ELECTRICAL RESISTANCE TOMOGRAPHY FOR SEDIMENT DEPTH MODELING IN CROATIA'S PALEOLITHIC ROCK SHELTER & CAVE SITES

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Archaeological investigations in cave and rock shelter environments present researchers with a unique set of challenges. Sediment depth modeling within cave or rock shelter sites aids researchers in placing excavations in productive locations. Electrical resistance tomography (ERT) is utilized more frequently in archaeology over the last ten to fifteen years and is well suited to modeling sediment depth profiles. However, its application to archaeological cave and rock shelter sites is somewhat limited due to space restrictions for data collection as compared to open air sites. Presented here are results from 2014 – 2023 where ERT was incorporated into the research design on a series of projects investigating Paleolithic cave & rock shelter sites in the Adriatic Region of Croatia. The technique shows potential for continued use in these environments though there are limitations to its applicability in these environments.

Key words:
Paleolithic, Adriatic Region, Cave, Rock Shelter, Remote Sensing, Geophysics, Electrical Resistance Tomography, Croatia

Introduction

Conducting archaeological investigations in cave and rock shelter sites presents researchers with multiple unique challenges as compared to typical open-air sites. Confined spaces, limited or no light, and complex stratigraphic sequences are frequently the norm. Additionally, the nature of limestone cave walls and floors often produces undulating, irregular surfaces with many pockets, troughs, and ridges where sediment may accumulate unevenly beneath a relatively flat surface level. This creates a problem for the research team to select productive locations for excavations within the site that meet the time constraints for the project and within the limited physical space available. An effort to address these issues through the use of Electrical Resistance Tomography (ERT) has been employed at several Paleolithic cave and rock shelter sites in Croatia between 2014 and 2022.

The ERT technique for archaeological prospection and sediment depth modeling employed in this study utilizes a GeoScan Research RM85 meter and adapted a PA20 probe array for linear pole-pole surveys. The technique showed potential for use in caves and rock shelters, particularly in remote sites or hard to reach areas within a cave, due to the portability of the equipment, its robust design which is water resistant, and flexible battery options allowing for all day or even multi-day use without access to electricity for recharging. Difficulties associated with this combination of technique and equipment are the large amount of electrical wire needed to support the pole-pole array, consistent data collection in either extremely wet or dry conditions, and the slow data collection process when compared to techniques such as Ground Penetrating Radar (GRP). Despite some of these difficulties which varied drastically from site to site, the technique proved useful in modeling sediment depth to bedrock at several caves and rock shelters included in this study.

Overview of Projects and Sites

The end of the Middle and the beginning of the Upper Paleolithic in Europe is a very interesting and turbulent time in both biological and behavioral aspects of Late Pleistocene hunter-gatherers. It is the timeframe which saw the demise of Neandertals (at least as a recognizable morphological group), and spread of anatomically modern humans throughout the region. Yet, this scenario is far from a simple one, and there are numerous issues and unknowns related to specific patterns of human occupation during the Upper Paleolithic. Various archaeological traditions/industries/cultures have been recognized in different regions and at different times, some of which are still poorly understood. In addition, the end of the Pleistocene saw a significant rise in sea levels and change in environmental and climatic conditions, specifically affecting the Adriatic coastline. The sea levels at the time of the Last Glacial Maximum were about 100 meters lower than today which dramatically changes the movement and patterning of people and animals in the region.[1] The loss of large continental plains and rapid change in environmental conditions, faunal and floral change and so on, put new and additional pressures on human groups in the area. However, while this is well documented on a larger scale, it is still unclear when or how localized changes in behavior occurred for people experiencing these changes.

Gaining a clear understanding of the above situation for Paleolithic peoples in the Adriatic Region is a broadly stated goal for each project and sites included in this study. The use of ERT surveys is incorporated into the research design of each project as a means to enhance the effectiveness of field time and funds available for the project. ERT surveys were conducted across four projects which incorporated six cave and rock shelter sites from the Dalmatian and Istrian regions of Croatia (map 1). Dalmatian sites include the Velika Pećina (Kličevica) and the well-known Mujina Pećina which were part of the projects directed by Dr. Ivor Karavanić. Projects under the direction of Dr. Ivor Janković include sites from the Istrian Peninsula. These include Pećina kod Rovinjskog Sela, Romualdova Pećina, Ljubićeva Pećina, and Abri Kontija 002.

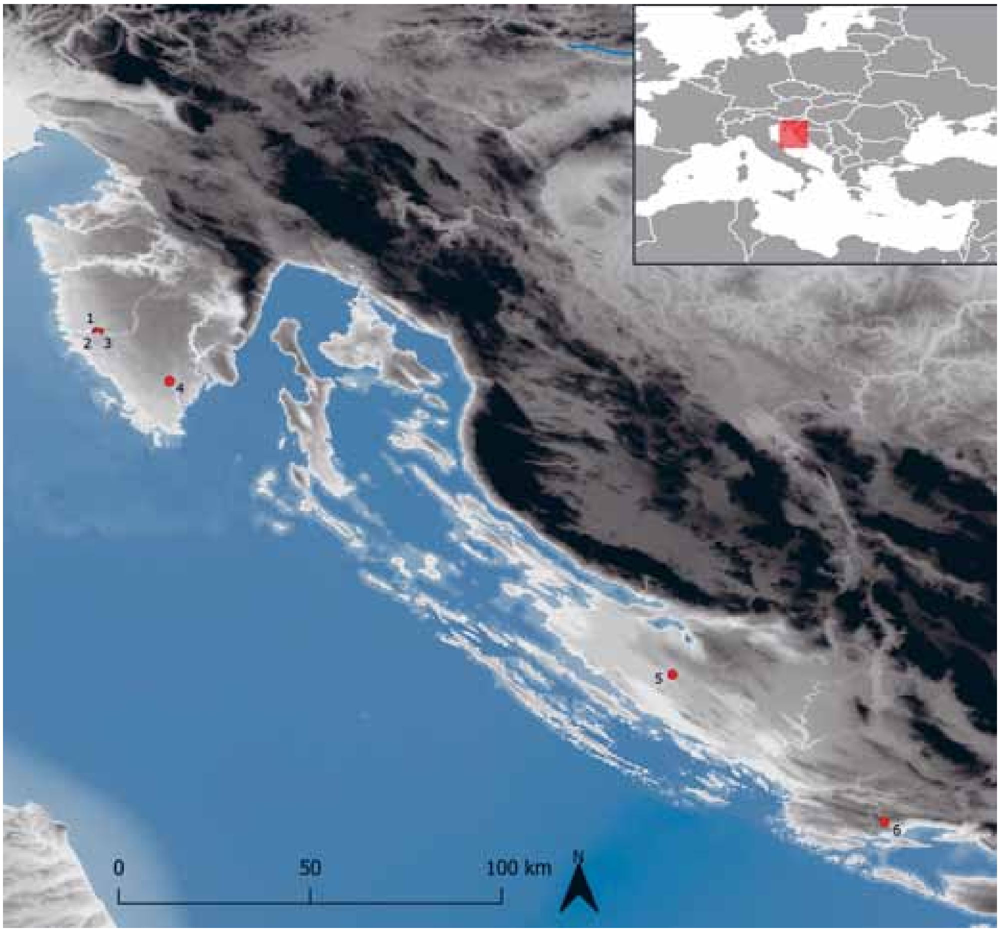
Recent research on the Paleolithic of Dalmatia and Istria

