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WHAT IS HIDDEN BENEATH THE EARTHEN MANTLES OF EARLY IRON AGE BARROWS AT THE FRINGES OF THE EASTERN ALPS?

Recent Results from Geophysical Prospections at Poštela (NE Slovenia)

Branko Mušič – Barbara Horn – Matija Črešnar

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The history of research on the Early Iron Age (EIA) hillfort of Poštela and its cemeteries began in the 19th century. One of the most popular targets for excavations were barrows, which are still being researched today. However, the research techniques and approaches have changed quite importantly. One of the most important changes has been a shift toward non- and low-invasive techniques, which have led to a number of important findings. The examples presented below highlight a number of case studies of barrow research from the Poštela archaeological complex near Maribor in Northeastern Slovenia. This is also where the first geophysical prospection of EIA barrows was carried out in 2006. However, the survey of a group of flattened barrows at Pivola, one of the cemeteries of the Poštela hillfort, was only the beginning of a long-term multi-method investigation of a number of barrow groups as well as several individual barrows in the area. Because the barrows are located in different natural environments and differ in their characteristics, continuous adaptations to the research approach were necessary, including the data acquisition and processing procedures required for archaeologically relevant interpretations.

INTRODUCTION

Early Iron Age (EIA) barrows, also called burial mounds or tumuli and occurring individually or in groups, characterise the cultural landscapes of Southeastern Alpine region and the Pannonian plain up to the present day. They are one of the most distinct remains of the EIA in the region, which stretches from the Eastern Alps all the way to the Danube River. As they are clearly recognizable in the landscape and often hold precious artefacts, they were among the first 'targets' of early antiquarians, collectors and the first established museums since the 19th century. Archaeological excavations, which were also born in that period, are still the most common way to research barrows, albeit the methods have undergone drastic evolution. However, geophysical methods, often combined with other non- or low-invasive methods, are increasingly gaining a reputation when it comes to investigations of EIA barrows. But what are the advantages of such research approaches, and what can be added to the information and knowledge gained by traditional research?

The examples presented below highlight a series of case studies of barrow research from the archaeological complex of Poštela near Maribor in Northeastern Slovenia. They share several characteristics, but also reveal a considerable diversity connected to their basic form, natural environment and their state of preservation. These techniques are therefore more than adequate to help sketch out the broad span of challenges we encounter when researching barrows in this way, although the examples are not representative of all possible scenarios.

Prehistoric archaeological contexts are, in general, the most delicate environments for effective geophysical research design. There is no unique strategy for field procedures applied for data acquisition nor for efficient processing flows required for archaeologically relevant interpretations. This is especially true for barrows. The effectiveness of a research design that is based on remote sensing methods and applied to specific archaeological features, such as barrows, relies largely on the selection of geophysical methods. It depends on their ability to reveal relatively small, central or eccentric burial chambers of different sizes and construction techniques. Furthermore, they are covered by mantles of varying composition, which also reflect the geological peculiarities of their surroundings. Additional challenges are their size and shape, with often steep slopes. As most of the better preserved EIA barrows in the Štajerska region (Slovenian Styria) are located in forested areas, the overgrown surface of the barrows poses an additional hindrance for successfully obtaining measurements. All of the above is a guarantee that this is no easy task even for modern technologies, and routine, 'cookbook' strategies are in these cases often less effective.

Due to similar constraints, a wide range of geophysical methods have been used for exploration elsewhere: seismic (*Forte/Pipan 2008*, 2614–2623; *Tsokas et al. 1995*, 1735–1742; *Vafidis et al. 1995*, 119–128), resistivity mapping (*Teržan/Črešnar/Mušič 2012*, 17–58; *Tonkov 1996*, 209–217; *2008*, 325–328), resistivity tomography (*Mušič et al. 2015*, 37–64; *Papadopoulos et al. 2010*, 192–205), ground penetrating radar (*Forte/Pipan 2008*, 2614–2623; *Goodman et al. 2009*, 479–508; *Mušič/Črešnar/Medarić 2014*, 19–47; *Verdonck et al. 2009*, 193–202), low frequency electromagnetic (*Basar et al. 2020*, 123–145; *Bevan/Roosvelt 2003*, 287–331; *Mušič/Črešnar/Medarić 2014*, 19–47), and magnetic (*Bevan/Roosvelt 2003*, 287–331; *Gorka/Fassbinder 2011*, 183–186; *Mušič et al. 2015*, 37–64; *Osten-Woldenburg/Chaume/Reinhard 2002*, 465, 466; *Smekalova/Voss/Smekalov 2008*). Each of the methods used has proven successful in certain circumstances, but there is (as yet) no universal solution to the approach of mound research.

POŠTELA ARCHAEOLOGICAL COMPLEX

The Poštela archaeological complex is centred around the Poštela fortified hilltop settlement, which occupies a strategic position, controlling the entire Drava-Ptuj plain, as well as the fringes of surrounding hills (Fig. 1). On the Habakuk plateau, just under the settlement, there were burials in flat cremation (urn) graves, as well as in barrows. The latter were arranged in two groups, namely the southern and the northern, stretching over two slightly sloping ridges. A series of individual barrows can be found on the slopes to the south-east of the settlement all the way to the lowlands. The largest group of barrows can be found at Pivola (Botanical Garden; Fig. 1; 2). It is, similar to the Habakuk barrow groups, associated with an urnfield (*Črešnar/Vinazza/Mušič 2019*, 439–448).

The research of the barrows on the Habakuk plateau (Fig. 1–3) began before the end of the 19th century and continued throughout the beginning of the 20th century. At least 15 barrows were excavated in that period, but, as expected, the data from these excavations is very scarce. Nevertheless, the study of the remaining finds and data led to an interesting conclusion, namely that the burials possibly belonged to two communities, who, judging by their grave goods, participated in different activities while alive (*Teržan 1990*, 55–70, 307–326).

The Pivola barrow group is located in the lowlands over 2 km air distance from the settlement. It is the largest closely joined barrow group belonging to the Poštela hillfort (Fig. 1; 2; 14; 15), although individual barrows in the surroundings and several notices of excavated barrows all the way from the mid-19th century onwards, point to possibly more lowland barrow groups.

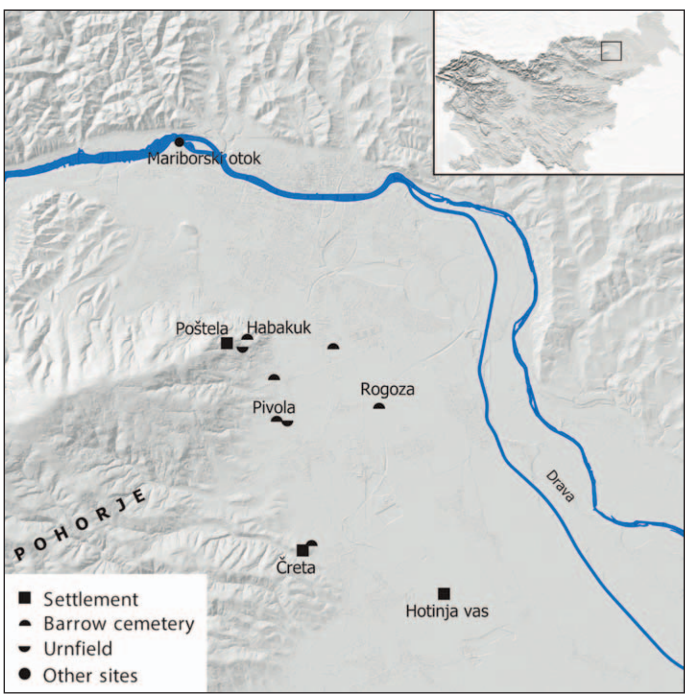


Fig. 1. Most important Early Iron Age sites between the Pohorje massif and the Drava River.

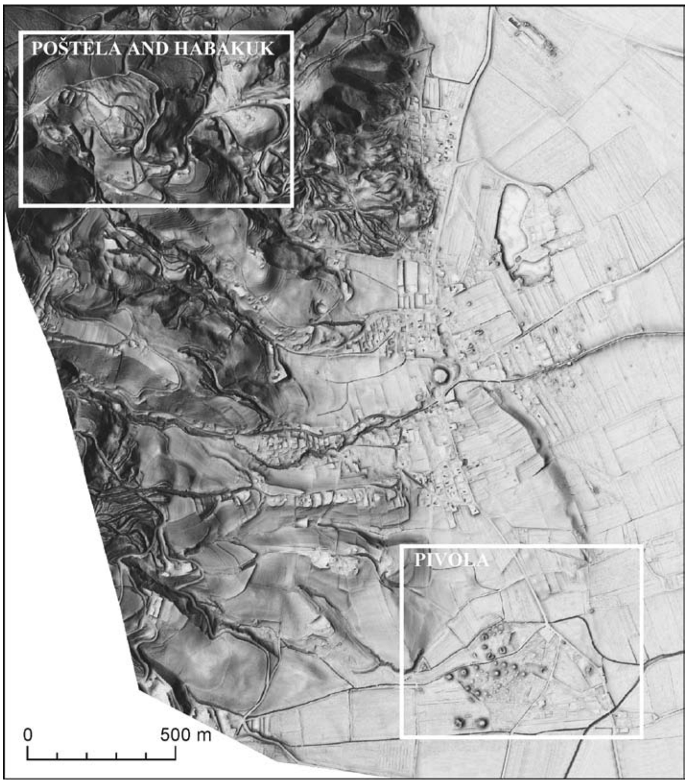


Fig. 2. Location of Poštela (near Maribor) archaeological complex, with Habakuk and Pivola cemeteries on LiDAR derived DTM (DTM by D. Mlekuž).

It comprises over 80 barrows, which can be separated into three groups based on their preservation. The forested southern part is the most extensive. This area was only recently turned into an archaeological park and enclosed into the Botanical Garden of the University of Maribor. The barrows of this group look mostly undamaged (Fig. 14: A). There is another group of barrows to the north, which lies on the ground of a former military base and therefore a series of barrows were reshaped into earthen shelters (Fig. 14: B). Barrows even further to northeast are located on agricultural fields and are therefore almost unrecognizable (Fig. 14: C). This group of barrows was the most badly damaged, as stones from the burial chambers of some barrows were already ploughed away. This is partly evident in the fields, but even more so from ground penetrating radar (GPR) results (Fig. 17; 18). For this reason, rescue excavations were conducted on barrows 13 and 14 (Fig. 14; 15), both holding remains of EIA horseman. The more important of these two is barrow 14, which belonged to a highly-ranked male warrior-horseman (*Strmčnik-Gulič/Teržan 2004*, 217–238; *2021*, 401–410; *Teržan 1990*, 326–329; *Teržan/Črešnar/Kramberger 2021*, 411–422; see also *Teržan/Črešnar/Mušič 2015* 61–82).

For this article, we are focussing on selected results of geophysical investigations on a number of barrows within the necropolises of Habakuk and Pivola (Fig. 1–4; 14; 15), once again elucidating some of our already published investigations (e.g. *Teržan/Črešnar/Mušič 2015*, 61–82). The present study is to be understood as a continuation of our research and a deepening of the topic.

As previous research has clearly shown, it is necessary to adapt the strategy of geophysical research to the size of the tumuli (especially the height and inclination of the slopes). Adjusted to the regional characteristics of barrows, our division consists of three groups: low (< 1 m), medium (1–3 m) and high (> 3 m; see *Mušič/Črešnar/Medarić 2014*, 19–47; *Mušič et al. 2015*, 37–64; *2018*, 317–334).

GENERAL DESCRIPTION OF THE GEOPHYSICAL RESEARCH DESIGN AND ARCHAEOLOGICAL IMPLICATIONS

In recent years, our research on the Poštela complex has been primarily focused on non- and low-invasive research (Fig. 2–4; 14; 15). As will be discussed later, we used ALS, which provided us with a 'base map' for a better understanding of the broader landscape and for a more comprehensive correlation of all the existing data. Furthermore, we have conducted intensive multi-method geophysical surveys followed by surface verification of ALS, and only occasionally also conducting targeted small-scale excavations for verification of geophysical results (Fig. 3; *Črešnar/Vinazza/Mušič 2019*, 443–446, fig. 3; 5–7). Despite the non-/low-invasiveness of the approach, important new data were gained. One of the more important findings, which led to a series of new conclusions, was the recognition of circular ditches, surrounding most if not all barrows in all the cemeteries around Poštela. First identified during the ALS data analysis, it furthermore, in combination with geophysical measurements, provided a basis for recognizing the chronological sequences of barrows of the northern Habakuk barrow group (Fig. 4; 5), which is explained elsewhere (*Črešnar/Vinazza/Mušič 2019*, 445, 446, fig. 6).

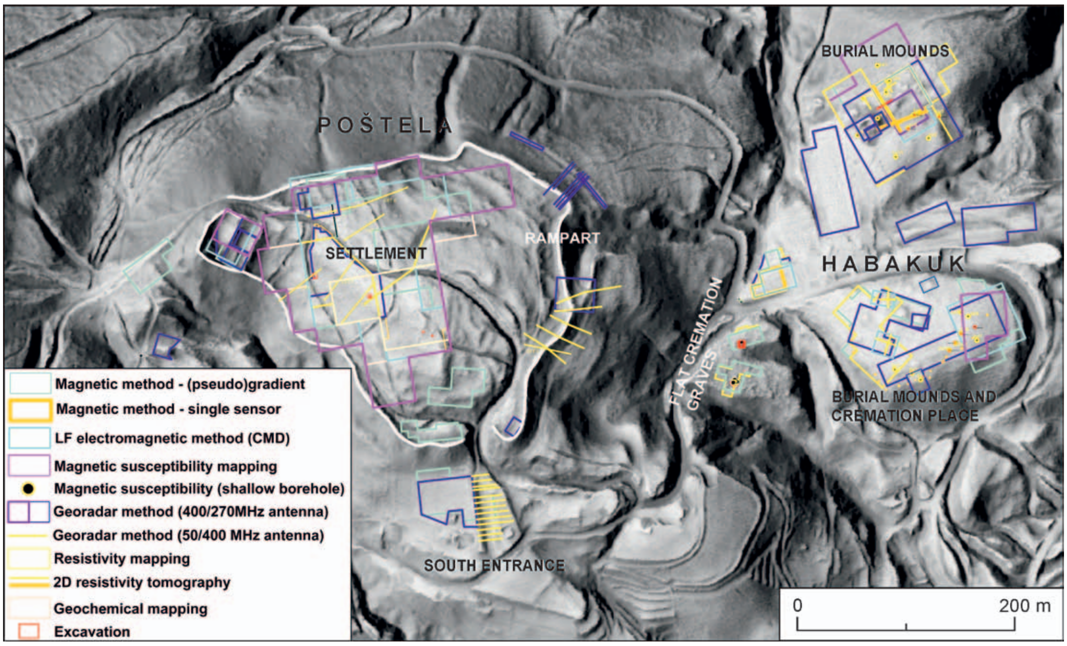


Fig. 3. Poštela hillfort and Habakuk cemetery. Geophysically surveyed areas, investigated by various geophysical methods, shallow drilling and trial trenching (see Fig. 2; DTM by D. Mlekuž; adapted from *Mušič/Črešnar/Medarić 2014*, fig. 2; *Mušič et al. 2015*, fig. 8).

In 2006, a geophysical survey, followed by archaeological excavations, was conducted for the first time in Slovenia as part of a rescue investigation of an EIA barrow. It was included in the research of barrow 13 of the cemetery at Pivola (*Teržan/Črešnar/Mušič 2012*, 17–58; *2015*). Since this mound was later excavated, we were able to compare the results and find good agreement between the results of both approaches (see *Mušič/Črešnar/Medarić 2014*, 19–47; *Teržan/Črešnar/Mušič 2007*, 159, 160; *2012*, 17–58; *2015*, 61–82;). The conclusions of this investigation provided a solid starting point for further geophysical exploration of other barrows, even though the very different circumstances required continuous additions to the approach. However, since then, geophysical methods have become one of the cornerstones of all further investigations on prehistoric necropolises with barrows (see e.g. *Črešnar/Mlekuž 2014*, 18–32). Different measurement methods were introduced step by step, and the results were compared to find the most suitable solutions for their integrated use and presentation.

