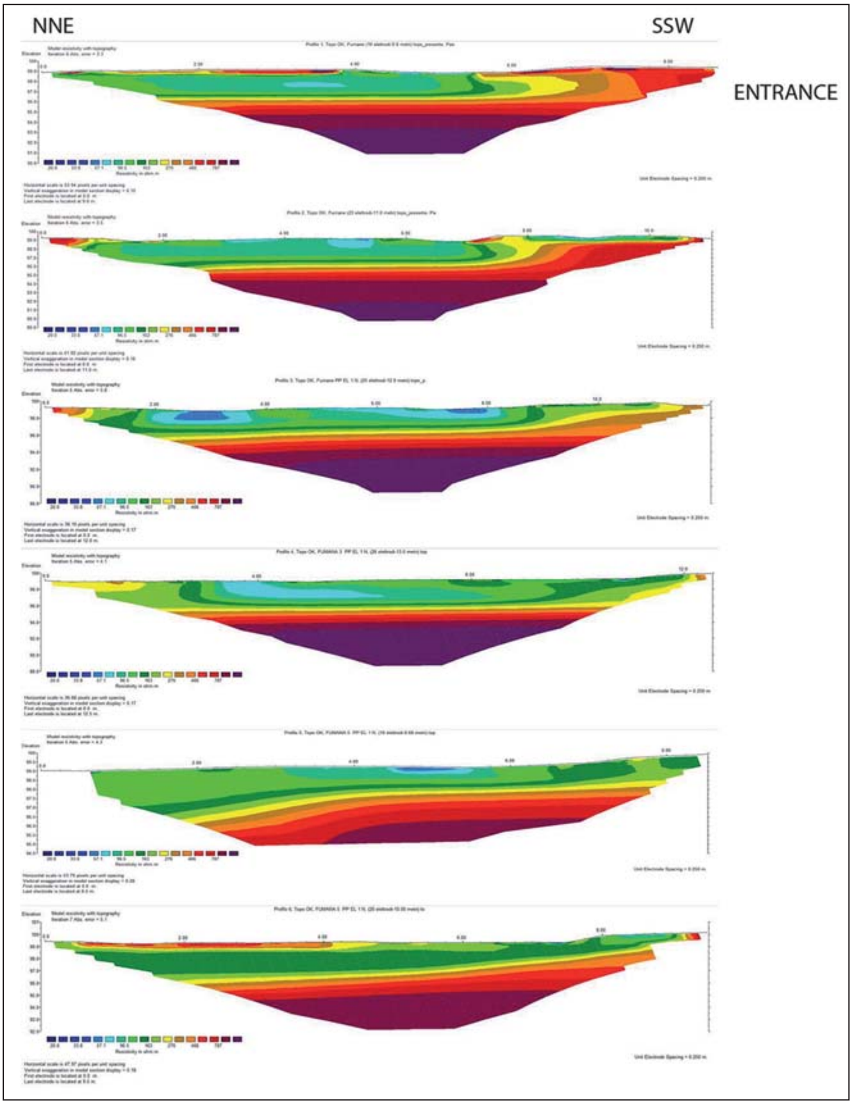

Fig. 4 - **Pole-Pole 2D inversion resistivity** models (ERT1-ERT6) (see Fig. 3 for the location of these profiles.

shows significant differences when it comes to the representation of the distribution of medium resistivity values reflecting an almost "bimodal" resistivity distribution, as can be seen in sections and depth slices of the three-dimensional model of the subsurface, resulting in predominance of law and high resistivity values (Fig. 5). The significant accumulation of fine