Recent research on various aspects of Paleolithic hunter-gatherers on the Croatian coast (Dalmatia and Istria) was conducted within the four major projects, all funded by the Croatian Science Foundation, namely the *Late Mousterian in the Eastern Adriatic – towards understanding of late Neanderthals' identity and their demise (LMEA) Project*, (HRZZ: 09-01-320) (2013–2017), and the *Last Neandertals at the Crossroads of Central Europe and the Mediterranean (NECEM)* (IP-2019-04-6649) (2020–2024) that focused on the sites in Dalmatia (although the site from other regions are also included in second project), and the two projects that focused on the region of Istria: *Archaeological Investigations into the Late Pleistocene and Early Holocene of the Lim Channel (ARCHAEOLIM)* (UIP-2013-11-7789) (2014–2017) and *Prehistoric hunter-gatherers in Istria and adjacent regions: patterns of late Pleistocene lifestyle and mobility (PREHISTRIA)*, (IP-2019-04-7821) (2020–2024). Thus, the four projects covered a wide temporal sequence, from the Middle Paleolithic (Neandertals), Late Middle Paleolithic and Early Upper Paleolithic (Neandertals and early anatomically modern humans), to the Upper Paleolithic (anatomically modern humans). This provided various sets of data related to changes in behavior and subsistence strategies, contact zones and so on, not only within the coastal zones (that were at different times much more inland), but a strong comparative basis for sites in other regions in Croatia and adjacent regions (e.g. Italy, Montenegro and so on).[2] In addition to field work, projects included comparative and new analytical studies of material from previously excavated relevant sites and detection of new locations of potential interest for future research, and new data on chronology of the Late Neandertal/early anatomically modern human presence at various sites.[3]

1 see Lambeck 1996; Surić, Juračić 2010, Peresani *et al.* 2021.

2 Karavanić *et al.* 2013; 2014; 2016; 2021; Komšo, Pellegatti 2007; Vukosavljević, Perhoč, Karavanić 2015; 2022; Vukosavljević, Karavanić 2017.

3 Karavanić, Barbir 2020; Banda *et al.* 2023; Karavanić *et al.* 2022; Karavanić, Banda, Paraman 2023.



MAP 1. Overview Map of sites mentioned in the text:
1) Abri Kontija 002
2) Pećina kod Rovinjskog Sela
3) Romualdova pećina
4) Ljubićeva pećina
5) Velika pećina u Kličevici
6) Mujina pećina
(made by L. Vidas).

Velika Pećina u Kličevici

Velika Pećina u Kličevici is situated in the northwestern part of the Kličevica river canyon in the village of Raštević, not far from Benkovac, approximately 30 km from the town of Zadar. The south-facing entrance of the cave is small (approximately 2 x 1.5 m) and the main channel of the cave is around 30 m long, 5 m wide and about 6 m high, with the back part of the cave forming two separate, several meter-long channels. Several researchers previously visited the cave, including S. Božićević, who published a layout and longitudinal section of the cave, and M. Savić, who collected a number of stone finds and chert specimens from both Velika Pećina and Mala Pećina in the Kličevica canyon, now kept at the museum in Benkovac.[4] M. Malez also visited the site, collected several artifacts and conducted small-scale excavation in the cave during the 1970s or 1980s.[5] New research at the site started when I. Karavanić and N. Čondić first visited the site with a small team in 2003 and collected several artifacts from the surface.[6] A test excavation was conducted in 2006, and systematic excavations were carried out from 2012 until 2015 as a joint effort by the Faculty of Humanities and Social Sciences at the University of Zagreb, the Archaeological Museum Zadar, the University of Wyoming and Illinois State University. The test trench from 2006 was expanded and four new trenches were opened in the cave, one of which did not yield any finds. All trenches were excavated to the underlying bedrock, except a trench near the entrance where the stratigraphy is comparatively much deeper. Subsequent excavations of this trench were executed in 2017 and 2021.

Layers from the Holocene period containing prehistoric ceramic finds were present only in the trench near the entrance while Pleistocene layers containing Middle Paleolithic finds (Mousterian artifacts with some animal bones and teeth) were present in all but one trench. The lithic tools are small (as in the so-called Micromousterian) and made of local chert. Among the tools, diverse sidescrapers are present, and among these, microlithic transverse scrapers are remarkable.[7] Faunal finds are very rare due to poor preservation factors. Based on unpublished OSL dates the lower levels were deposited during MIS 4 or even at the end of MIS 5, while radiocarbon and U/Th dates of upper layers suggest late occupation during the time of the Middle/Upper Paleolithic transition, around 40 ka cal. BP.[8]

4 Karavanić, Čondić 2016.
5 Karavanić *et al.* 2018.
6 Karavanić, Čondić, Vukosavljević 2007.
7 Karavanić, Vukosavljević 2019.
8 Karavanić *et al.*2021.

FIGURE 1. Pećina kod Rovinjskog Sela rock shelter and cave entrance (photo by R. Becker).