Numerous barrows, ranging from slightly different geometric proportions and dimensions at the Habakuk necropolis to the extreme variability at Pivola, were a great challenge for us for the reasons described above. Our focus for this article is on barrow investigations in different circumstances, namely on smaller and medium-sized mounds on the Habakuk necropolis, located in a forested area, and on several smaller mounds at Pivola, located in the lowland agricultural zone. The latter were moreover partially damaged or even completely destroyed by ploughing.

Following the field conditions of each selected part of the Poštela complex, namely Habakuk and Pivola, various geophysical techniques were applied. We highlight the analyses of results from ground penetrating radar (GSSI SIR3000, 400 MHz antenna), magnetic method (Geometrics G-858, gradient mode), magnetic susceptibility (KM-7, SatisGeo), resistivity mapping (Geoscan RM15, twin probes array), and 2D resistivity tomography (ARES, GF Instruments; mostly dipole-dipole array). Surveys were conducted on a case-by-case basis, using the geophysical method best suited to the extent of the survey area, the expected potential for finds, and/or estimated efficiency. In this paper, we emphasise the somehow innovative research design for the geophysical exploration of EIA barrows.

The natural conditions in the northern part of the Pivola necropolis, partly extending into the agricultural zone, i.e. uniform geological composition of quaternary sandy clays with rare gravel intercalations (medium low magnetic susceptibility, medium resistivity and medium dielectric permittivity), are favourable for all applied geophysical techniques. On the contrary, the explorations of the southern part of Pivola necropolis within the Botanical garden, and the Habakuk northern barrow group were especially delicate and required adequate, site sensitive, multi-method approaches. The first one has a more chaotic

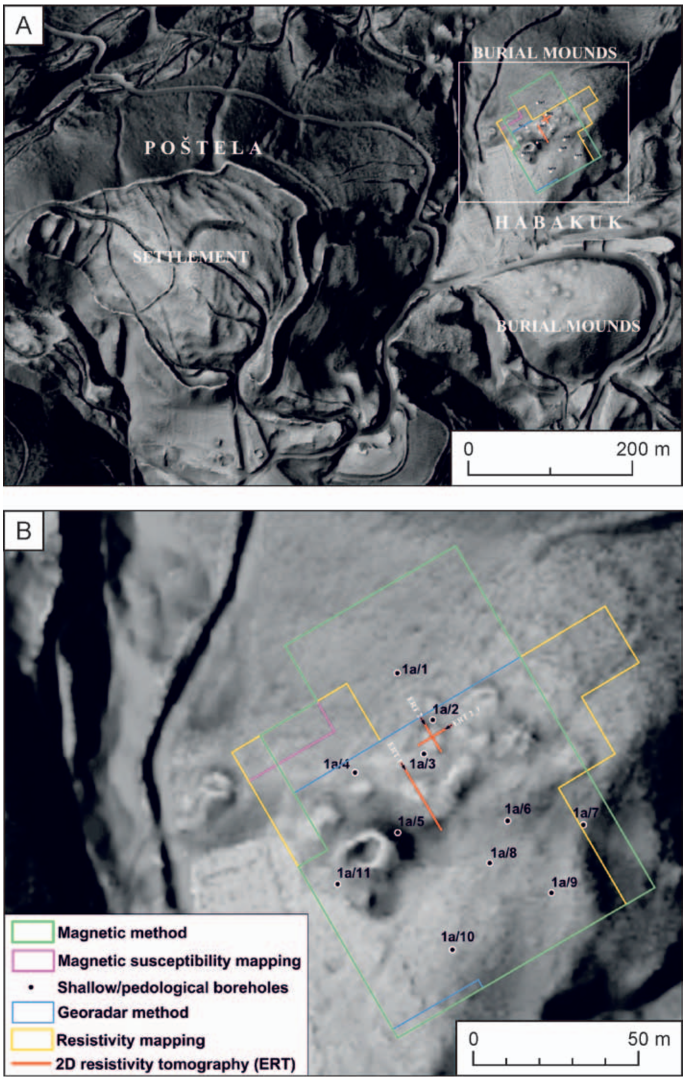


Fig. 4. Poštela hillfort and Habakuk cemetery (A). Northern part of the cemetery (B), investigated with magnetometry, GPR, resistivity mapping and selected profiles for 2D resistivity tomography (adapted from *Mušič et al. 2018*, fig. 1; 4).

geological composition with prevailing gravel sediments in quaternary deluvial and alluvial (proluvial) sediments (low magnetic susceptibility, high resistivity and high dielectric permittivity). The Habakuk plateau is characterized by hard geology composed of variable metamorphic rocks (low, medium to possibly high magnetic susceptibility, high to very high resistivity and medium to low dielectric permittivity). According to the geological map of the Geological Survey of Slovenia (*Žnidarčič/Mioć 1988*) and on-site observations (*Rižnar 2011a*; *2011b*), the dominant stone type at the Poštela site is amphibolite metamorphic facies, which consist of rather weakly magnetic mineral assemblages. The prevailing minerals are hornblende and amphibole. Excavations have shown that quartzite inclusions in amphibolite bedrock are strong sources of negative magnetic gradients, while in places a high proportion of magnetite in amphibolite causes extremely strong positive gradients. All of these magnetic anomalies were erroneously attributed to archaeological remains at the beginning of the investigations. Therefore, the most appropriate research design was determined based on the previous geophysical results and the evidences from the various small-scale excavations still in progress.

A testing polygon was initially selected within the necropolis at Pivola to verify the reliability of the results using the data from the rescue excavation of barrow 13 conducted in 2006 (*Teržan/Črešnar/Mušič 2007*, 159, 160; *2012*, 17–58; *2015*, 61–82). In the meantime (2006–2022), more than 3.5 ha within the Pivola necropolis and about 4 ha in selected areas of the Poštela settlement, as well as more than 2.5 ha in the necropolis with barrows on the Habakuk plateau were investigated. The ever-evolving multi-method approach included magnetic, GPR and low frequency electromagnetic methods, resistivity and magnetic susceptibility mapping, as well as 2D resistivity tomography profiles over barrows, fortifications, etc. (Fig. 2; 3; see also *Medarić/Mušič/Črešnar 2016*, 67–93; *Mušič/Črešnar/Medarić 2014*, 19–47; *Mušič et al. 2013*; *2015*, 37–64; *2018*, 317–334; *Teržan/Črešnar/Mušič 2015*, 61–82).

The magnetic method produced exceptionally meaningful results for the Habakuk and Pivola barrow groups. For magnetic prospections a total field magnetometer *Geometrics G-858* was used in gradient mode, which generally amplifies the weak magnetic anomalies of small structures at shallow depths in favour of long-wave anomalies caused by the geological background. Measurements of the apparent magnetic susceptibility (KM-7, SatisGeo) of samples of top soil revealed rather low values in the range between 0.05×10^{-3} SI and 0.9×10^{-3} SI (mean: 0.23×10^{-3}) at Habakuk and medium susceptibility values in the range between 0.39×10^{-3}SI and 1.01×10^{-3} SI (mean: 0.57×10^{-3}SI) at Pivola. These preliminary results show surprisingly significantly higher values at Pivola. The magnetic susceptibility variations created more complex magnetograms at Pivola than at Habakuk. Nevertheless, the induced magnetization at Pivola clearly shows the ring-ditches around barrows (Fig. 16). An archaeologically identical situation with ring-ditches around barrows is more clearly visible at Habakuk (Fig. 9). Besides ditches, other

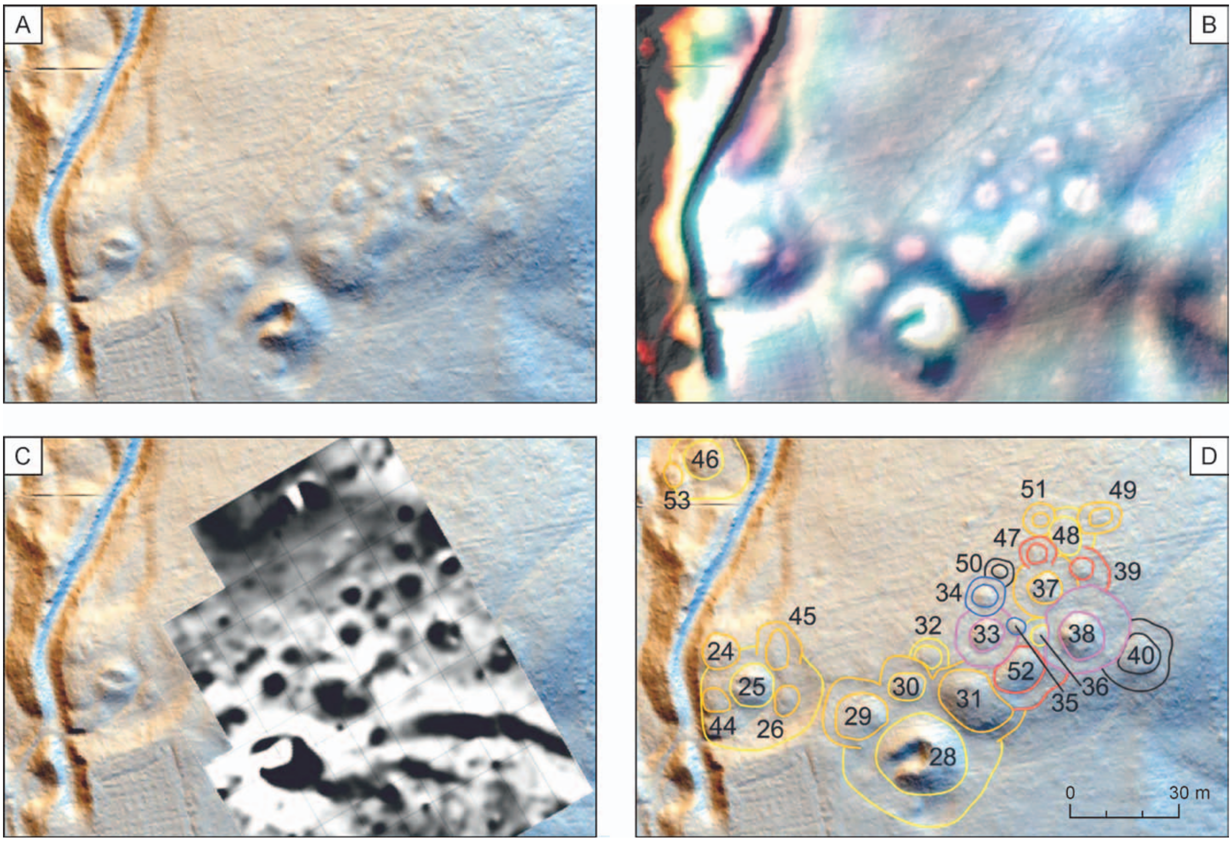


Fig. 5. Habakuk. The northern part of the necropolis. A – shaded DTM; B – local relief analysis (execution D. Mlekuž); C – results of magnetic measurements; D – 'horizontal stratigraphy' of a group of mounds with relative construction phases (sequence: yellow – orange – red – magenta – blue; black coloured mounds are not sufficiently dated; after *Črešnar 2017*, fig. 3; *Črešnar/Vinazza/Mušič 2019*, fig. 6).

archaeologically relevant magnetic anomalies and areas were identified on the basis of magnetic background variability. These can probably be interpreted as areas of different human activities within or in the immediate vicinity of the barrow groups.

A more reliable recognition of archaeologically relevant magnetic anomalies was assured by determining the deeper magnetic sources with a significant background noise reduction using the *Upward continuation* (Fig. 9: A, C, D; *Mušič 2008*, 53–67; *Telford/Geldart/Sheriff 1990*). Transformations like *Vertical derivatives* (Fig. 9: B) are opposed to the *Upward continuation*, and are normally used for the recognition of high frequency magnetic disturbances from sources close to the surface. High frequency spatial distribution of *Vertical derivatives* often corresponded to areas diffusely polluted by strongly magnetic iron minerals of archaeological, modern or natural origin. Due to the bipolar nature of the geomagnetic field, magnetic anomalies located away from the magnetic poles are asymmetric. In general, the *Reduction to the pole* transformation (RTP; see *Martens et al. 2012*, 84–93; *Mušič 2008*, 53–67, fig. 4; 8; *Telford/Geldart/Sheriff 1990*) significantly reduces the complexity of the distinctive bipolarity of induced magnetic anomalies. This transformation should be taken into account in areas with complex magnetic anomalies to reduce their bipolarity and enable more reliable interpretation. The first experiments at the Habakuk northern barrow group showed rather limited efficiency of the RTP on the 'raw' magnetograms in such specific conditions, and was instead applied together with the *Upward continuation* algorithm which made the magnetic interpretation easier and more exact (Fig. 9: E).

Ground penetrating radar (GSSI SIR3000, 400 MHz antenna), resistivity mapping (Geoscan RM15, Twin probes array) and 2D resistivity tomography (ARES, dipole-dipole array) were preferred methods to discover stone chambers in the central parts of the barrows. The selection of each method, or combination of methods, was based largely on the size of the mounds, their overgrowth and thus their accessibility for measurement, and the composition of the mound mantles, which was predicted based on the geological composition of the necropolis.

THE HABAKUK CEMETERY

Geophysical surveys were carried out in the wider surroundings of the Poštela archaeological complex in many separate areas, in a manner dictated by the specific circumstances related to the defined objectives, and with limitations due to the diverse and often changing environmental conditions. The manner of surveying depends on the scale, especially considering the demanding conditions of fieldwork and the range of techniques used. To illustrate the point, we have chosen the example of the northern mound group of the Habakuk necropolis (Fig. 3; 4). It provides a detailed insight into the complexity of the data obtained by geophysical surveys. It also shows the complementary nature of the data obtained by LiDAR scans and various geophysical methods, where these data were used for gaining insight into the evolution of the barrow group (Fig. 5; *Črešnar 2017*, 257–259; *Črešnar/Vinazza/Mušič 2019*, 445–447).

On the LiDAR derived DTM, the location of the entire group of barrows is so clear that even the smallest barrows can be recognized. It is located in an area that rises slightly above the immediate surroundings. On the north to northwest side, the plateau with the barrows gradually merges into a slope with a gentle incline, while to the northeast the plateau becomes a very gentle slope, which continues all the way to the lowlands and on which holloways testify to ancient communications (*Mlekuž/Črešnar 2014*). On the south or southeast side, the plateau drops steeply, with a height difference of several meters. From the south or southeast side, the difference in elevation between the viewer's location and the plateau with the mounds is clearly perceptible, and thus the plateau is also the central topographical feature of this area (Fig. 4: B).