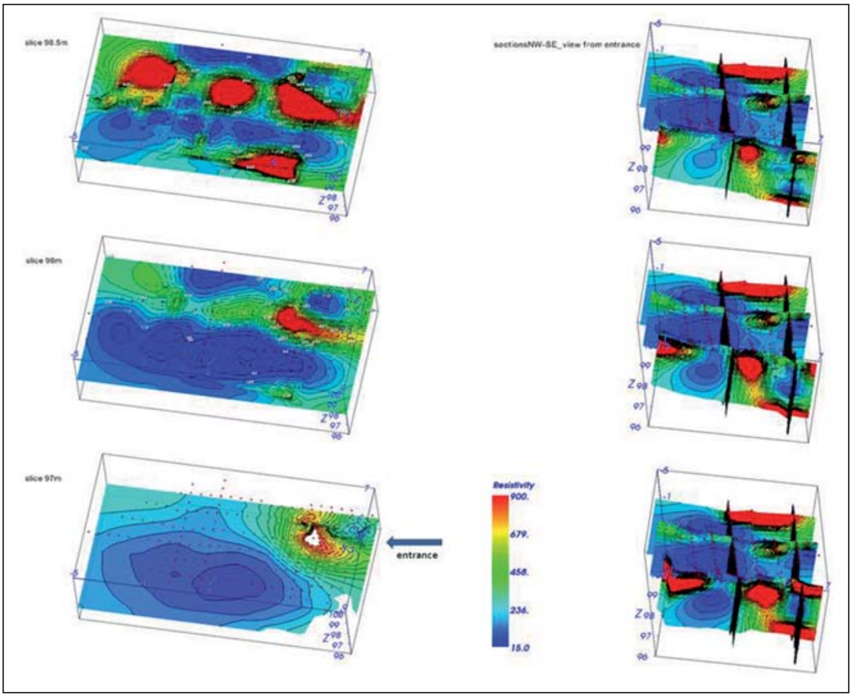

Fig. 5 - Three dimensional resistivity images of the investigated stratigraphic deposit. The depth axis represents absolute elevation (m a.s.l.). In this case, the images show the resistivity distribution from different view points and at different depths ranging between 0.5 m and 1.5 m; (right) Sequential view of vertical sections as seen from the cave entrance (oriented in NNE-SSW and SSE-NNW direction).

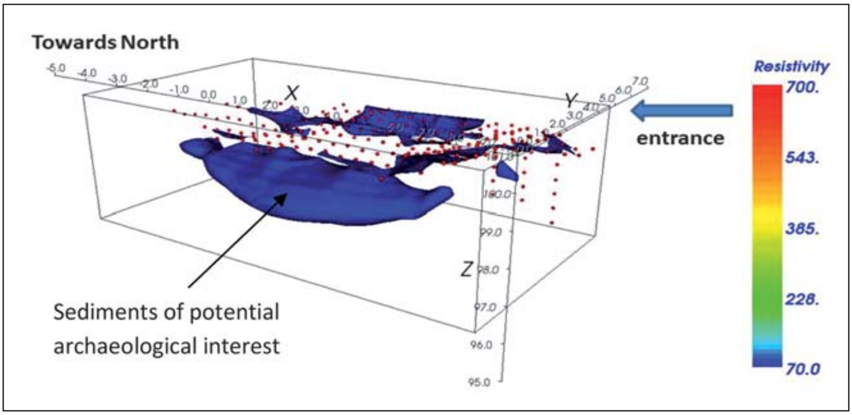

Fig. 6 - Three dimensional model of the cropped low resistivity volumes below 75 Ohm.m.

grained sediments (forming an almost bowl-shaped structure) characterized with low resistivity values (<70 Ohm.m) is noticeable in the central part of the principal gallery B and in the north-eastern part of the cave, becoming thinner moving in south-west direction (Fig. 6). The deposit is very shallow closer to the cave walls, becoming thicker along the central axis. The maximum depth of this deposit varies from few centimeters up to 4m. Using the information from the main stratigraphic sequence and observations made during the excavations, fine grained sediments, i.e. low resistivity values, can be associated to the accumulations of residual sands disturbed by frost heaving, cryo-clastic breccia and aeolian dust present in micro units A7-A13 and dolomitic dust present in micro units B1-B7 in the first two meters of the deposit and most probably saturated with water flowing , sporadically, from the cave walls and ceiling . More coarse-grained materials, cemented layers and stones resulting from intense frost shattering (micro unit B8) may be responsible for some medium resistivity values (70-200 Ohm.m) noticed especially at the SW part of the cave. Some shallow high resistivity values (>200Ohm.m) observed especially in the first 0.5m closer to the SW wall of the cave close to the entrance, can be attributed to the isolated limestone blocks imbedded in the low resistivity material. The estimated thickness of the deposit is between around 4 and 5m (Fig. 4).

Discussion

The obtained results, offer the possibility to extract useful information concerning the nature of sedimentary infill that can help in formulating further considerations about past Paleolithic activities based on previous excavations and understanding of geological context of archaeological levels in a completely non-invasive way. Nevertheless, it should be underlined, that due to the impossibility to validate the data using the classical methods such as test pits or coring, the interpretation of the results remains approximate and further excavations and studies are needed to confirm them. The implementation of advanced three dimensional acquisition techniques had a double purpose in this survey. On the one hand, it allowed the correct reconstruction of the cave geometry and provided elevations used in the topographical correction of the ERT data inverison. On the other hand, it represented an important step towards the creation of an accurate digital documentation of already known findings as well as those still to be discovered in the future. Also it shall become an open communication tool for interested researchers as well as for a wider public and why not for those whom are interested in archaeological culture.

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