Mujina Pećina

Mujina Pećina lies north of the towns of Kaštela and Trogir, not far from a road leading toward Labin. The cave is approximately 10 m long and 8 m wide and its mouth is located on a slope of a ravine at about 280 m above sea level. The initial finds were collected by M. Malez and his team in 1977 from the surface, both inside and outside of the cave, and the first test excavation was undertaken in 1978.[9] Systematic excavations started in 1995 and lasted until 2003 as a joint project of the Department of Archaeology, Faculty of Humanities and Social Sciences at the University of Zagreb and the Museum of the Town of Kaštela. A standard methodology for excavating Paleolithic sites was applied, using a grid system and recording the coordinates of individual finds. Stratigraphic profiles, between 1.2 and 2.2 m deep, contained sediments composed of large fragments of carbonate rock, gravel and sand grains, silt and some clay.[10] Based on radiocarbon chronology, the stratigraphic sequence covers the period between 49 and 39 cal. ka BP,[11] but unpublished OSL dates strongly suggest that the oldest layers were deposited during MIS 4 or even at the end of MIS 5. Lithic tools are mainly small (Micromousterian) made on local nodules.[12] Sidescrapers, simply retouched pieces and notches/denticulates are frequent in almost all layers. During occupational episodes humans processed animal remains, mostly large bovids, cervids, and caprids.[13] The dominance of prime-age adults among red deer, chamois/ibex and large bovids in the analyzed assemblages from the upper layers suggests hunting activities by hominins and there is strong evidence that people used Mujina Pećina seasonally during the autumn and spring.[14] The oldest layers are richest in human-related finds, indicating much more intensive human activity at the site than in more recent layers.[15]

Romualdova Pećina

Romualdova Pećina is a cave, located on the southern slope near the end of the present day coastline in the Lim channel. Although several earlier researchers visited the site, noting remains from various archaeological periods, the cave itself was known to locals since the Middle Ages. According to legend, St. Romuald lived there for several years around year 1000 AD, giving the cave its name. The first systematic excavations at the site were conducted in the 1960s and 1970s by M. Malez.[16] He found numerous remains of Pleistocene fauna (most abundant were the cave bear remains), and several lithic artifacts that he described as "younger Aurignacian and early Gravettian", or that of the so-called "Perigordian complex".[17] Later excavations by D. Komšo, and systematic work at the site by I. Janković confirmed

9 Petrić 1979; Karavanić *et al.* 2008.

10 Rink *et al.* 2002; Boschian *et al.* 2017.

11 Rink *et al.* 2002; Boschian *et al.* 2017.

12 Karavanić *et al.* 2008; Perhoč 2020; Šprem, Bošnjak, Karavanić 2020.

13 Miracle 2005.

14 Miracle 2005.

15 Nizek, Karavanić 2020.

16 Malez 1960; 1962a; 1962b; 1968; 1971; 1978.

17 Malez 1981, 130.

that Upper Paleolithic hunter-gatherers occupied the site during at least two distinct times, i.e., the earlier and later phases of the Upper Paleolithic.[18] Interestingly, in addition to the Upper Paleolithic habitation, lower layers yielded Mousterian finds, confirming that Neandertals also used the cave.[19] Recent discovery of the first parietal cave art at Romualdova Pećina opened new questions related to the behavioral/symbolic aspects of Upper Paleolithic peoples in the region.[20]

Abri Kontija 002

The site of Abri Kontija 002 was discovered during a field survey in 2007.[21] It is located on the northern slopes of the Lim channel in Istria, about 2 kilometers from Romualdova Pećina. Systematic research at the site started in 2014 as a part of both ARCHAEOLIM and PREHISTRIA projects, and is still ongoing. The site proved to be extremely interesting, as the dating (in preparation) suggests humans were using the site at around 30 kya, filling in the temporal gap between the other sites mentioned. In 2014 a small excavation trench (1.5 x 1.5 m, later expanded to 1.5 x 4.5 m) was opened on the plateau right in front of the cave mouth.[22] Based on the results of dating and preliminary geoarchaeological work, the deposition of sediment was rather fast, most likely a result of seasonal cycles of temperature changes, causing breakage of the limestone overhang. Although the excavated area is rather small, sediments are extremely rich in terms of archaeological material (animal bones, lithic material, shells, ochre, traces of burning and so on),[23] pointing to an area of high activity. One of more interesting things is the very early appearance of a backed blade industry at the site (around 30 kya), making this one of the earliest sites with this cultural innovation in the area.

Pećina kod Rovinjskog Sela

The cave is located on the southern slopes of the Lim channel in Istria, Croatia, not far from the Romualdova Pećina. The site includes both a cave and significant rock shelter component (Fig. 1), making it unique in this study. Of note, the Abri Kontija 002 rock shelter site also includes a cave component, though it is currently nearly completely filled with sediment and cannot be surveyed using ERT. At Pećina kod Rovinjskog Sela, the first signs of possible Pleistocene or early Holocene occupation were discovered during the field survey by D. Komšo in 2007,[24] and, starting from 2015, small-scale excavations at the site, including the geophysical work discussed here, was done within the scope of the ARCHAEOLIM project.[25] Several lithic artifacts can be ascribed to the Upper Paleolithic (Gravettian), based on preliminary typological and technological analysis, as well as the results of radiometric dates from Horizon B of the site.

FIGURE 2. Ljubićeva Pećina main chamber (photo by I. Janković).

Ljubićeva Pećina

Ljubićeva Pećina is a cave located near the village of Marčana in Istria, about 15 km from the city of Pula. It was formed in Cretaceous limestone and the cave itself is rather spacious with the upper chamber consisting of one large chamber, one smaller side chamber, and two vertical pits (Fig. 2).[26] Although the earliest mention of the cave in written documents was in 1926, the first systematic excavations started in 2008 as a joint project of Croatian Conservation Institute and Museé d'Anthropologie préhistorique de Monaco.[27] During the 2008 – 2011 fieldwork, materials from the Late Upper Paleolithic, Neolithic, and Bronze Age were collected from the side chamber of the cave's upper main chamber.[28] Of particular note is the Late Upper Paleolithic occupation of the site. Based on the results of the radiometric dating of part of the layers, it is possible to distinguish at least two episodes of human use of the site during the Pleistocene, between 13,330