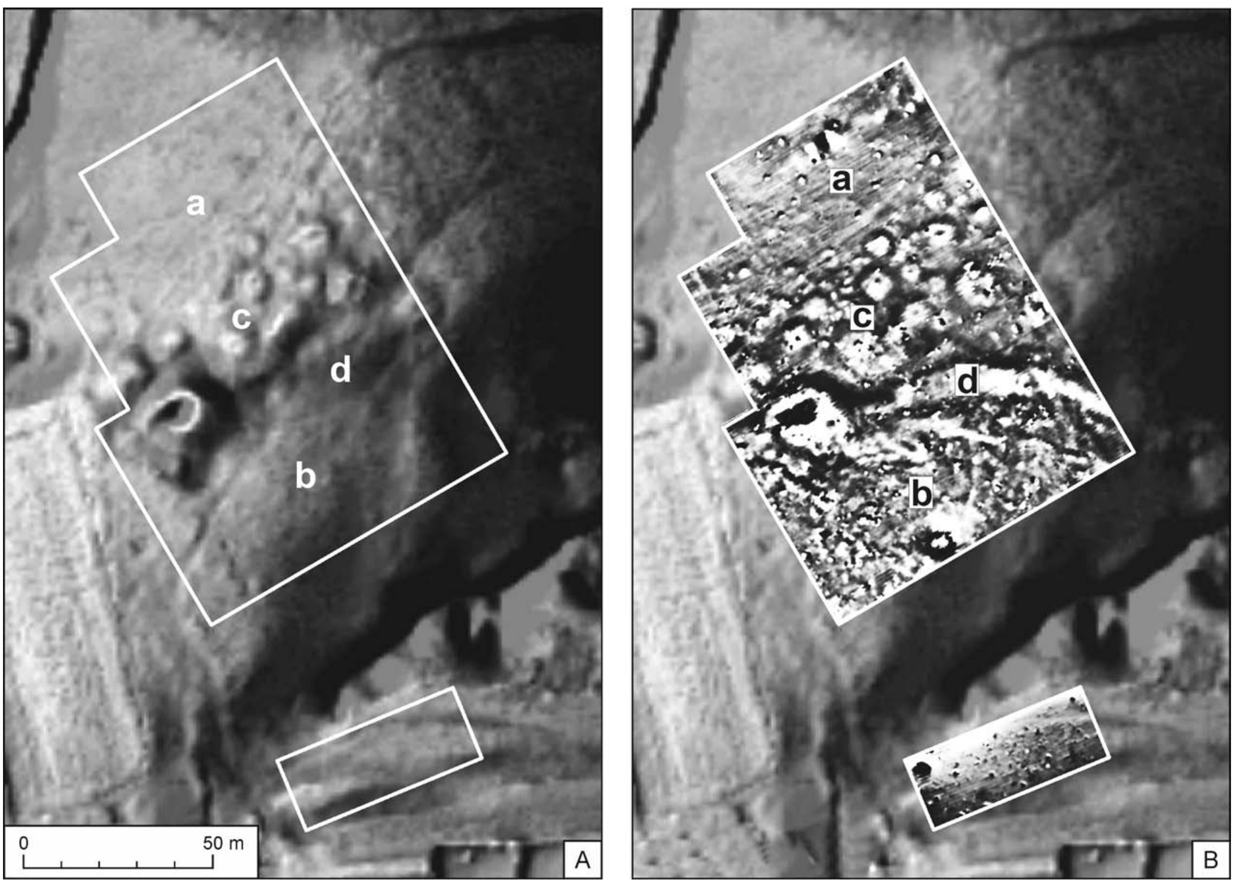
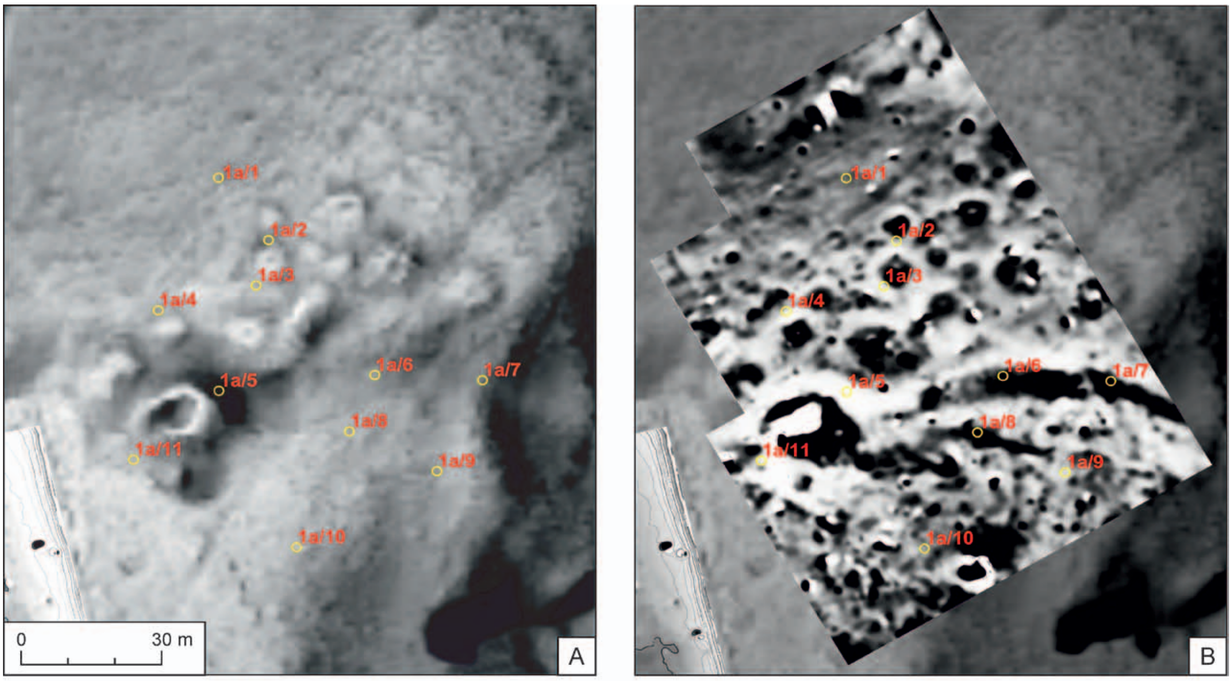


Fig. 6. Habakuk. The northern part of the necropolis, surveyed by the magnetic gradient method on DTM (A) and the magnetogram of the gradient of the total magnetic field (B). Magnetically 'silent' area (a), area with variable magnetic susceptibility of the upper soil layer (b), central part of the mound necropolis with circular ditches around barrows and some approximately roughly square shapes of possible central stone chambers (c), broad band with stronger magnetic anomalies of natural origin (d; adapted from *Mušič et al. 2018*, fig. 2).

Magnetic method and magnetic susceptibility measurements

Magnetic prospecting was carried out with a Geometrics G-858 magnetometer in (pseudo)gradient mode with a distance of 0.7 m between two vertically placed sensors, where the lower sensor was 20–30 cm above the ground, in the distance between parallel profiles 0.5 m.

The mantles of the mounds at the Habakuk necropolis are characterized by relatively higher magnetic field gradients than the immediate surroundings, while the magnetic gradients in the area of the circular ditches around the barrows, which were created during the extraction of soil for the erection of the mound, are slightly negative (Fig. 5: C; 6: B; 7: B; 9). Such archaeological forms are often preserved bellow the ground, even in cases where the body of the barrow has already been completely levelled with the surroundings due to interventions in modern times. In such cases, the research strategy and



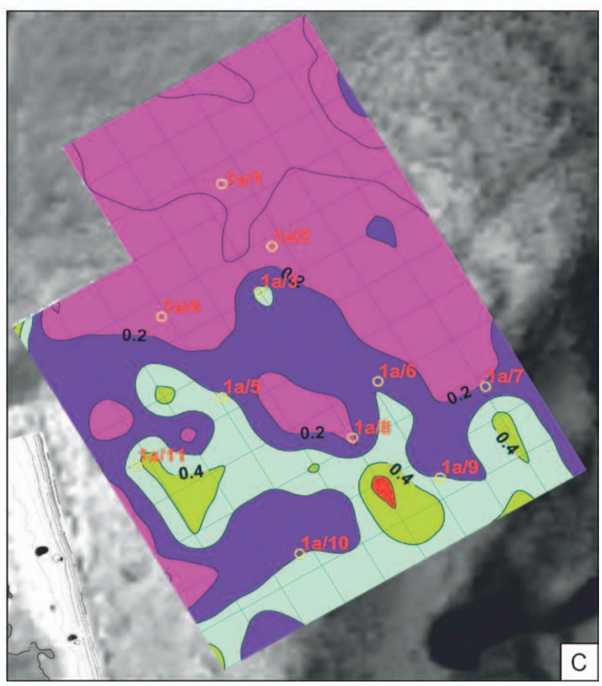
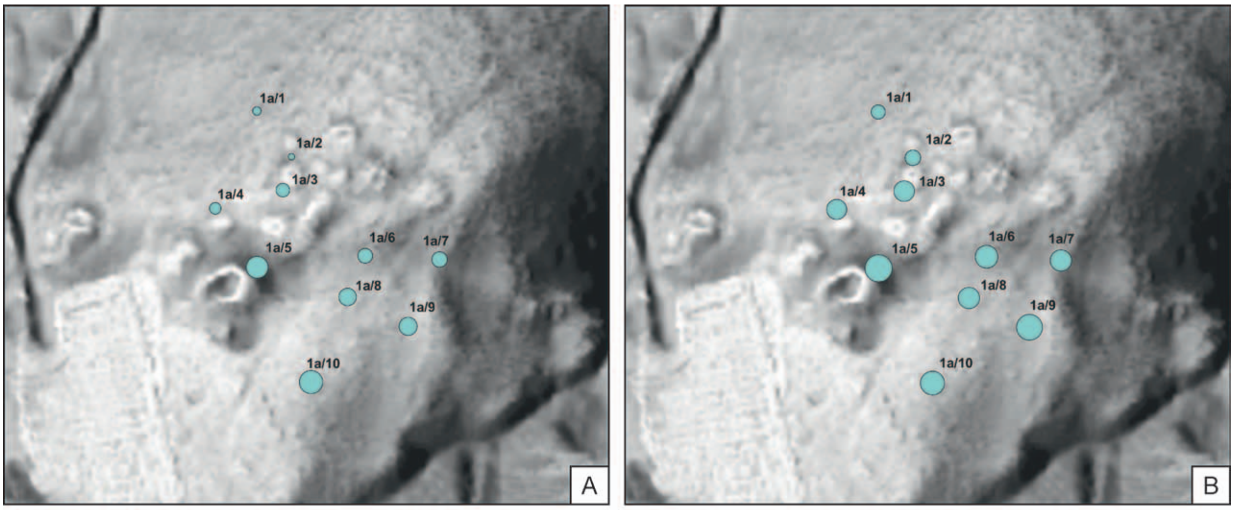


Fig. 7. Habakuk, northern group of barrows. LiDAR map with positions of shallow soil boreholes (A), low-pass filtered magnetic gradient results (B), and topsoil magnetic susceptibility mapping (× 10^{-3} SI) results to a depth of about 5 cm, carried out in a regular grid of 10 × 10 m (C). The highest magnetic susceptibility values were mostly measured in a relatively flat area south of the mound group (adapted from *Mušič et al. 2015*, fig. 16).



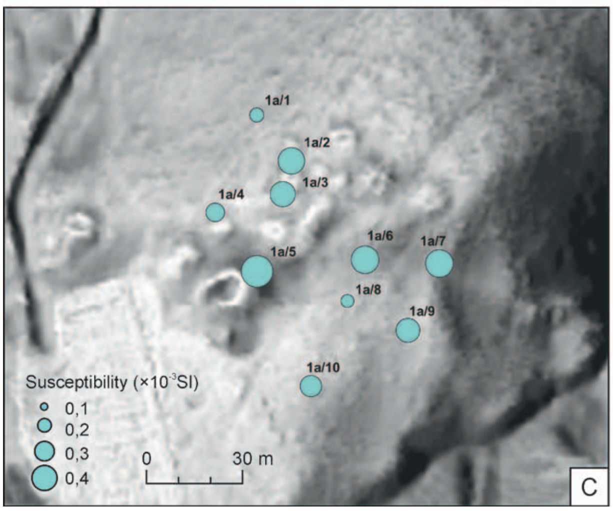


Fig. 8. Habakuk, northern group of barrows. Mean values of magnetic susceptibility measured with the *Kappameter KT-5* at the surface (A) and at two depth intervals in shallow boreholes (B – 0–30 cm; C – 30 cm to solid bedrock at a depth of about 50–60 cm). Susceptibility values vary, but are lowest at the surface and highest at several locations in the final depth interval. We conclude that this is not an effect of bedrock because the susceptibility of the amphibolite (about 0.2–0.25 × 10^{-3} SI) is lower than these values. We assume that all values above 2.5–3 × 10^{-3} SI could be of archaeological origin. The main reason is usually activities related to high temperatures. For example, in the southern part of the same necropolis, an EIA ritual deposit, containing large amounts of fragmented pottery and animal bones, was discovered based on magnetic susceptibility measurements (in addition to magnetometry and the low-frequency electromagnetic method; adapted from *Mušič et al. 2015*, fig. 17).

the interpretation of the results, e.g. the magnetic method, do not differ from conventional procedures (*Mušič et al. 2015*, 37–64). The relatively rapid execution of measurements even in difficult environments, enables large areas to be covered in a relatively short time. This makes the magnetic method particularly effective for the delineation of necropolises by the identification of barrow perimeter/circular ditches alone (see e.g. *Czajlik et al. 2016*, 57–73; *Osten-Woldenburg/Chaume/Reinhard 2002*, 465, 466).

In general, the situation is entirely opposite, when the possibility of the magnetic method for central stone burial chambers recognition is under detailed inspection. Namely, stone made chambers are rarely clearly visible in the central part of barrows on the results of the magnetic method.

Contrary to this general statement, at the Habakuk necropolis there are more or less obvious in several places in the form of roughly square floor plans of relatively stronger positive gradients (Fig. 6: B; 7: B; 9).

All prominent magnetic anomalies in the immediate vicinity of barrows clusters are also very important. These may represent the magnetic effect of various remains associated with different funeral activities, etc. (see e.g. *Mušič/Črešnar/Medarić 2014*, fig. 16).

On the southern slope under the plateau with the mounds, the results of the magnetic method clearly show a 5 to 10 m wide bend of weakly positive magnetic gradients, which runs approximately in the east-west direction towards the largest barrow (Fig. 9: A: b). The magnetic gradient does not exceed 3 nT/m, which means that it can be a weak magnetic source at a shallow depth or a stronger source at a greater depth. It is an unusual form of magnetic anomaly, which we have not seen elsewhere in the area of the Poštela complex (see the explanation in the caption to Fig. 11).

Although the large ratio between the mantle volume and stone burial chambers often makes it difficult to identify their magnetic effect, in some cases it is still possible to observe anomalies that could indicate the contents of the mounds (*Bevan/Roosvelt 2003*, 287–331; *Fassbinder et al. 2009*, 59–61; *Gorka/Fassbinder 2011*, 183–186). Caution is required when interpreting the results of magnetic measurements,

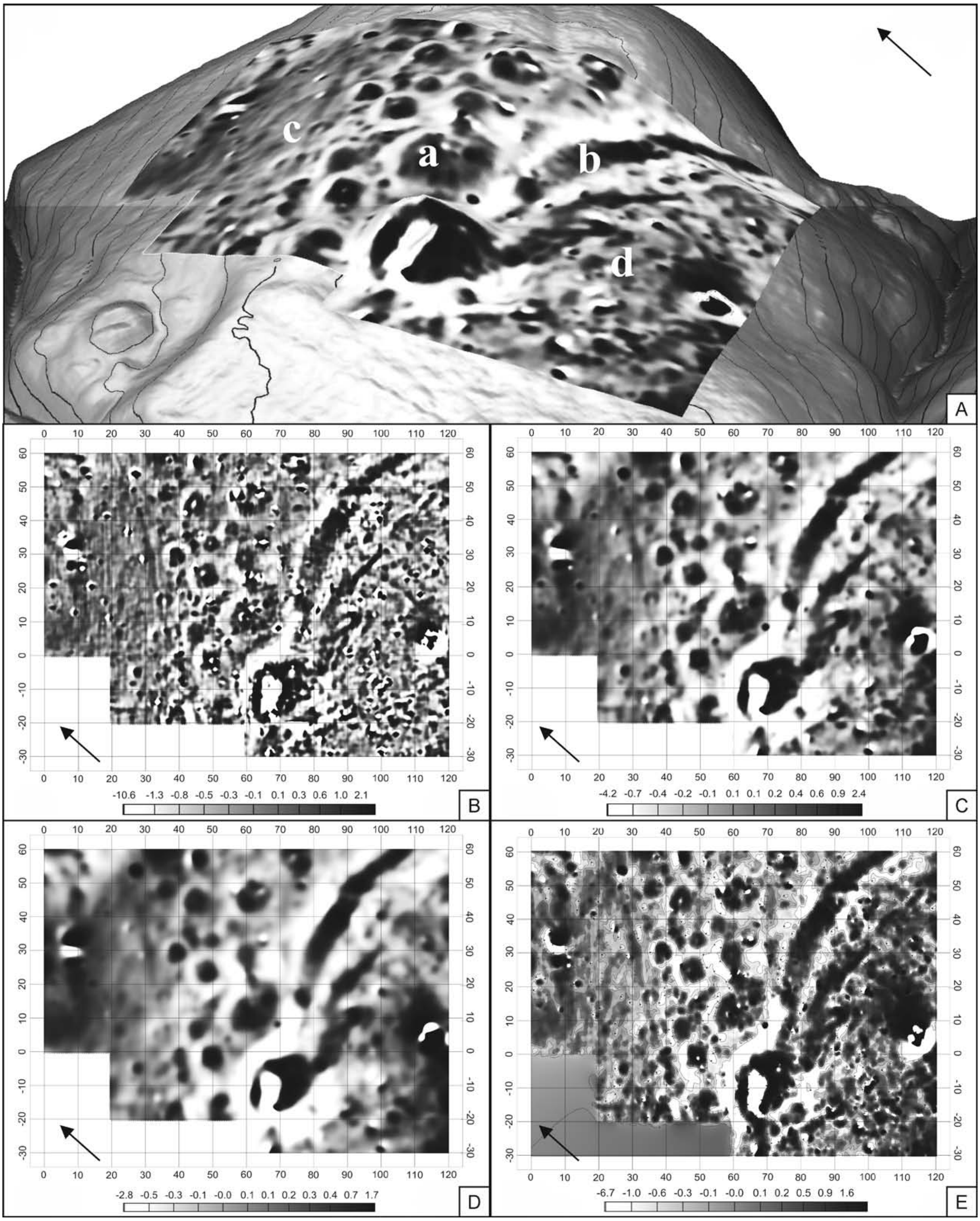


Fig. 9. Habakuk, northern group of barrows. Magnetic map on the LiDAR derived DTM for an arbitrarily selected 3D view of the magnetic response of the mounds after applying the *Upward continuation* algorithm (A). Advanced magnetic processing steps: *Vertical derivatives* (B), *Upward continuation* with recalculated magnetic anomalies at 0.75 m (C) and 1.5 m above the actual height of the magnetic profiles (D), *Reduction to pole* and *Upward continuation* 0.3 m above the actual height of the magnetic profiles (E). Central parts of barrows, surrounded by circular ditches with a diameter correlating with the barrows (a), wide band of relatively stronger magnetic anomalies of geological origin along the eastern edge of the topographic elevation with barrows (b), magnetically 'quiet' area (c), and area with variable magnetic susceptibility of possibly archaeological origin (d; adapted from *Mušič et al. 2018*, fig. 3; 10).

as the anomalies can be partly caused by the shape of the mound. Without understanding the effect of topography, we can reach premature conclusions about the archaeological structures in the central part of the mound. The topographic effect increases strongly with the slope of the mound, less so with its height, so that the effect is much more pronounced for smaller mounds with a steep slope (*Bevan/Roosvelt 2003*, 287–331; *Smekalova/Bevan 2002*). The small height of the mounds, on the other hand, means that potential chambers and other burial structures are located closer to the surface. This increases the possibility that, in cases where there are sufficient differences in susceptibility between the material in the mound fill and the rock material of the burial chambers, we can actually identify them with magnetometry (see *Mušič et al. 2018*, 317–334).

The data on the relatively low magnetic susceptibility of amphibolites, metamorphic rocks forming the eastern part of the Pohorje Mountain (*Rižnar 2011a*; *2011b*; *Žnidarčič/Mioć 1988*), are important for the magnetic exploration of the barrows of the Habakuk necropolis. The apparent magnetic susceptibility (KM-7, SatisGeo) of the upper part of the strongly weathered amphibolite is at most 0.3×10^{-3} SI. The highest values of the magnetic susceptibility of the silty layer above the weathered amphibolite are about 0.45×10^{-3} SI. Such a small difference in magnetic susceptibility between soil variations and rock material, from which the burial chambers in the mounds were also built, did not give much hope for their identification on magnetograms (*Mušič/Črešnar/Medarić 2014*, 19–47; *Mušič et al. 2015*, 37–64).

Despite the small measured differences in magnetic susceptibility between soil and bedrock, the results of magnetic measurements were useful for reliable archaeological interpretation (Fig. 5). The results of the gradient measurements of the magnetic field gave good results regarding the circular ditches, which were also recognized in the analysis of the LiDAR data (*Črešnar/Mlekuž 2014*, 18–32) and possibly also some stone chambers (see *Mušič/Črešnar/Medarić 2014*, 19–47; *Mušič et al. 2015*, 37–64; *2018*, 317–334).

The circular ditches are already clearly visible on the displays of the 'raw' values of the gradient measurements (Fig. 6: B; 7: B) and after the application of the *Upward continuation* algorithm (Fig. 7: B; 9: C, D). With regards to identifying possible stone burial chambers in the central parts of the mounds, we have to compare the results of different processing steps, whereby we also introduced the calculation of *Vertical derivatives*, which slightly emphasizes lateral changes in magnetic anomalies (Fig. 9: B) and *RTP transformation*, which reduces bipolarity of magnetic anomalies (Fig. 9: E). In some places, approximately square shapes can be seen fairly clearly in the central parts of the mounds. This suggests that it is most likely the magnetic response of stone burial chambers, but such an interpretation requires caution. Such shapes can also be the result of the shape of the mounds, the heterogeneous composition of the mantle, and/or the diverse archaeological remains in the central part of the mound. In addition to the induced magnetization in the areas of stone chambers, remains with a relatively stronger thermoremanent magnetization can also be expected (ceramic pots and burnt clay), which, in addition to other factors already mentioned, visually change the original magnetic response of the chamber.

If we summarize the findings, it appears that in the analysis of the northern group of mounds on Habakuk, we can recognize at least five phases of the expansion of the burial ground, while some mounds cannot be precisely placed due to their poor relationships with other mounds. Confirmation that our analysis is going in the right direction is also the fact that we can identify mound 38 (Fig. 5) as one of the youngest mounds, in which a female person with a rich bronze costume was buried, according to which we can date it to the last phase of the settlement of Poštela in the Early Iron Age or Ha C2/Ha D1 (*Teržan 1990*, 66–70, pl. 61).

Ground penetrating radar method

The results of the GPR method using a 400 MHz high-frequency antenna (Fig. 10), were quite similar to those obtained by geoelectric resistivity mapping described in next chapter (Fig. 12). The strongest GPR reflections were measured on the mounds, which we interpret as effects of the rock composition of the mound mantles and possibly partly also the effect of central stone chambers. The distinct GPR signals occur frequently also in the spaces between the mounds, which is mostly consequence of a solid bedrock at a depth of less than 1 m (Fig. 10).

Besides the dominating archaeological topics, we are also interested in the explanations of some archaeologically relevant natural phenomena that can be understood from the results of geophysical research. One of them is the plateau on which the mounds were placed. The mound necropolis is located on an amphibolite plateau that rises several meters above the immediate surroundings. The assumption is that it was most likely a tectonically uplifted amphibolite block. The rapid lateral transition in the solid

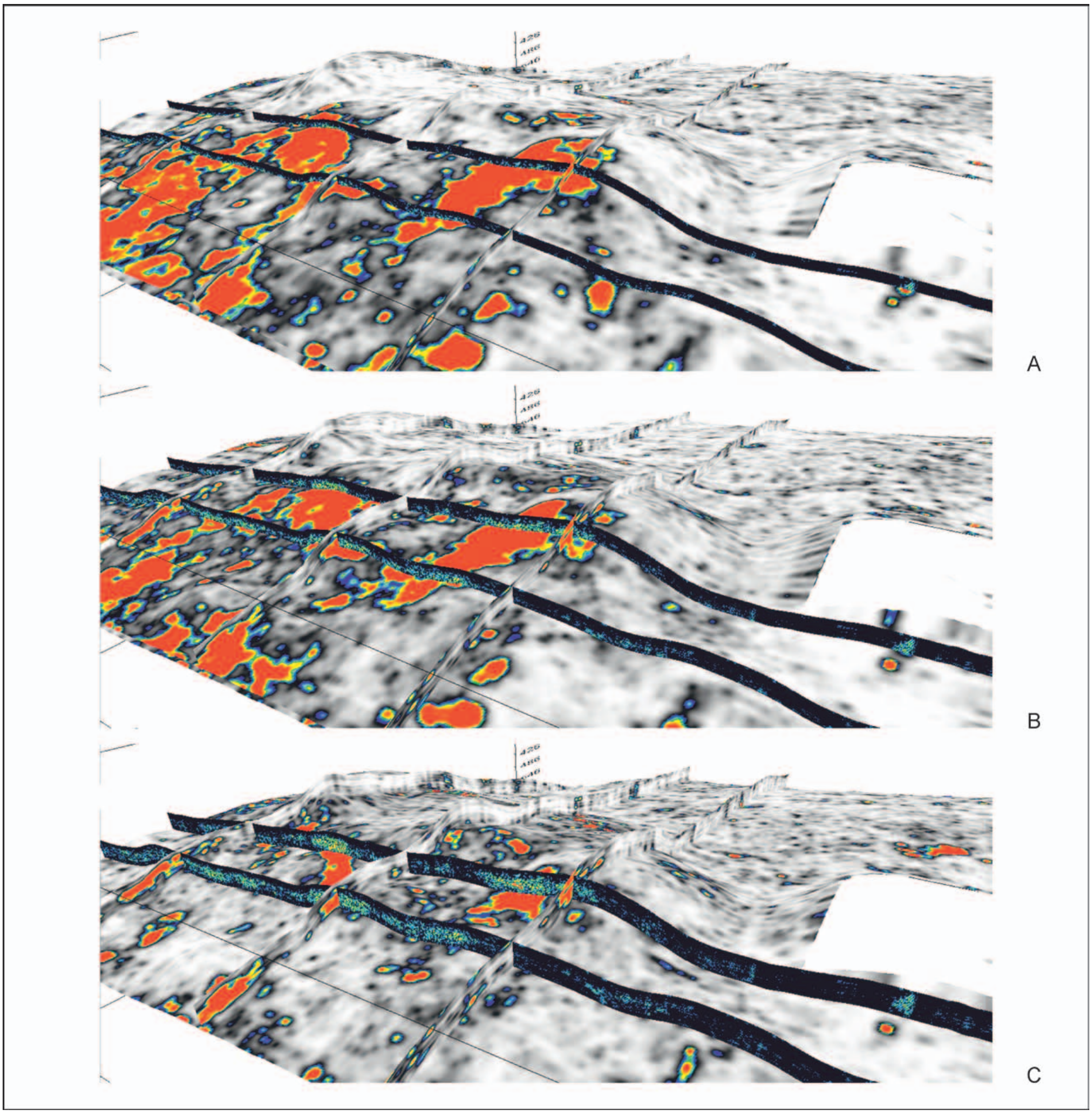


Fig. 10. Habakuk, northern group of barrows. 3D representation of GPR signals recorded with a 400 MHz antenna on LiDAR derived topography at three depth intervals. A – 0–0.5 m; B – 0.5–1 m; C – 1–1.5 m. Relatively strong GPR reflections were measured both above and between the barrows (view from the northwest; adapted from *Mušič et al. 2015*, fig. 11).

bedrock on the east side of the plateau is very evident on the magnetic (Fig. 11: MAG) and GPR results (Fig. 11: GPR).

Using the GPR method, we examined the eastern steep edge of the plateau with the mounds (Fig. 11: DEM and GPR) for a possible step between the bedrock and sediments deposited as a mass flow adjacent to the plateau where the mounds are located. On the horizontal slices of the GPR signals, this boundary of solid bedrock is very evident at depths between 1 and 2 m (Fig. 11: GPR). Strong GPR echoes at the bedrock edge correspond to a broad band of magnetic anomalies, confirming their natural origin (Fig. 11: MAG). Throughout the south-eastern half of the study area, the absence of GPR reflections is due to attenuation of GPR signals in gravitationally transported fine-grained material or colluvium. We were interested in the explanation of all these consistent findings, which we further supported with ERT measurements (Fig. 11: ERT).

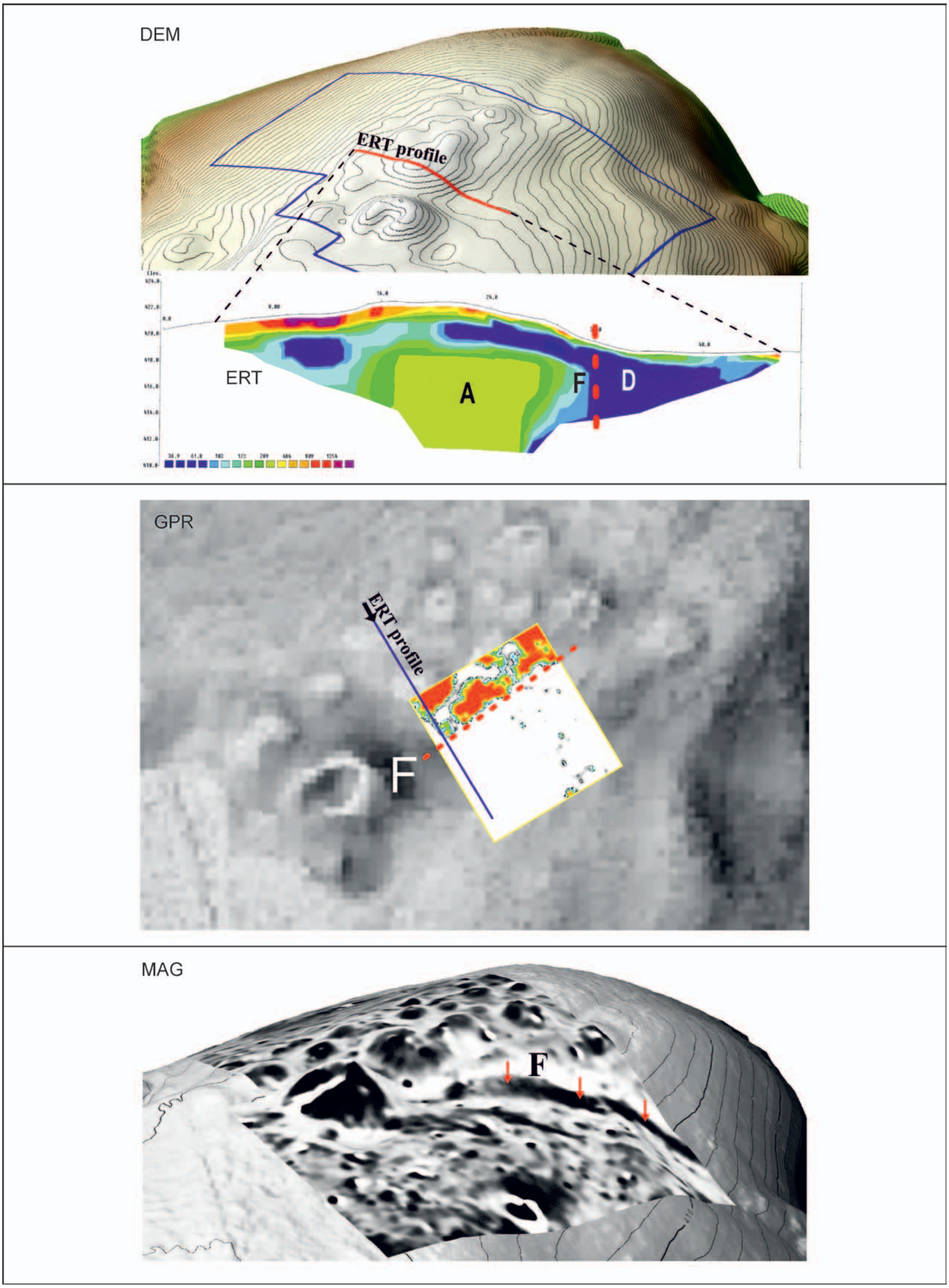


Fig. 11. Habakuk, northern group of barrows. Uplifted solid bedrock block of amphibolite (A), electrically highly conductive material (gravitationally transported material/colluvium/mass flow [D]), steep vertical boundary (fault?) between solid bedrock and fine grained gravitationally transported sediment (sand/silt [F]; adapted from *Mušič et al. 2015*, fig. 13; 14; 20).