18 Komšo 2008; Janković *et al.* 2016; 2017a; 2017b; 2017c.

19 Janković *et al.* 2016; 2017a; 2017b; 2017c.

20 Ruiz-Redondo *et al.* 2019; 2020; 2022; Komšo *et al.* 2019.

21 Komšo 2008.

22 Janković *et al.* 2017a; 2017b.

23 Janković *et al.* 2016; 2017a; 2017b; 2017c; 2022.

24 Komšo 2008.

25 Becker *et al.* 2017; Janković *et al.* 2016; 2017a; 2017b; 2017c.

26 Percan *et al.* 2020.

27 Percan, Komšo, Bekić 2009.

28 Percan, Komšo, Bekić 2009; 2020; Percan 2010; 2011; 2012.

and 13,120 cal. BP (11,350 ± 50 uncal. BP, GrA 40926) and between 16,120 and 15,670 cal. BP (13,260 ± 70 uncal. BP, Beta-249371). The excavations produced lithic artifacts (various blades, bladelets, backed blades etc.), several bone tools, faunal remains, traces of ocher and other archaeological evidence dating to the Upper Paleolithic.[29] The preliminary analysis of the lithic finds is in accordance with the dating results and points to the Late Epigravettian period, which is dated between 17,500 and 11,700 cal. BP.[30] New systematic investigations of part of the site (in trench B in the smaller cave chamber on the upper level of the site) were carried out in 2020 and 2021 and were preceded by laser scanning and geophysical data collection,[31] yielding additional evidence for Paleolithic habitation of the site during the Late Glacial/Epigravettian.[32]

ERT Methodology for Caves & Rock Shelters

Earth resistance surveys for archaeological purposes have been utilized since the mid-1900s and are considered a primary technique for conducting subsurface geophysical prospection in archaeology.[33] Earth resistance can be used for both broad area, fixed depth surveys and also for creating 2D and 3D depth profiles even with the same instrumentation.[34] Other prospecting techniques, such as magnetic survey, GPR, and conductivity, have been introduced since the mid-20th century though the use of resistance survey remains a staple remote sensing technique on archaeological sites.[35]

Several probe arrays may be employed for resistance surveys such as a pole-pole, Wenner, Schlumberger, gradient array, dipole-pole, and dipole-dipole; though utilizing several of these in archaeological contexts is fairly specialized or site specific.[36] The twin probe array is likely the most commonly used in archaeology as it is the recommended configuration for fixed depth broad area surveys from GeoScan Research of England makers of the widely utilized, though now discontinued, RM15 and RM85 resistance meters.[37] Earth resistance surveys that utilize a twin probe array for fixed depth broad area coverage are ideally suited for identifying building foundations, historic or prehistoric trenches, pits, middens, or any feature that has a moisture content significantly different from its surrounding soil/sediment matrix.[38]

Where the twin probe array starts to be problematic is when used for tomographic surveys or the production of 2D or 3D depth profiles.[39] Other four probe arrays such as pole-pole, Wenner, Schlumberger, dipole-pole, and their variants are utilized for ERT surveys.[40] Specially designed ERT meters such as the AGI SuperSting and IRIS SYSCAL systems allow for tens or even hundreds of electrodes to be placed across a landscape. They facilitate the rapid collection of data from these points through the use of switch boxes that fire the probe pairs in sequence along a given tomography line. Additionally, these systems are often used to collect readings from probes spread quite some distance apart and so they use Wenner or Schlumberger arrays, or one of their variants, to collect the data. The most common application of ERT profiles for archaeological purposes is the investigation of large earthworks such as tells and mound features.[41] These surveys employ dedicated ERT systems because of the open spaces and large distances where tomography lines can be placed. Conversely, the limited space and restricted tomography line distances common to cave and rock shelter sites present a different set of problems in ERT survey design.

The goal of testing ERT surveys at cave sites in the Adriatic presented in this study is to develop a reliable means for modeling depth of cave sediments to bedrock as a guide for site excavation efforts. It is important to note that the interest in ERT discussed here does not imply a disinterest in exploring GPR as a valuable technique for acquiring 2D and 3D depth profiles at cave sites. Gathering both GPR and ERT data from these sites is ideal and using both techniques on any cave site where conditions allow is preferred.

The application of ERT to cave environments varies significantly from open air sites due to natural constraints from working underground. The first and generally most obvious difference is the space available to conduct the survey. Since resistance tomography profiles need to be collected along straight lines where precise probe spacing at each station matters a great deal, it can be difficult to find a suitable area to survey inside a cave. The natural bends and corners of a cave channel may limit the length of any given profile which directly affects the depth that can be measured in those locations. Additionally, the presence of large rocks, exposed bedrock, and calcium carbonate layers (flowstone) can be problematic due to the inability to precisely place an electrode. As such, it is certainly the case that not all cave sites are suitable for ERT surveys. Careful consideration of the applicability of any remote sensing technique to a particular site must be evaluated prior to conducting a survey. This is just as true, and perhaps more so, for cave sites due to additional limiting factors within a cave.

Though the most common probe arrays for conducting resistivity tomography surveys are the inline arrangements such as Wenner and Schlumberger (and their variants), the pole-pole probe array is selected as the preferred array for use at the cave and rock shelter sites in this study. Testing of the ERT technique with a GeoScan Research RM85 meter began in the summer of 2013 at the Bukovac cave site near Lokve, Croatia. This testing regime

29 Percan, Komšo, Bekić 2009; Percan 2010; 2011; 2012; Simonet 2013.

30 Percan, Komšo, Bekić 2009; Simonet 2013.

31 Janković *et al.* 2019; 2022.

32 Janković *et al.* 2022.

33 Clark 1997; Bevan 2000, 1; Monfort 2013, 154.

34 Dabas et al. 1994; Samouëlian *et al.* 2005.

35 Clark 1997; Leopold, Plöckl, Forstenaicher-Völkel 2010.

36 Dahlin 1996; Aspinall, Gaffney 2001; Papadopoulos *et al.* 2006.

37 Walker 2000.

38 Schmidt 2001.

39 Noel, Xu 1991.

40 Dogan, Papamarinopoulos 2003.

41 Berge, Drahor 2011a; 2011b.

FIGURE 3. Data collection from the main chamber of Romualdova pećina in 2017 (photo by I.Janković).

included surveys with both Wenner and Schlumberger arrays which were used to collect both tomography data and single station depth profiles.[42] There is a subtle but potentially significant drawback to using the Wenner and Schlumberger arrays at cave sites. The need for all four probes to be included within the survey line reduces the number of available stations within each tomography line. The small spaces in cave sites reduce the potential for tomography line length which directly impacts the potential depth of the survey. As such, using an inline probe array which limits each survey profile by two readings is not optimal. The testing at Bukovac cave in the Gorski kotar region of Croatia, which included several array types demonstrated that completing a full tomography profile with an RM85 by stringing wire out for the reference probes and setting up a pole-pole array for data collection was a much better use of both the limited available space, personnel, and time spent moving wires than were either the Wenner or Schlumberger arrays. Reducing the time, people, and space required to set up a profile line, collect the data, and clear the area for other excavation activities proved a great benefit to the overall research efforts at the site.