The amphibolite block itself is clearly visible on the ERT profile model measured by *Wenner alpha* electrode array (Fig. 11: ERT). The transition between the high-resistivity amphibolite block (Fig. 11: A) and the low-resistivity silty sediment on the east side (Fig. 11: D) coincides with magnetic and GPR anomalies at this location. We assume that this extremely sharp geological boundary represents one of the faults along which the amphibolite block was uplifted (Fig. 11: F), which later served as a topographically elevated auditorium for burials in prehistoric times.

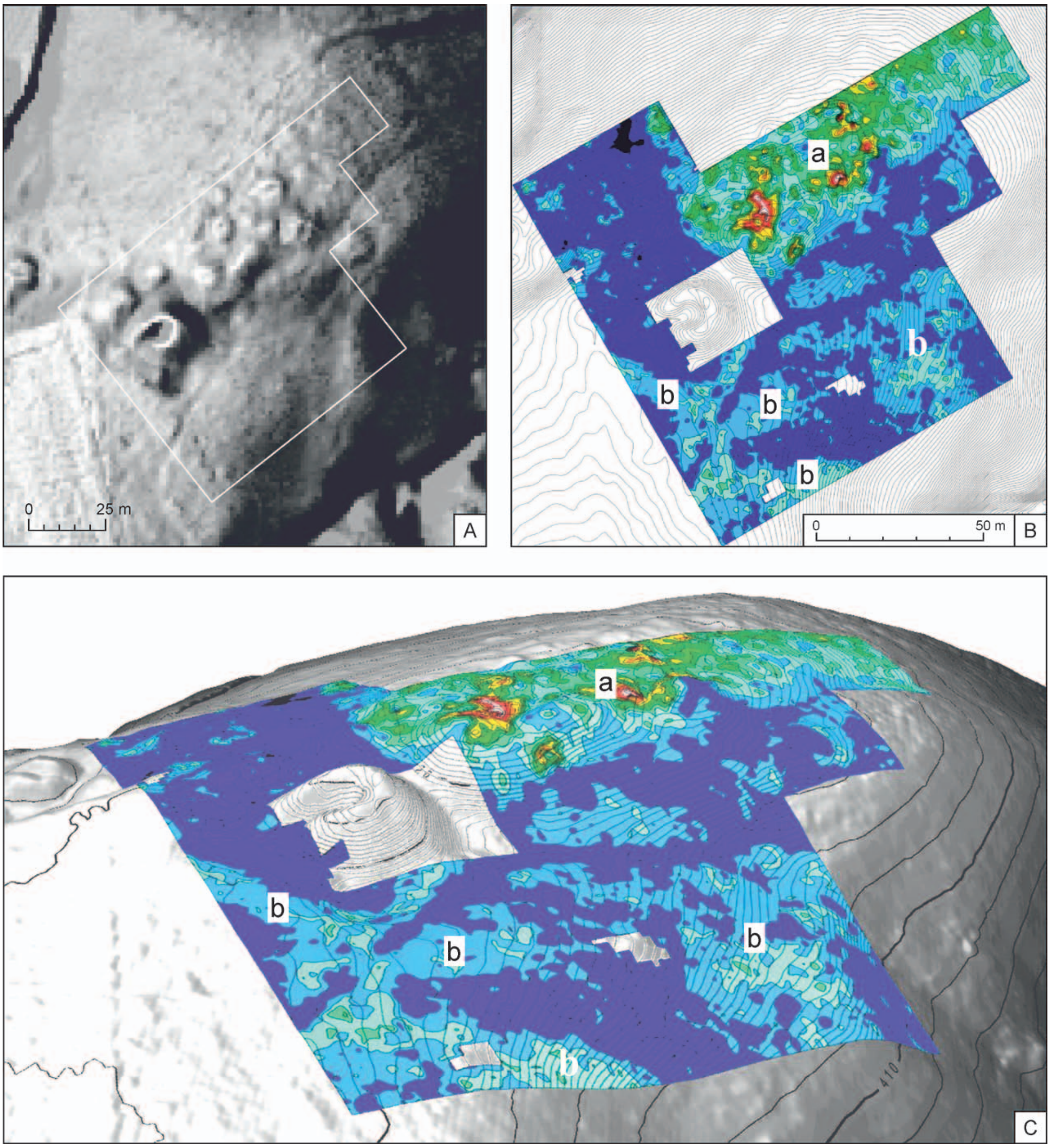


Fig. 12. Habakuk, northern group of barrows. Area covered by resistivity mapping (A). In general, the highest resistance values were measured on the slightly elevated plateau with barrows (B: a), which is most evident in the 3D view (C: a). Possible stone chambers cannot be clearly identified due to the heterogeneous composition of the mound mantles with a high percentage of rock debris. Somewhat higher resistivity values than the local background are also found on the south side on a relatively flat surface, which could be an anthropogenically altered composition, but a natural origin cannot be completely ruled out (B: b; C: b; adapted from *Mušič et al. 2015*, fig. 10).

Geoelectric resistivity method

Resistivity mapping

We used the geoelectric resistivity method in the manner of geoelectric mapping (Geoscan RM15) to primarily determine the high-resistivity effect of rock material in barrows and shallow-lying bedrock using the Twin probes array technique (see e.g. *Mušič/Horvat 2007*, 219–283). The highest resistivity values were measured on a slightly higher part of the terrain with a northern group of barrows on Habakuk (Fig. 12: A, B). Comparison with isohypses on DEM explains that smaller areas of markedly high resistivity are present both in mounds and in the spaces between mounds (Fig. 12: C). High-resistivity anomalies up to 1 m depth most likely represent the effect of the high-resistivity composition of the barrows mantle with stone made chambers, as well as solid geological bedrock in the intermediate spaces between the mounds. The high-resistivity composition of the mound mantles may indicate a relatively high proportion of rock debris, but we assume that some of these anomalies are also due to the stone-made chambers, as shown by the results of 2D resistivity tomography (Fig. 13: k). For the space between the mounds, it was confirmed by shallow pedological drilling that fragments of weathered amphibolite bedrock can already be found in some places at a depth of 0.5 m. Shallow pedological boreholes were placed based on the results of the magnetic method and were primarily intended for measuring the magnetic susceptibility of the drilled samples at two depths, thereby checking the shallow sources of magnetic anomalies (Fig. 8). Along with the data on the thickness of the amphibolite silty-sand weathered material above the solid bedrock on the plateau with barrows, these results were useful for understanding the results of the resistivity mapping and GPR methods. When we used the GPR method with a high-frequency 400 MHz antenna (GSSI SIR3000), we obtained similar results to the geoelectric mapping. The most pronounced reflections were measured on parts of the mound mantles, which we interpret as the combined effect of the rock composition of the mound mantles and stone made chambers, as well as on the intermediate spaces between the mounds, which is the result of a solid bedrock at depths of less than 1 m.

Electrical resistivity tomography

In 2015, the first electrical resistivity tomography measurements (ERT) for the purpose of (geo) archaeological research in Slovenia were carried out in the northern part of the Habakuk mound necropolis (*Mušič et al. 2015*, 37–64; *2018*, 317–334).

The higher resistivity amphibolite bedrock of the plateau with barrows, and the gravity-transported material with better electrical conductivity (mainly silt and sand) at the lower, relatively flat area to the south, were defined on the 2D resistivity models (see *Mušič et al. 2015*, 37–64). These models of the profile ERT 1 over the medium-high barrow 31 (Fig. 13), were created using measurements from three different electrode arrays (dipole-dipole, Wenner alpha and Wenner-Schlumberger; see *Mušič et al. 2015*, 37–64). Subsequently, low mound 33 was also investigated using the ERT method (Fig. 13).

Barrow 31

Since the dipole-dipole electrode array proved to be the most appropriate of the three previously verified electrode arrays that we had at our disposal for the investigation of the internal structure of mound 31 (Fig. 13: ERT 1), we mainly used this technique for the ERT investigation of the barrows. With the ERT 1 profile, we wanted to get a more detailed insight into the composition of mound 31 with a shorter inter-electrode distance (0.5 m) and thus better resolution. In the resistivity tomography model, the high-resistivity anomalies representing the remains of the stone made burial chamber (Fig. 13: k) are well separated from the lower-resistivity of weathered amphibolite material (Fig. 13: b, c) above the higher-resistivity solid amphibolite bedrock (Fig. 13: d). The diameter of mound 31 is around 18 m, and the chamber was probably built of amphibolite rocks using the dry-wall technique, given the resistance values (300–750 Ωm). The diameter of the chamber in the direction of the ERT profile is approx. 4.5 m, and its height is about 1 m. The very high resistivity surface layer above the chamber extends to a depth of approximately 0.5 m. The chamber is located at a depth interval approximately between 0.3 and 1.5 m below the surface.

Barrow 33

The ERT profiles (ERT 2 and ERT 2_1) with a length of 11.7 m, measured in two mutually perpendicular directions (Fig. 13: ERT 2, ERT 2_1), with inter-electrode distances of 0.3 m and a dipole-dipole electrode configuration, clearly defined the remains of stone burial chambers in the central part of the mound with a diameter of about 10 m. At the location of the burial chamber there are very high resistivity values (700–8000 Ωm). In the direction of the profile ERT 2 the assumed diameter of the chamber is about 2.5 m, in the direction of the profile ERT 2_1 it is 3 m. The height of the preserved part of the chamber is approx. 0.75 m in both ERT profiles (Fig. 13: C, D). The resistivity values of the weathered amphibolite in most of the base of mound 33 (200 Ωm; only at the extreme NE edge of the ERT 2_1 profile is 700 Ωm reached) are similar to those of the ERT 1 profile on the NW side of mound 31. This most likely means that a relatively larger proportion of rock debris of the weathered amphibolite is present in a large area of the NW part of the mantle, which was also confirmed by shallow drilling for magnetic susceptibility measurements at depths of 0–0.5 m and 0.5–1 m (Fig. 8; see also *Mušič et al. 2015*, 37–64, fig. 16; 17).

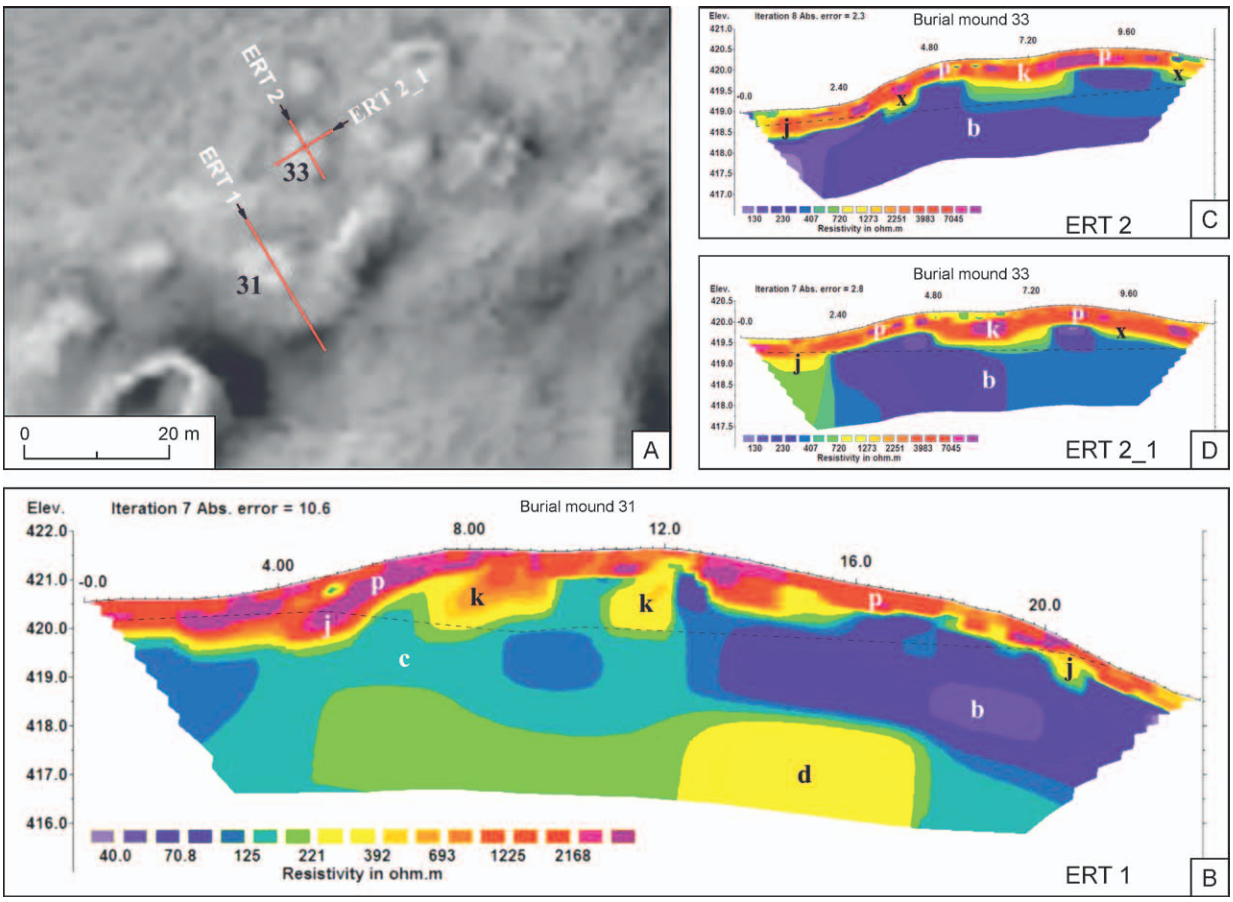


Fig. 13. Habakuk, northern group of barrows. Barrow 31 (B): 2D ERT model of profile ERT 1. k – remains of a stone chamber with high resistivity (300–750 Ωm); p – very high resistivity barrow mantle (over 1500 Ωm) near the surface and low resistivity inner part of barrow below the depth of 0.5 m (60–150 Ωm); j – most likely a mound circular ditch filled with highly resistive material; b – fine-grained material with a high moisture content (up to 100 Ωm); c – water saturated amphibolite substrate (100–200 Ωm); d – higher resistivity suggests partially weathered amphibolite bedrock. Barrow 33: 2D ERT model of profiles ERT 2 (C) and ERT 2_1 (D) measured in perpendicular directions (A). k – very high resistivity remains of a stone chamber (700–8000 Ωm); most likely, the ceiling of the chamber has settled, also inferred from the concave central part of the mound above the chamber; p – the mantle of the mound with high resistivity (over 1000 Ωm) extends to 0.5 m below the surface, with much lower resistivity values of 150–400 Ωm in the inner part of the mound; j – the circumferential ditch around the mound, which was later filled with higher resistivity material gravitationally transported from the mound, corresponds in location to the circular magnetic anomaly; x – stone structures with high resistivity, 0.7 m wide and 0.3 m high, remain unexplained; b – weathered remains of amphibolite bedrock (200–700 Ωm; adapted from *Mušič et al. 2018*, fig. 4–6).

THE PIVOLA CEMETERY

As described above, the area at Pivola is very complex also because of the different ways of land use, which importantly affected our research approach (Fig. 14; 15).