The last bit of consideration in designing the ERT surveys included in this study is the resistance meter itself. GeoScan's RM85 is small enough to be handheld, easily transported in a pack when traversing vertical sections of a cave site via ropes, and can operate on batteries negating the need for daily recharging in cases where multiple days in the cave are necessary. None of the sites in this study required multiday stays deep inside the cave, though the capacity is there with this equipment should the need arise and seems worth noting. Additionally, the unit is water resistant which proved useful in several of the cave sites where drops from the cave roof were a frequent, if not unrelenting, occurrence.

Processing the data collected with the RM85 was accomplished with the same set of software for each site. TerraSurveyor software allowed for data download from the RM85 instrument and export to a spreadsheet format. Microsoft Excel handled conversions of readings in ohms to apparent resistivity (ohm-m) and creation of a text file compatible with Res2DInv software including elevation data along each profile line. Res2DInv software handled the inversion modeling. Frequently, the L1 Norm regularization for the least squares optimization at a 0.05 data constraint factor could be utilized with a robust model inversion constraint at a 0.005 cutoff factor for reduced effect of high surface resistivity. A convergence limit of 1% Root Mean Square Error (RMS) across two iterations was most commonly used as the optimization limit. Where very high values appear at the sides of the model as the iterations approach the 1% convergence, the "reduce effect of side blocks" function in the Res2DInv software reduced this effect.[43]

The change in probe spacing utilized within each profile line is likely the most significant advance over the course of these projects. The surveys conducted from 2014 - 2015 utilized a probe spacing of 0.25-0.50 m between each reading along a survey line. While some sites in the survey produced a sediment depth model at this data density, it was noted that several sites did not. In 2017 the Romualdova Pećina site was resurveyed at a probe spacing of 0.10 m along the same survey lines utilized in 2015 at 0.50 m spacing.[44] This increase in data density significantly improved the sediment depth model for the site and the 0.10 spacing was utilized for all ERT surveys in this study conducted between 2017 - 2022. Though the time associated for conducting the data collection increased significantly, the higher data density proved beneficial in several instances as detailed below (Fig. 3).

42 Chouker 2001.

43 Loke, Acworth, Dahlin 2003; Loke 2017.

44 Becker *et al.* 2019.

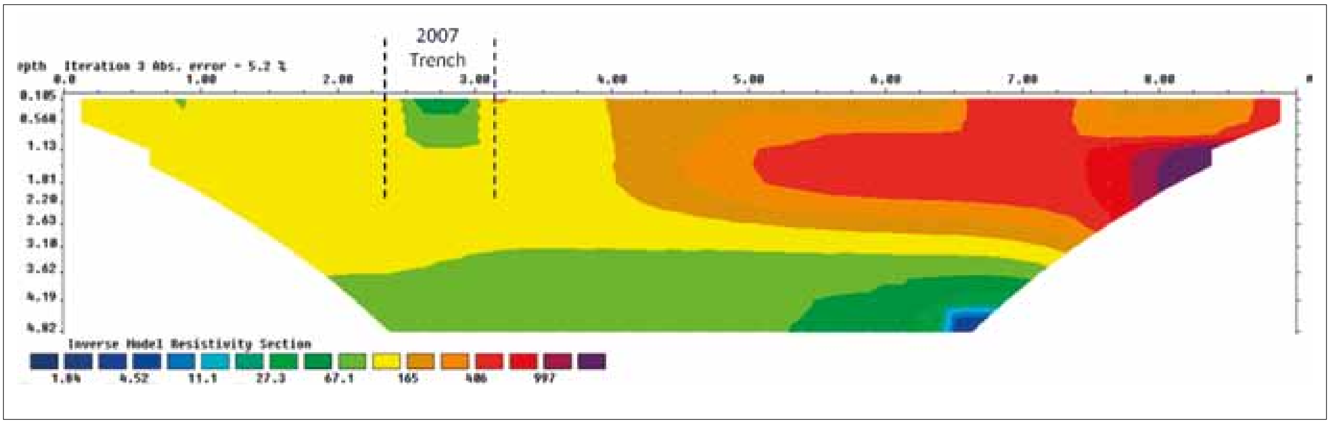


FIGURE 4. ERT profile from Pećina kod Rovinjskog Sela showing Komšo's 2007 trench (made by R. Becker).

Results

The result of each ERT survey is presented in chronological order according to when the survey took place rather than within the context of the larger project as presented above. This arrangement better aligns with presenting the advancement of the field methodology associated with these surveys over time and emphasizes this progression.

2014 Survey of Velika Pećina in Kličevica

The 2014 ERT survey in Velika Pećina in Kličevica consisted of 3 m long profiles located near the cave entrance and five longer profiles towards the rear of the first chamber. The location of the 3 m profiles was of particular interest due to planned excavations in the location during the 2014 field season and the unknown depth of sediment so close to the entrance. The 3 m profiles used a probe spacing of 0.50 m, which,[45] is much too low of a data density to produce a reliable sediment depth model. The resulting inverse model from these data showed little to no variability in the subsurface strata and did not clearly indicate an estimated depth to bedrock. This was made clear as the excavations in the location of these profiles ground truthed the location.

The five ERT profiles located towards the back of the first chamber of Velika Pećina in Kličevica did not produce useable results either at a 0.50 m probe spacing though they did include more data points due to their increased length. A series of storms brought high amounts of ground water into the cave at the time of the survey, saturating the sediments. Whether the data from the profiles near the back of the first chamber were unproductive due to the survey design or an environment of high saturation is difficult to discern. In either case, the ERT survey of Kličevica demonstrated a need for improved field methodology and data collection in order to produce useable sediment depth models.

2015 Survey of Pećina kod Rovinjskog Sela

The 2015 survey at the Pećina kod Rovinjskog Sela site held constant the probe spacing of 0.50 m but, given the sizeable rock shelter area and cave portion of the site there was much more space in which to work. Also, finding the location of the 2007 test excavation conducted by D. Komšo somewhere near the mouth of the cave added a question to the research design beyond sediment depth modeling which ERT survey is well suited to answer. The work included thirty-two ERT profiles spanning both inside the cave portion and outside in the rock shelter area. Lengths of each profile ranged from 6 m to over 20 m providing a wide range of data set sizes for the sediment depth modeling. The larger data sets from longer profiles located in the rock shelter area of the site provided usable sediment depth estimates as determined through ground truthing excavations conducted in 2016. Additionally, the 2007 test excavation was located as a result of this survey[46] (Fig. 4).

The ERT profiles from inside the cave area did not produce depth models with the same level of detail or clarity as those from outside the cave though the data sets were of similar sizes. Certainly, the sediments from the two areas may be subject to variations in depositional forces and the sediments inside the cave were more saturated which may account for this difference. However, the issue of producing quality sediment depth models through ERT survey with an RM85 in cave environments remained unresolved.

45 as noted in Becker, Karavanić, Vukosavljević 2017.

46 Becker *et al.* 2017.

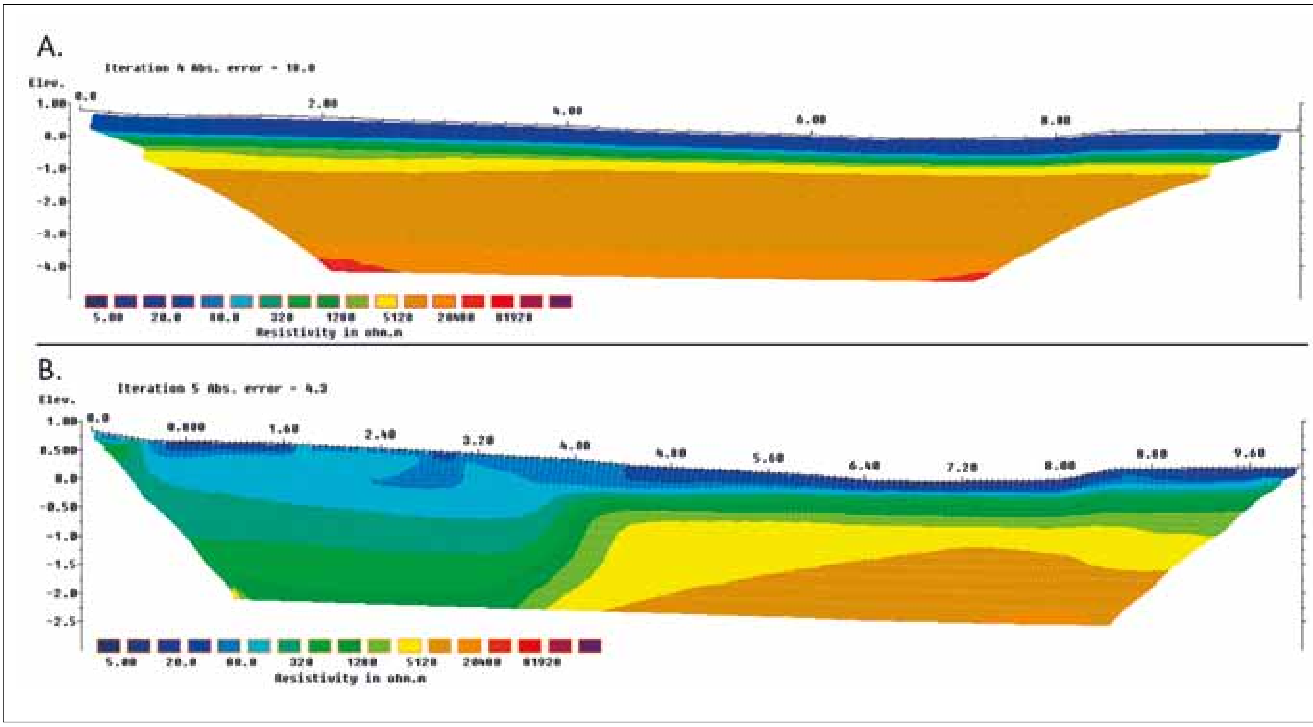


FIGURE 5. (A) Low & (B) high data density ERT profiles from Romualdova pećina (made by R. Becker).

2015 and 2017 Surveys of Romualdova Pećina

The Pećina kod Rovinjskog Sela site and Romualdova Pećina site were surveyed in the same year. Both are situated on the southern rim of the Lim Channel within a few kilometers of one another. However, the Romualdova Pećina site lacks any substantial external component. The 2015 ERT survey of Romualdova Pećina was conducted in the first chamber of the site where past and, at the time, active excavation activities had open trenches in excess of two meters in depth. A similar survey design of 0.50 m probe space was used for the 10 m long profile. The open excavation trenches located to either side of the ERT profile showed clearly that the sediment depth modeling was not reliable at this data density. Given that the 2015 Romualdova Pećina results looked very similar to the results from the cave area of Rovinjsko Selo, it was clear a new survey design was needed for the cave environments.

In 2017 the same 10 m profile was surveyed, using the same equipment and data processing software, but at 0.10 m probe spacing. The survey design was to specifically address the variable of data set size informing the inversion modeling process while holding as many other variables constant. The 0.10 m spacing did produce a sediment depth model along the 10 m long profile that well fit the actual sediment depths in the still open trenches. This high data density survey design also created a situation for testing the minimum probe spacing needed to confidently produce a reliable sediment depth model (Fig. 5). By removing data points from the 0.10 m data set, test data sets of various probe spacings from the same 10 m profile can be created out of the 0.10 m data set that was actually collected. Data sets for 0.20 m, 0.25 m, and 0.50 m probe spacings were created out of the 0.10 m data set. The resulting inversion modeling of the sediment depth for these different probe spacings showed the 0.20 m and 0.25 m spacing to retain a good deal of reliability. However, the 0.50 m probe spacing derived from the 0.10 m data set produces a model very similar to the 2015 survey data which was actually collected at 0.50 m.[47] As such, the 2017 survey at Romualdova Pećina demonstrated the need for high data density ERT surveys, between 0.10 m to 0.25 m probe spacing, in these cave environments.[48]