Magnetic method

Under these circumstances we should not expect magnetic anomalies that would indicate the presence of burial chambers, but we can expect magnetic anomalies from possible circular ditches, which were confirmed by magnetic measurements (Fig. 16). In this way we supplemented the results of the georadar method, which did not, on their own, clearly confirm the presence of perimeter ditches, as well as the results of excavations that mostly targeted only the central burial chambers (Fig. 17–20). In the case of barrow 13, where three trial trenches were laid out to target the circular ditch, it was only possible to identify the remains of the mantle.

Ground Penetrating Radar method

This GPR method, using a 400 MHz antenna, was preferred for solving research questions concerning the exact location and size of dry-stone burial chambers in barrows as well as their preserved height

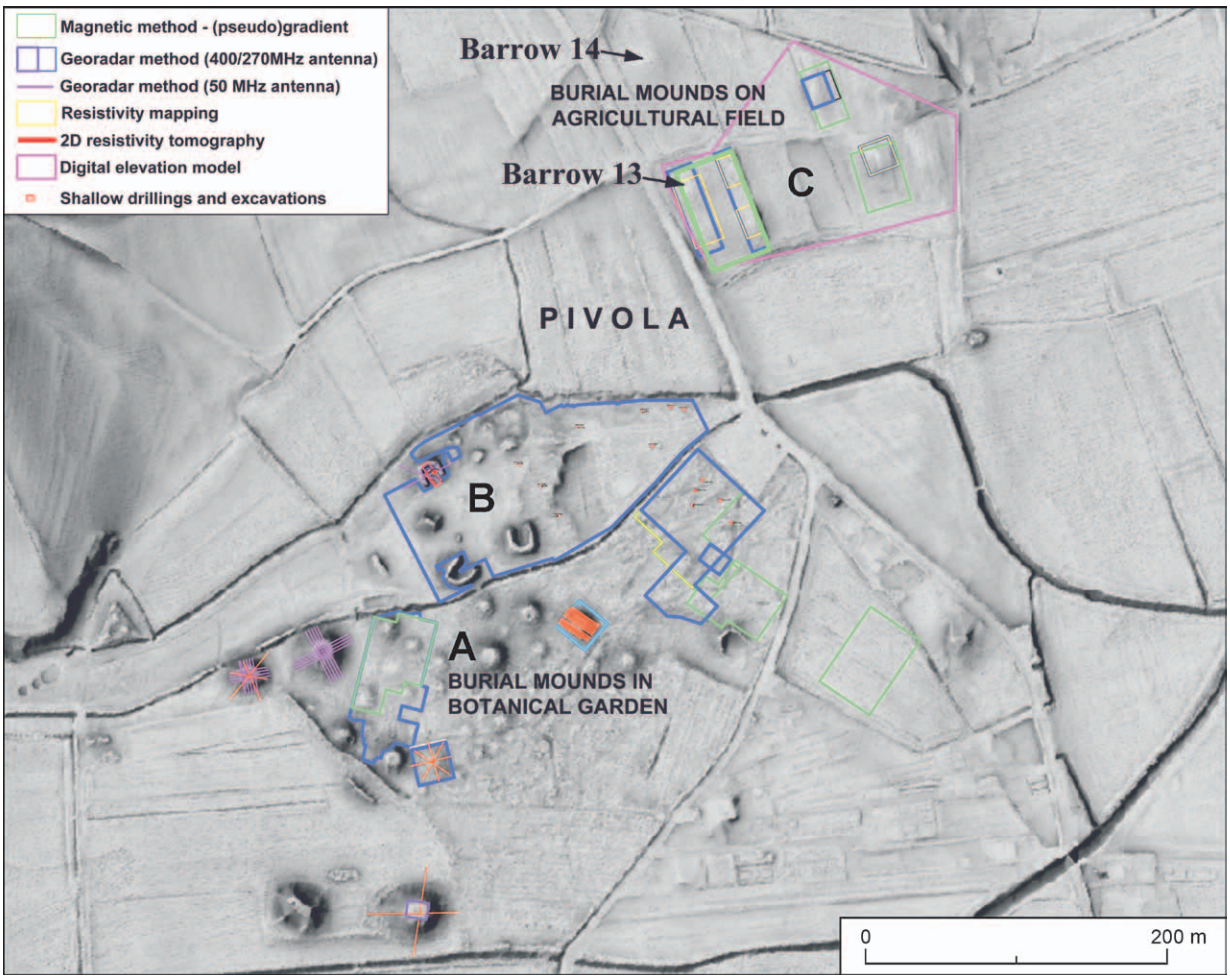


Fig. 14. Pivola cemetery (areas A, B and C) with the mapped geophysically surveyed areas, investigated by various geophysical methods, shallow drilling and small excavations (see Fig. 2). A – former forest, never cultivated and thus well preserved barrows; B – former military base, reshaped barrows; C – agricultural area, barrows are almost levelled (LiDAR map created by D. Mlekuž).

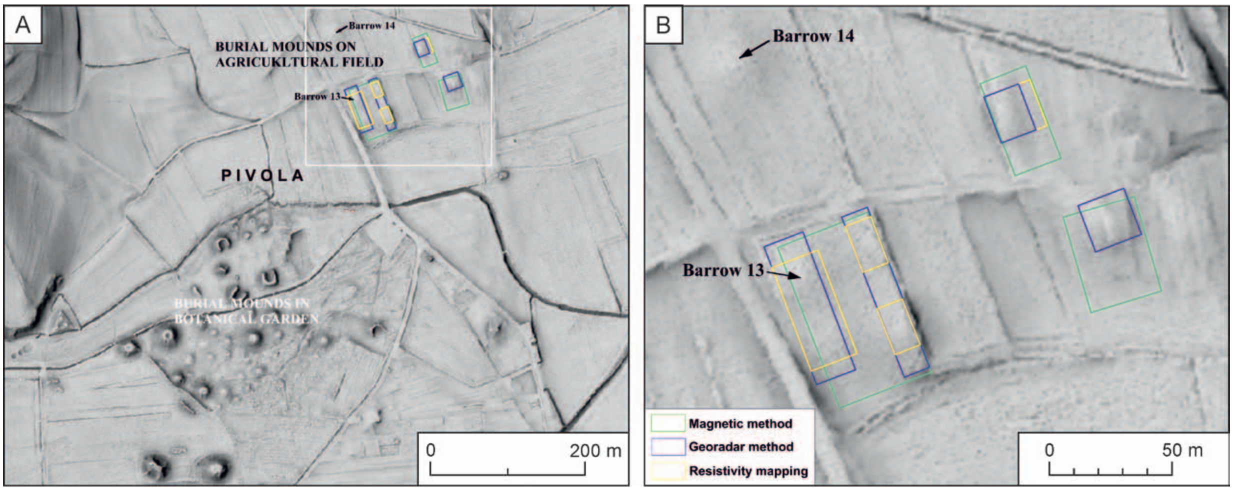


Fig. 15. Pivola cemetery. Areas in the northern part of the necropolis at agricultural fields with almost levelled barrows in Pivola (A), investigated with magnetometry, GPR and resistivity mapping (B; LiDAR map created by D. Mlekuž).

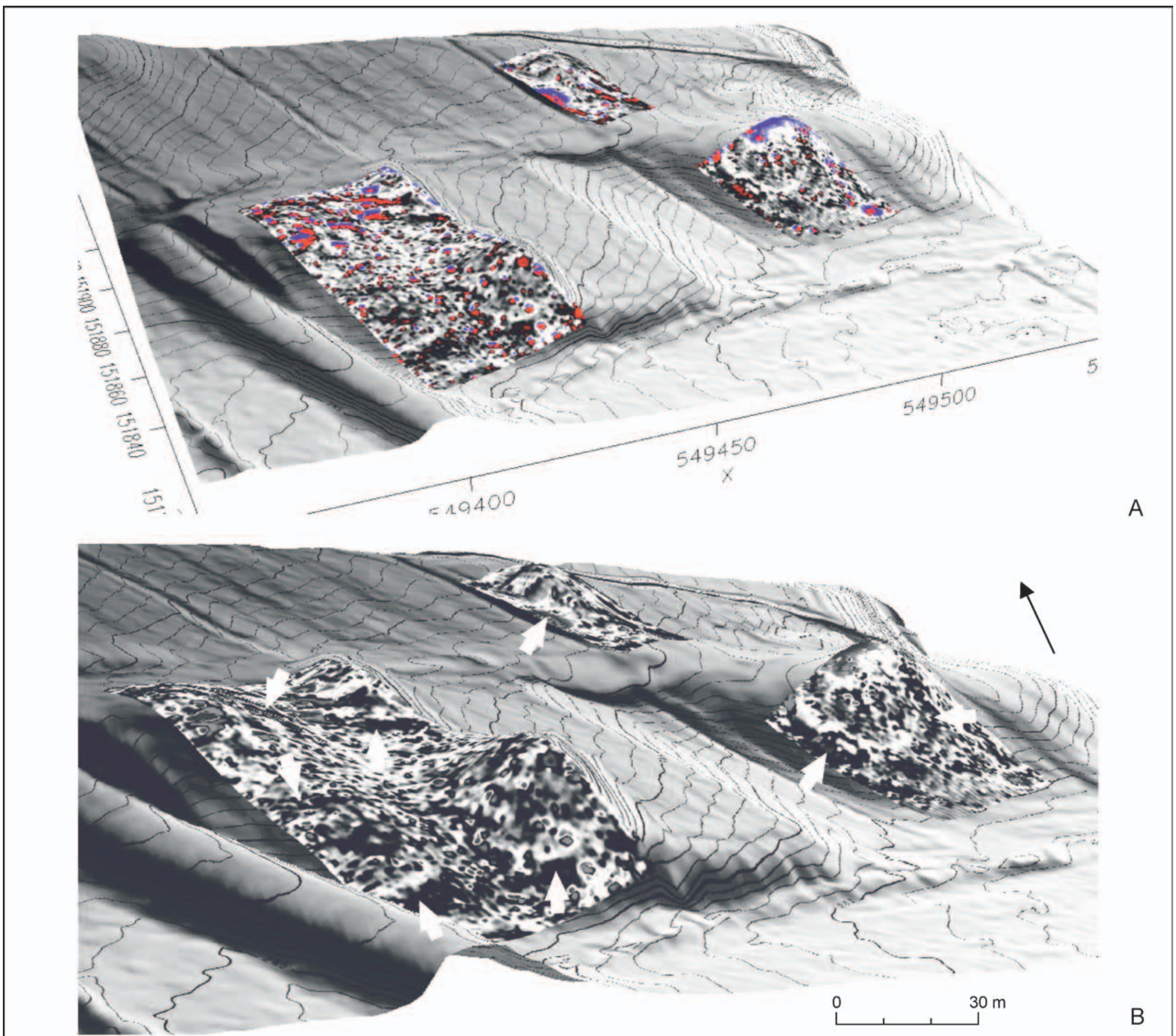


Fig. 16. Pivola cemetery, northern group of barrows. Magnetic maps on a digital elevation model. Strong, point-like magnetic anomalies are the result of many small iron objects on the modern agricultural field (A). The ditches around the tumuli identified on the magnetograms are marked by white arrows (B; adapted from *Teržan/Črešnar/Mušič 2015*, fig. 8).

(Fig. 17–20). Advanced processing flow with topographic correction was applied for a more intensive study of barrow composition (Fig. 18; see *Goodman et al. 2006*, 157–161). After case sensitive processing flow, the noise was significantly reduced and slight irregularities in mound composition appeared as faintly visible background variability with sparse remains of dry-stone chambers. To represent the GPR results, the *time slices method* was used. This shows a series of parallel, equally spaced profiles in distance of 0.5 m (Fig. 17; 19).

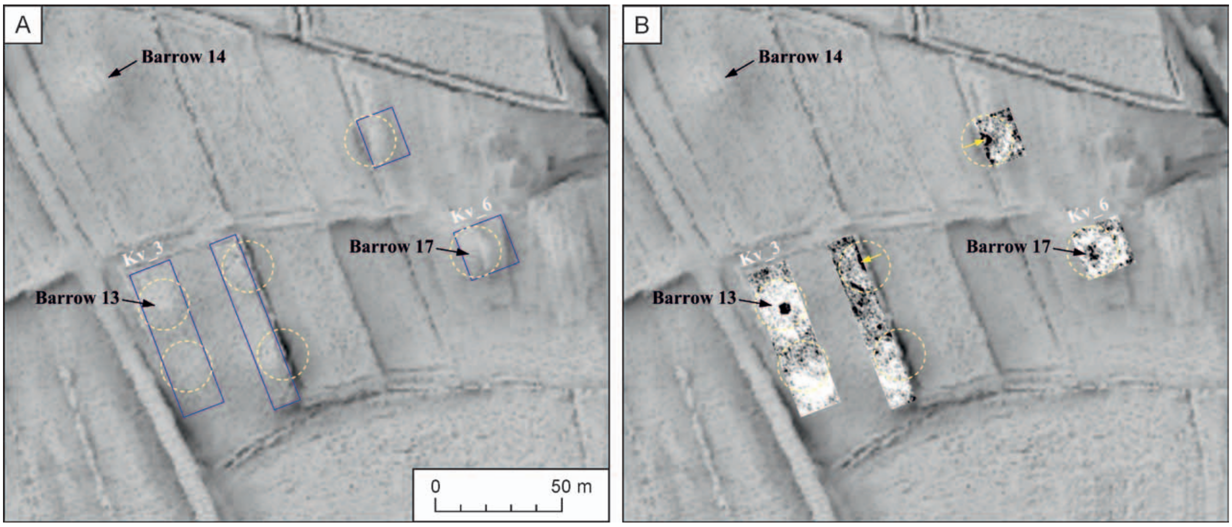


Fig. 17. Pivola cemetery, northern group of barrows. A – areas surveyed by GPR on LiDAR derived DTM with yellow circles indicating mound location and size; B – GPR results in the depth interval 70–80 cm (LiDAR map created by D. Mlekuž).

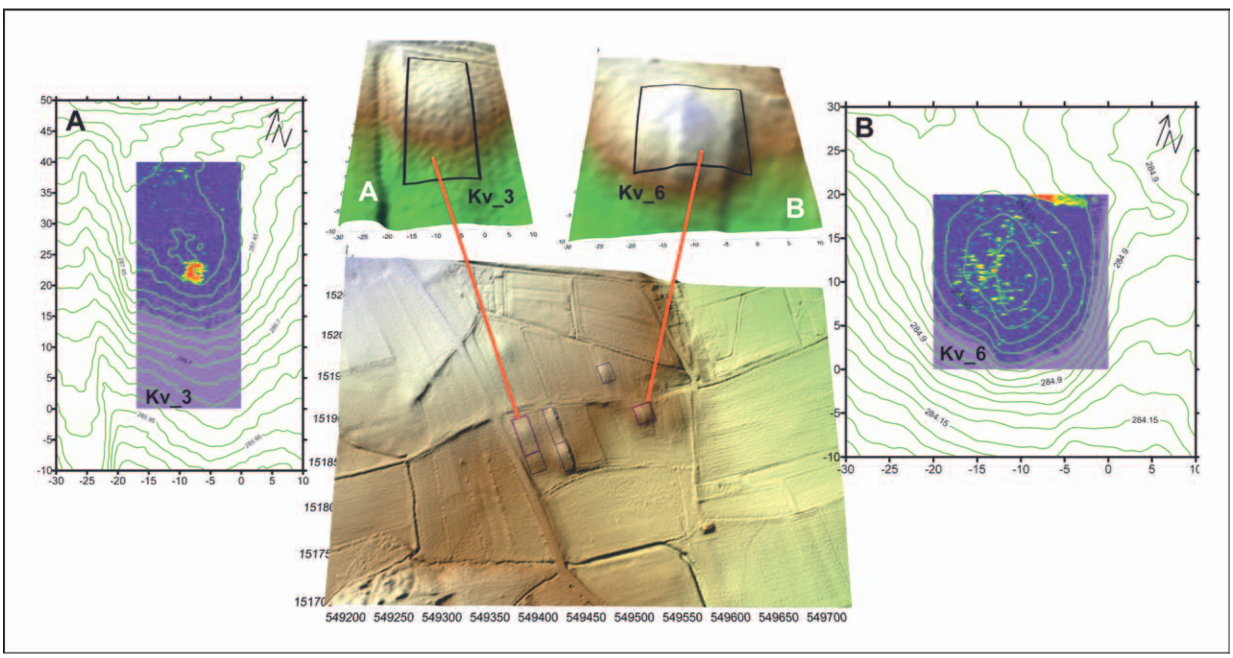


Fig. 18. Pivola cemetery, northern group of barrows. Topographic correction of the results of the GPR method with a 400 MHz antenna (A and B). The figure shows an eccentric position of the burial chambers and a clear difference in the degree of preservation. The chamber of barrow 13 (A – Kv_3) is well preserved (see Fig. 17; 19; 20), while the chamber of barrow 17 (B – Kv_6) is almost completely destroyed by deep ploughing (see Fig. 17). After the topographic correction, the mantle of the mound with a strong attenuation of the GPR signals (dark blue areas) is also in its original position (adapted from *Mušič/Črešnar/Medarić 2014*, fig. 4).