2021 Survey of Ljubićeva Pećina

A 2021 ERT test profile was located in the side chamber of the Ljubićeva Pećina site. The profile was 8 m in total length and used the 0.10 m probe spacing which proved successful at the Romualdova Pećina site in 2017. This profile did model the sediment depth within the side chamber fairly accurately. This is confirmed by the open trench in the same side chamber from previous excavations in 2008 – 2011. The main interest in the Ljubićeva

47 Becker *et al.* 2019.

48 Becker *et al.* 2019.

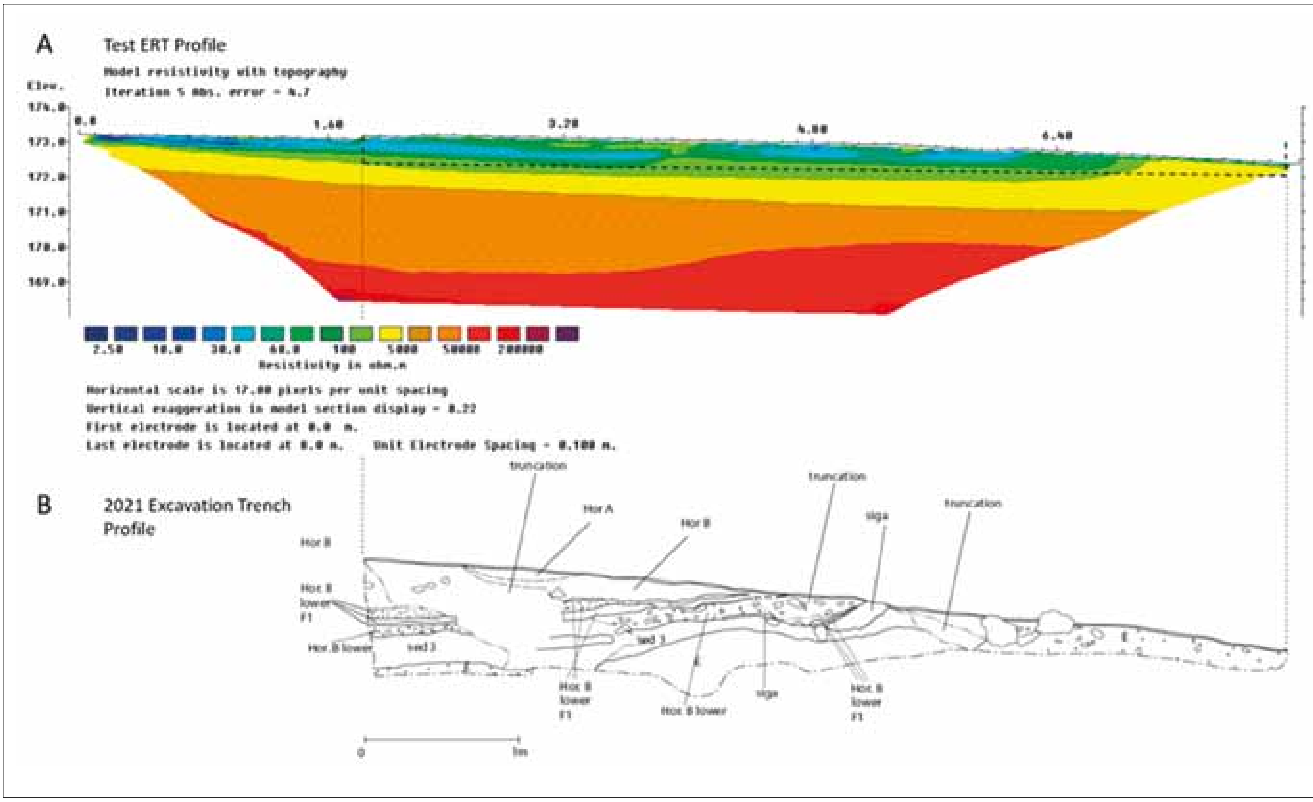


FIGURE 6. Ljubićeva Pećina (A)ERT profile with upper disturbance/intact sediment highlighted, (B) profile drawing of the same location after excavation (made by R. Becker).

The upper portion of the tomography profile shows a high amount of disturbance to a maximum depth of approximately 1.2 m at about 3.8 m along the profile line (Fig. 6: A). This zone of heavy disturbance reduces in depth until it is no longer expressed in the model at approximately 7.0 m along the profile. Mostly undisturbed sediments are modeled underlying the zone of disturbance and at the surface from 7.0 m to the end of the ERT profile at 8.0 m. The zone of heavy bioturbation observed in the previous excavations is modeled in the ERT data as subsurface disturbance varying in depth to approximately 1.2 m below surface. The profile reveals that the disturbed zone is more heavily concentrated in the central and back portion of the side chamber where the modern surface is relatively flat. The area of heavy bioturbation decreases along the profile line approaching the mouth of the side chamber corresponding to an increase in slope of the modern surface.

Pećina data are the additional results it produced which were useful to the excavation team. The high data density allowed for detailed modeling of areas of heavy bioturbation in relation to undisturbed sediments in the upper 1 – 1.5 m of sediment along the profile line (Fig. 6).

The 2008 - 2020 excavations in the side chamber provide context for relating the areas of disturbance seen in the ERT model and those sediments dated to the Upper Paleolithic occupation of the site. Our main reference point for locating intact portions of the Upper Paleolithic sediment is the underlying Horizon E, labeled as "E" in the lower portions of the excavation profile (Fig. 6: B). Horizon E is, more or less evenly distributed throughout the whole of the upper chambers and marks the termination of Pleistocene human occupation at the site. It has a distinctive bright color (5YR5/6 yellowish red), has very little or no evidence of human activity, and is essentially undisturbed, being absent of heavy bioturbation from badgers.

Through the 2020 and 2021 excavations, the team has been able to define a sediment representing human occupation of the cave during the Late Pleistocene, a mixture of sediments representing various occupational events during the Neolithic and Eneolithic, and a thin surface layer of recent activity mixed with cultural remains dating to Bronze Age across the modern surface. Of primary importance to this research project is the sediment deposited by human activity during Late Pleistocene (Sediment 3). Its color ranges from black (10YR2/1) to dark greyish brown (10YR4/2). Around 30% of the rubble is of cultural origin - various bone fragments, ochre, lithic material. When present, Sediment 3 has been observed to lie immediately superior to Horizon E in the stratigraphic sequence.

While the presence or absence of intact portions of Sediment 3 itself cannot be identified in the ERT profile, these data well model the interface between the Horizon E and the heavily disturbed sediments above which is where Sediment 3 is known to occur. As such, excavations during the 2021 field season concentrated on the side chamber's central and back areas based on the modeling produced by the ERT profile.

FIGURE 7. Ljubićeva Pećina data collection for profile in Figure 6 (photo by I. Janković).

2022 Survey of Mujina Pećina and Abri Kontija 002

Research design at Mujina Pećina for the 2022 ERT survey was to use sediment depth models as a means to estimate of the volume of sediments remaining, which in turn is useful for planning future sampling and excavation strategies at the site. Three ERT profile lines of 4.2 m, 5 m, and 4.6 m were surveyed around the interior portion of the fairly small Mujina Pećina chamber in the remaining sediment surrounding the open excavation trench. A probe spacing of 0.10 m was used for each profile line. The sediments at Mujina Pećina contain a very large percentage of gravels and small clasts produced by roof fall inside the cave. The high resistance in this type of sediment makes quality data collection difficult and the severe drought conditions of the 2022 field season proved too much for the field methods used here to produce a useful sediment depth model from these data.

The Abri Kontija 002 site is located in the Lim Channel in Istria which is many hundred kilometers away from Mujina Pećina near the city of Kaštela in Dalmatia. However, the 2022 drought conditions were far reaching and the results of the 2022 ERT survey at Abri Kontija were much the same. A total of eight ERT profile lines were collected ranging from 5 m to 14 m in length. For each profile, the 0.10 m probe spacing was used. Despite using many liters of water to wet the probes and sediment, quality data collection was difficult at best. Similar to the Mujina Pećina results, the 2022 Abri Kontija 002 data produced unreliable sediment depth models.

Though Abri Kontija 002 is a dry rock shelter (there is a filled cave though the ERT survey took place in the rock shelter portion) and Mujina Pećina does have sediment difficult for ERT surveys; the poor results at both sites are currently attributed to difficulties from extreme drought conditions. It may be the case that quality data collection in each location would be possible under more favorable circumstances for the ERT technique which relies on the presence of some amount of ground moisture. Currently, however, that determination cannot be made as both present additional challenges, in terms of sediment conditions, for conducting ERT surveys.

Conclusion

Utilizing ERT survey at Paleolithic cave and rock shelter sites in the eastern Adriatic of Croatia from 2014 – 2022 has centered on the main research question of producing reliable models for sediment depth to bedrock. This research would in turn facilitate excavation efforts for each of the associated projects. In total, portions of six cave and rock shelter sites have been surveyed to date from the Dalmatia and Istria regions of Croatia. The major turning point in this research came when the data density utilized in cave sites was significantly increased following the 2017 re-survey of early tomography profiles in Romualdova Pećina. Reducing the probe spacing along each profile line to 0.10 m from 0.50 m drastically increased the total data set size for the inversion modeling to work with given a profile line of the same length. For the sites included in this study, the high data density provided the inversion modeling with sufficient data to produce reliable sediment depth models at several sites as discussed above.

There are, of course, drawbacks to using the high data density survey. The time it takes to complete each profile line increases dramatically. For instance, collecting data for the eight profile lines at Abri Kontija 002 in 2022 took nearly three weeks with the crew working six days a week. Granted, the data collection conditions were quite difficult with moisture regularly being added to the probes and sediment which, in turn, slowed the data collection process. Despite these drought conditions in 2022, the process is exceedingly slow when compared to other techniques such as GPR survey.

The 2017 survey at Romualdova Pećina does show that greater probe spacing may be used and still produce a reliable sediment depth model (at least under those conditions). Reducing the data density will naturally speed up the survey time for a given profile line. Using 0.20 m and 0.25 m probe spacings represent a compromise between time spent on survey and how fine-grained the resulting model may be. These probe spacings have been shown to work well for sediment depth modeling in cave sites but are unlikely to produce the detailed sediment modeling found in the upper portions of the Ljubićeva Pećina survey which was taken at the 0.10 m probe spacing (Fig. 7).

The tension between time, funding, and necessary level of detail is ever present when considering geophysical prospection survey design in support of an excavation team. As always, the maximum number of techniques that can be brought to bear on a site is recommended. Combining ERT surveys with GPR data from along the same profile lines and collected during the same field work session would be ideal. These combined methods surveys have long been the industry standard and for good reason. In reality, a GPR unit is not always available or well suited to cave and rock shelter environments. That is not to mention the funding needed to support the GRP work. Similarly, ERT can struggle to collect quality data in very dry, or rocky, or very wet conditions as has been identified above. Despite the difficulties identified here, conducting archaeological research in Paleolithic cave and rock shelter sites can be enhanced through subsurface modeling. Advances in ERT survey design and modeling quality in recent years is providing Paleolithic archaeologists with yet another tool with which to carry out research in these specialized environments.

SAŽETAK

MODELIRANJE DUBINE SEDIMENATA ELEKTRIČNOM REZISTENTNOM TOMOGRAFIJOM NA HRVATSKIM PALEOLITIČKIM POLUPEĆINSKIM I PEĆINSKIM NALAZIŠTIMA

Arheološka istraživanja u pećinama i pripećcima pred istraživaće stavljaju niz jedinstvenih izazova. Modeliranje dubine sedimenta unutar špilja ili pripećaka pomaže istraživačima u kvalitetnijem planiranju mjesta na kojima će vršiti istraživanja. Električna otporna tomografija (ERT) se posljednjih deset do petnaest godina sve češće koristi u arheologiji i ima velik potencijal za modeliranje dubinskih profila sedimenta. Međutim, upotreba ove metode na arheološkim nalazištima unutrar špilja i pripećaka donekle je smanjena zbog prostornih ograničenja za prikupljanje podataka u usporedbi s nalazištima na otvorenom. U radu su predstavljeni rezultati istraživanja provedenih između 2014. i 2023. godine u kojima je ERT predstavljala integralni dio projekata istraživanja paleolitičkih lokaliteta istočne jadranske obale, smještenih u špiljama i pripećcima. Rezultati ukazuju na velik potencijal ove metode, uz određena ograničenja koja su uzrokovana samim odlikama i osobitostima pojedinih nalazišta.

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