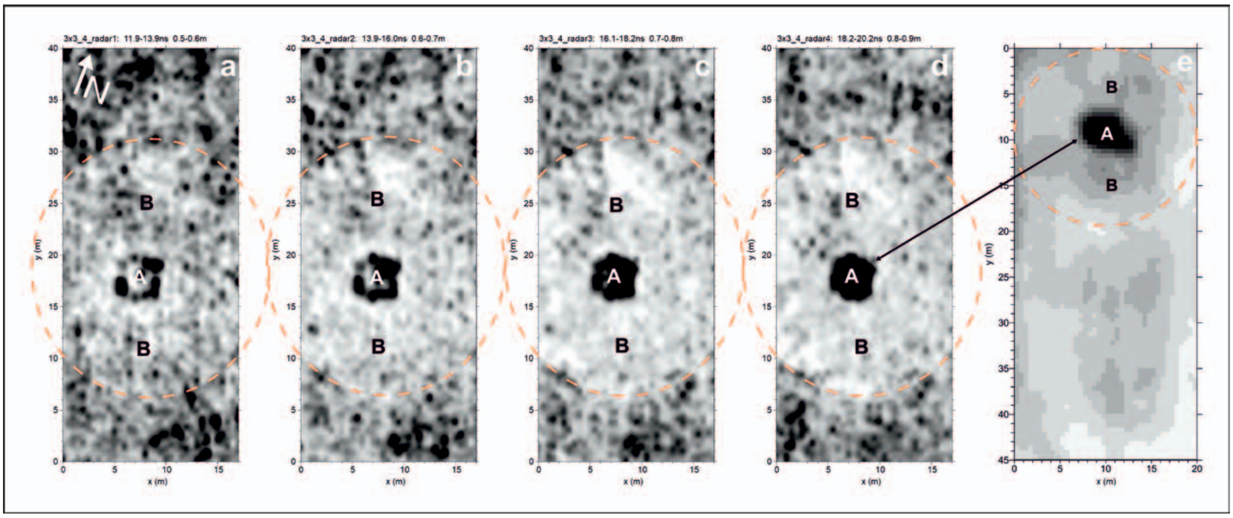


Fig. 19. Pivola cemetery, northern group of barrows, barrow 13. GPR time-slices for four depth intervals from 0.5 to 0.9 m (a–d) and resistivity mapping (e). Distinct georadar reflections from the stone burial chamber and high resistivity values in the central part of the mound are clearly visible (A). The size of the almost entirely destroyed mound is determined based on the attenuation of GPR signals and significantly lower resistivity in the area of the barrow mantle (B, indicated by circles).

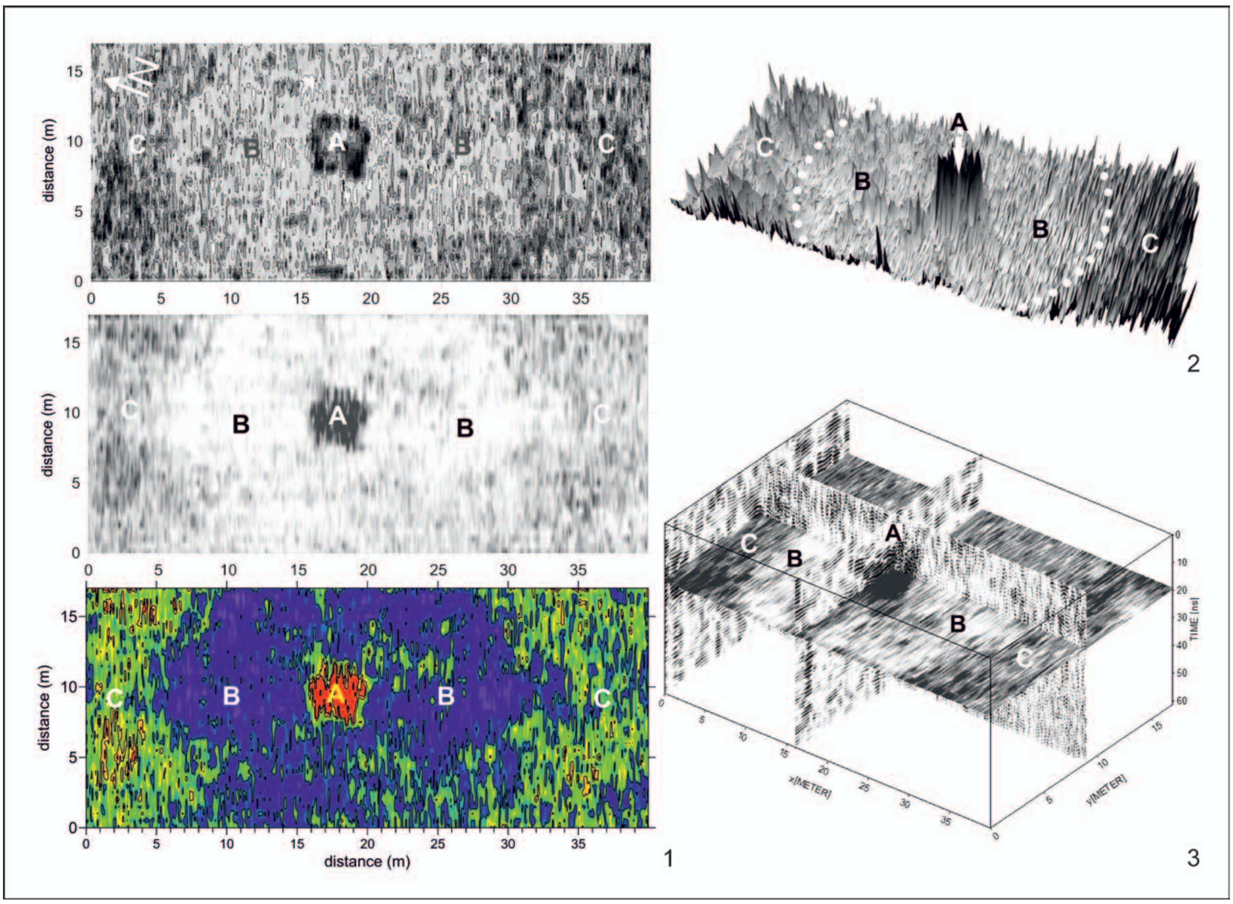


Fig. 20. Pivola cemetery, northern group of barrows, barrow 13. The GPR time-slice at the depth interval 60–70 cm (1) represents distinct echoes from a dry-stone burial chamber in the barrow centre (A), attenuation of the GPR signal in the water saturated mound mantle made of sandy clay (B) and chaotic echoes in the nearby surroundings on sandy gravel in the modern agricultural field (C). Display of GPR amplitudes (2) and 3D view (3; adapted from *Mušič/Črešnar/Medarić 2014*, fig. 6; *Teržan/Črešnar/Mušič 2015*, fig. 13; 16).

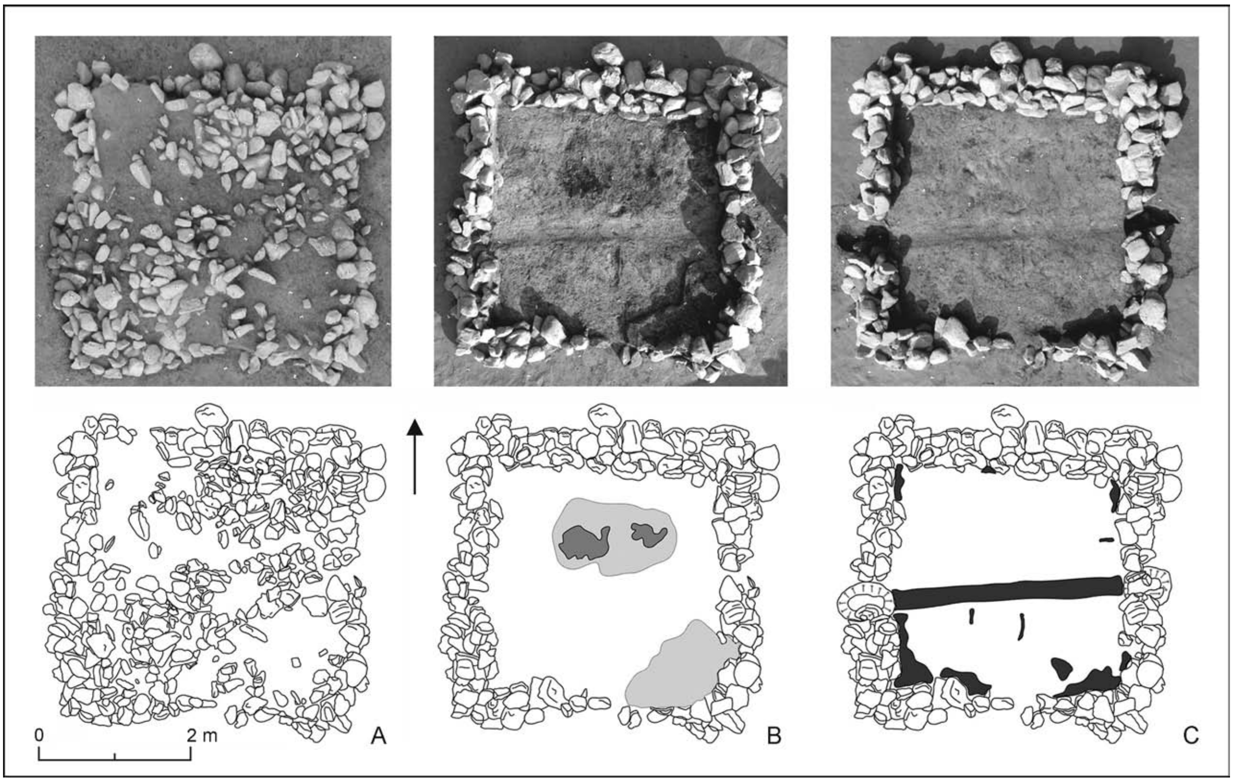


Fig. 21. Pivola, barrow 13. Display of the three successive phases of excavation of the burial chamber on a georeferenced vertical photography and in a computer rendering made on the basis of this photographs. When the burial chamber was discovered, it was covered and filled with a rubble layer of stone (A), after its removal, two larger concentrations of burnt soil and burnt human remains (B) were discovered. The emptied mound revealed details important for understanding its construction, as there were two pits for vertical wooden poles in the eastern and western walls. Along the inner sides of the chamber and at the bottom we found the remains of a weathered layer that indicates a former wooden construction (C).

High quality GPR data enabled a precise 3D visualization as well as analyses of the measurement results in a 3D environment (Fig. 20). Within this 3D mode, the distinct GPR echoes become archaeologically relevant by providing cross sections of the investigated soil volume in arbitrary directions, as well as detailed insight into the spatial relationships of the dry-wall structures, their depths, widths and level of preservation.

As is clear from the results of the ground-penetrating radar measurements, most of the barrows located on cultivated land have been badly damaged by ploughing, and the central stone chambers are rarely well preserved (Fig. 17–20). In most cases, the burial chambers are badly damaged or completely destroyed. Of the six barrows investigated by the georadar method, the burial chamber was at least partly preserved only at mound 13 (Fig. 18–20), which was for that reason also (rescue) excavated (Fig. 21). The presence of remains of burial chambers can be mostly recognized from the loose stone material in the central parts of the mounds, in some places with sparse remains of the chambers in the original position.

DISCUSSION

The recent decades of intensive archaeological investigations have resulted in many new data related to the Late Bronze Age and the Early Iron Age of Northeastern Slovenia.[1] However, the construction related

[1] The majority of sites excavated during development-led investigations are not published, but there are several exceptions. The best example is the Arheologija na avtocestah Slovenije – AAS (Archaeology on Slovenian Highways) series, which will include over 150 excavated sites from the excavations, accompanying the building of the Slovenian highways. The monographs can be freely downloaded on the web page of the Institute for the protection of Cultural heritage of Slovenia (https://www.zvkds.si/eng/publications/aas-collection/).

interventions, which present the vast majority of research, are never aimed at specific questions, so it is hardly to be expected that they will answer any of them. At the opposite end of the spectrum, however, there are some research projects that do target well-considered goals (e.g. *Črešnar/Mele 2020*; *Teržan/Črešnar 2014*; *2021*). All, however, having the same goal – the broader understanding of Poštela (one of the most important archaeological sites in Northeastern Slovenia) and its region in the Late Bronze and Early Iron Ages.

The steps taken until now helped us to get a new insight into the Poštela complex. The LiDAR deriving DTM, already processed by D. Mlekuž back in 2010, when Poštela became one of the first intentionally scanned Early Iron Age complexes in the region, has pronounced the individual 'features' to be parts of one organism. These can, however, only be understood by researching each of them both separately and interweaved with its surroundings (*Črešnar/Mlekuž 2014*, 18–32).

Confrontation of archaeological data and the results of LiDAR DTM analysis brought about a list of locations and areas, which were chosen for further research. The next step taken was, as a rule, to use the geophysical methods, which were presented in detail in this article, but they were occasionally also followed by other means of ground truthing. The Poštela and Pivola barrow necropolises are used here to illustrate the complexity of individual archaeological situations that require an investment of effort to employ different research procedures, thereby avoiding simplistic interpretation. The results of some geophysical surveys are informative in this sense, but it is obvious that in different natural environments of time-synchronous but different-sized mounds, the best results can only be obtained by using different geophysical methods (multi-method geophysical approach). During our work, it was ascertained that due to the different composition of mound mantles and different geological peculiarities, all geophysical methods are not always equally effective for determining the composition of mounds.

Verification approach includes also low-invasive methods such as drilling or trial trenching, which are limited to areas where most informative results are expected. These methods must be correctly located and conducted to yield maximum results for a particular site, but may also be used for similar situations in broader areas studied with other methods.

There are many different details and examples of how we can use data integration to make important discoveries in non-invasive research. With the first geophysical surveys of barrows in 2006, we began to learn about the possibilities of archaeological geophysics at prehistoric sites. The results allowed us to better plan the excavation of the already selected barrow 13 at Pivola. By examining other mounds on farmland in the surroundings, we were able to determine that many of them were already severely damaged. Special care is needed to prevent their complete destruction and erasure from the cultural landscape (*Teržan/Črešnar/Mušič 2012*, 17–58; *2015*, 61–82).

With the research starting in 2011, we took a new path, as the results from non-invasive methods, i.e. geophysics and LiDAR, became our guides for our further research steps, i.e. coring, trial trenching and small-scale excavations. At the same time, after the excavations, we often revisited the baseline data, reviewing and re-analysing it to extract even more from it, since we only recognized certain features during excavations, which were not visible or understandable in the primary results of the geophysical measurements or vice-versa. That is for instance the case of barrow 13, where only the excavation could show the distinction between the various parts of the stone remains of the burial chamber construction and discern between the rubble and the dry-stone construction and its wooden elements (Fig. 21).

Along this research path, we often encountered situations that we could not explain at the time, but the new approaches that the results required often improved already established procedures (e.g. *Mušič et al. 2015*, 37–64; *2018*, 317–334). There are many examples of how, with the help of the integration of archaeological data with non-invasive research, we arrive at important findings also at Early Iron Age barrow necropolises

The research at the Poštela Early Iron Age complex and its surroundings is far from finished, as there is no end in sight to the new questions raised by our research, the number of which always outruns the number of answers we get.

CONCLUSIONS

With the first geophysical surveys of barrows in 2006, we began to learn about the possibilities of archaeological geophysics at prehistoric necropolises. With this results, we were able to better plan the excavation of the already selected object, mound 13 at Pivola (Fig. 15; 17–21). By researching other mounds on agricultural land in the surrounding area, we were able to assess that many of them are already badly damaged (Fig. 17; 18) and that special care is therefore needed to prevent their complete destruction and erasure from the cultural landscape (*Teržan/Črešnar/Mušič 2012*; *2015*). With research from 2011 onwards, we turned the way of our research, as geophysics, in addition to ALS, became a guide for our new excavations.

Generally speaking, stone made chambers are rarely clearly visible on the results of magnetic method. Small differences in magnetic susceptibility between soil variations, weathered amphibolite and solid rock material, from which the burial chambers were also built, did not give much hope for their identification on magnetograms on Habakuk necropolis. With regards to identifying possible stone burial chambers, we introduced the calculation of *Vertical derivatives* (Fig. 9: B) and *RTP transformation* (Fig. 9: E). It can be concluded that contrary to general assumption, stone chambers are quite obvious in several places in the form of roughly square floor plans of relatively stronger positive gradients (Fig. 6: B; 7: B; 9). However, this suggests that the magnetic response of stone burial chambers is recognizable. Such an interpretation requires caution due to possible magnetic effect of heterogeneous composition of the mound mantle.

One of the more important findings, which led to a series of new conclusions, was the recognition of circular ditches, surrounding most if not all barrows. The analyses of the ALS data clearly revealed ditches around the barrows. The ditches even intersect in places, suggesting stages of development of the barrow groups (Fig. 5: D). At the northern group of mounds on Habakuk, we can recognize at least five phases of the expansion of the burial ground. We can identify mound 38 (Fig. 5) as one of the youngest mounds, in which a female person with a rich bronze costume was buried, according to which we can date it to the last phase of the settlement of Poštela in the Early Iron Age or Ha C2/Ha D1 (*Teržan 1990*, 66–70, pl. 61).

The circular ditches are already clearly visible on the displays of the 'raw' values of the magnetic gradient measurements (Fig. 6: B; 7: B) and better after application of the *Upward continuation* algorithm (Fig. 7: B; 9: C, D). The mantles of the mounds at the Habakuk necropolis are characterized by relatively higher magnetic field gradients, while the magnetic gradients above circular ditches around the barrows, are slightly negative (Fig. 5: C; 6: B; 7: B; 9).

The GPR method results revealed numerous areas of strong georadar reflections in the area of the barrows and also in the spaces between them. Distinct GPR reflections on the mounds which we interpret as effects of the coarse-grained rock material in composition of the mound mantles and most probably also the effect of stone burial chambers (Fig. 10).

With the resistivity mapping the highest values were measured on a slightly higher part of the terrain with a northern group of barrows on Habakuk (Fig. 12: B: a). Similarly to GPR survey results high-resistivity anomalies most likely represent the effect of the high-resistivity composition of the barrows mantle with stone made chambers, as well as solid bedrock in the intermediate spaces between the mounds. Comparison of resistivity measurements with isohypses on DEM explains that smaller areas of markedly high resistivity are present on mounds (Fig. 12: C: a). We assume that some of these anomalies are due to the stone-made chambers also on the basis of the results of 2D resistivity tomography (Fig. 13: k).

Since the dipole-dipole electrode array proved to be the most appropriate for 2D resistivity tomography (ERT) surveys on barrows, we used this technique for the ERT investigation of the barrows at Habakuk necropolis. With the ERT 1 profile, we wanted to get a detailed insight into the composition of mound 31 with a short inter-electrode distance of 0.5 m and thus better resolution (Fig. 13: ERT 1). In the resistivity tomography model, the high-resistivity anomalies (300–750 Ωm) representing the remains of the stone made burial chamber (Fig. 13: k) are well separated from the lower-resistivity of weathered amphibolite material (Fig. 13: B, C) above the higher-resistivity solid amphibolite bedrock (Fig. 13: D). The diameter of the chamber in the direction of the ERT profile is approx. 4.5 m, and its height is about 1 m. The chamber is located at a depth interval approximately between 0.3 and 1.5 m below the surface.

The ERT profiles (ERT 2 and ERT 2_1), measured in two mutually perpendicular directions (Fig. 13: ERT 2, ERT 2_1), with inter-electrode distances of 0.3 m and a dipole-dipole electrode configuration, clearly defined the remains of stone burial chambers in the central part of the mound (700–8000 Ωm). In the direction of the profile ERT 2 the assumed diameter of the chamber is about 2.5 m, in the direction of the profile ERT 2_1 it is 3 m. The height of the preserved part of the chamber is estimated to 0.75 m in both ERT profiles (Fig. 13: C, D). The height of the preserved part of the chamber is approx. 0.75 m in both ERT profiles. The resistivity values of the weathered amphibolite in the base of mound 33 (200 Ωm) are similar to those of the ERT 1 profile across the mound 31. This most likely means that a relatively larger proportion of rock debris of the weathered amphibolite is present in a large part of the mantle, which was also confirmed by shallow drilling for magnetic susceptibility measurements at depths of 0–0.5 m and 0.5–1 m (Fig. 8; see *Mušič et al. 2015*, 37–64, fig. 16; 17).

Results of the magnetic method clearly show a wide bend of weakly positive magnetic gradients, which runs approximately in the east–west direction towards the largest barrow (Fig. 5: C; 6: B; 7: B; 9: A: b). This is a unique type of magnetic anomaly not known anywhere else at Poštela. Using 2D resistivity tomography and GPR, it was proved that there is an abrupt lateral transition between a larger amphibolite block and fine-grained sediments. We assume that this extremely sharp geological boundary represents the fault along which the amphibolite block was uplifted (Fig. 11: F), which served as a topographically elevated auditorium for burials in the Early Iron Age.

At the Pivola necropolis faintly visible circular ditches were revealed by magnetic method measurements (Fig. 16). In this way we supplemented the results of the GPR method, which did not clearly confirm the presence of perimeter ditches, as well as the results of excavations that in the case of barrow 13 mostly targeted only the central burial chamber, which was previously recognized by the GPR results (Fig. 17–21).

GPR results show that most of the barrows on agricultural land have been badly damaged by ploughing, and in most cases the burial chambers are badly damaged or completely destroyed (Fig. 17; 18). Of the six barrows investigated by the georadar method, the burial chamber was relatively well preserved only in the mound 13. Distinct GPR reflections from the stone burial chamber and high resistivity values in the central part of the mound are clearly visible. The size of the almost entirely destroyed mound is determined based on the attenuation of GPR signals and significantly lower resistivity in the area of the barrow mantle (Fig. 19).

High quality GPR data at the mound 13 enabled a 3D visualization as well as analyses of the measurement results in a 3D environment (Fig. 20). Within 3D mode, the distinct GPR echoes become archaeologically informative by providing detailed insight into the spatial relationships of the dry-stone structures, their depths, widths and level of preservation.

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Čo sa skrýva pod zemnými násypmi mohýl zo staršej doby železnej na okraji Východných Álp?

Aktuálne výsledky geofyzikálneho výskumu v Poštele (SV Slovinsko)

Branko Mušič – Barbara Horn – Matija Črešnar

Súhrn

Mohyly (tumuli) zo staršej doby železnej (ďalej EIA, z angl. *Early Iron Age*), ktoré sa vyskytujú jednotlivo alebo v skupinách, charakterizujú kultúrnu krajinu regiónu juhovýchodných Álp a Panónskej nížiny až do súčasnosti. Sú jedným z najvýraznejších pozostatkov EIA v regióne, ktorý sa rozprestiera od Východných Álp až po Dunaj. Keďže sú v krajine jasne rozpoznateľné a často sa v nich nachádzajú vzácne artefakty, patrili medzi prvé „ciele“ raných zberateľov starožitností a zbierkotvorcov prvých založených múzeí od 19. storočia. Archeologické vykopávky, ktoré sa tiež zrodili v tom období, sú stále najbežnejším spôsobom výskumu mohýl, hoci metodológia prešla dramatickým vývojom. Geofyzikálne metódy, často v kombinácii s inými neinvazívnymi alebo málo invazívnymi metódami, získavajú pri výskume mohýl EIA čoraz väčšiu popularitu.

Nižšie uvedené príklady zdôrazňujú význam série prípadových štúdií výskumu mohýl z archeologického komplexu Poštela pri Maribore v severovýchodnom Slovinsku. Tieto mohyly majú niekoľko spoločných charakteristík, ale zároveň odhaľujú značnú rozmanitosť súvisiacu s ich základným tvarom, prírodným prostredím a stavom ich zachovania. Uvedené príklady sú preto viac než vhodné nato, aby pomohli načrtnúť širokú škálu výziev, s ktorými sa pri výskume mohýl týmito metódami stretávame, hoci nie sú reprezentatívne pre všetky možné scenáre.

Archeologický komplex Poštela

Archeologický komplex Poštela sa sústreďuje okolo opevneného hradiska Poštela, ktoré má strategickú polohu a kontroluje celú Drávsko-ptujskú rovinu, ako aj okraje okolitých kopcov (obr. 1; 2). Na planine Habakuk, tesne pod sídliskom, sa pochovávalo v plochých žiarových (urnových) hroboch, ako aj v mohylách. Najväčšia skupina mohýl sa nachádza v Pivole (poloha Botanická záhrada). Je podobne ako skupiny mohýl z Habakuku spojená s urnovým pohrebiskom (*Črešnar/Vinazza/Mušič 2019*, 439–448).

V posledných rokoch sa naše výskumy na planine Habakuk primárne zameriavali predovšetkým na neinvazívny a nízkoinvazívny výskum (obr. 1–13). Využívali sme ALS, vykonávali intenzívny geofyzikálny prieskum s následným overovaním výsledkov v teréne a len ojedinele aj cielené výkopy malého rozsahu (*Črešnar/Vinazza/Mušič 2019*, 443–446, obr. 3; 5–7). Napriek málo invazívnemu prístupu sa podarilo získať dôležité nové dáta.

Skupina mohýl z Pivoly sa nachádza v nížinnej polohe vo vzdušnej vzdialenosti viac ako 2 km od sídliska. Je to najväčšia skupina mohýl v tesnej blízkosti hradiska Poštela (obr. 1; 2; 14–20).

V tomto článku sa zameriavame na vybrané výsledky geofyzikálnych výskumov viacerých mohýl na nekropolách z Habakuku a Pivoly, ktoré spresňujú aj niektoré naše už publikované výskumy (napr. *Teržan/Črešnar/Mušič 2015*, 61–82). Predkladanú štúdiu treba chápať ako pokračovanie nášho výskumu a prehĺbenie témy.

V rámci nekropoly v Pivole bol vybraný testovací polygón na overenie spoľahlivosti výsledkov s využitím údajov zo záchranného výskumu mohyly 13, realizovaného v roku 2006 (pozri *Teržan/Črešnar/Mušič 2007*, 159, 160; *2012*, 17–58; *2015*, 61–82). Medzitým (2006–2022) bolo preskúmaných viac ako 3,5 ha v rámci nekropoly v Pivole a približne 4 ha vo vybraných priestoroch sídliska Poštela, ako aj viac ako 2,5 ha na mohylovom pohrebisku na planine Habakuk. Stále sa vyvíjajúci multimetodický prístup zahŕňal magnetické, georadarové a nízkofrekvenčné elektromagnetické metódy, odporové mapovanie a mapovanie magnetickej susceptibility, ako aj 2D odporové tomografické profilovanie mohýl, opevnení a pod. (obr. 2; 3; pozri *Medarić/Mušič/Črešnar 2016*, 67–93; *Mušič/Črešnar/Medarić 2014*, 19–47; *Mušič et al. 2013*; *2015*, 37–64; *2018*, 317–334; *Teržan/Črešnar/Mušič 2015*, 61–82).

Pohrebisko na planine Habakuk

Geofyzikálne výskumy sa realizovali v širšom okolí archeologického komplexu Poštela na mnohých samostatných plochách spôsobom, ktorý diktovali špecifické okolnosti súvisiace s definovanými cieľmi, a s obmedzeniami vyplývajúcimi z rôznorodých a často sa meniacich podmienok prostredia. Spôsob prieskumu závisí od rozsahu, najmä s ohľadom na náročné podmienky terénnych prác a rozsah použitých techník. Na ilustráciu sme vybrali príklad severnej skupiny mohýl habakuckej nekropoly (obr. 3; 4).

Magnetická metóda

Magnetické vlastnosti kruhových priekop mohýl, ktoré sa z hľadiska minerálneho zloženia len málo líšia od prírodného prostredia, do ktorého boli vykopané, možno vizualizovať pomocou moderných magnetometrov. Magnetickou metódou často rozpoznáme výplne kruhových priekop mohyly, ktoré vznikli pri ťažbe zeminy využitej na stavbu mohyly. Hoci veľký pomer medzi objemom plášťa a kamenných hrobových komôr často sťažuje identifikáciu ich magnetického pôsobenia, v niektorých prípadoch je predsa len možné pozorovať anomálie, ktoré by mohli naznačovať obsah mohýl.

Kruhové priekopy sú zreteľne viditeľné už v „surových" dátach gradientových meraní (obr. 6: B; 7: B) a v spracovaní pomocou algoritmov *upward continuation* (obr. 7: B, 9: C, D). V súvislosti s identifikáciou možných kamenných pohrebných komôr v centrálnych častiach mohýl musíme porovnať výsledky rôznych krokov spracovania, využijúc napr. *calculation of vertical derivatives*, ktorý mierne zvýrazňuje laterálne zmeny magnetických anomálií (obr. 9: B), a transformáciu *reduction to the pole*, ktorá znižuje bipolaritu magnetických anomálií (obr. 9: E).

Georadarová metóda (Ground penetrating radar/GPR)

Výsledky GPR metódy s využitím vysokofrekvenčnej 400 MHz antény (obr. 10) boli podobné výsledkom získaným geoelektrickým meraním (obr. 12). Najsilnejšie georadarové ozveny boli namerané na špecifických miestach mohyly, čo interpretujeme ako vplyv horninového zloženia plášťov mohyly, prípadne kamenných hrobových komôr. Objavujú sa i v priestoroch medzi mohylami ako dôsledok vplyvu pevného skalného podložia v hĺbke menšej ako 1 m (obr. 10).

Odporové meranie

Metódu geoelektrického odporu na geoelektrické mapovanie (Geoscan RM15) sme použili predovšetkým na určenie efektu vysokého odporu horninového materiálu v mohylách a plytko uloženom podloží technikou *twin probes array* (pozri napr. *Mušič/Horvat 2007*, 219–283). Najvyššie hodnoty odporu boli namerané na mierne vyvýšenej časti terénu so skupinou mohýl (obr. 12: A, B). Vysokoodporové anomálie do hĺbky 1 m s najväčšou pravdepodobnosťou predstavujú vplyv vysokoodporového zloženia plášťa mohýl s kamennými komorami, ako aj pevného geologického podložia v priestoroch medzi mohylami.

Elektrická odporová tomografia (Electrical resistivity tomography/ERT)

Na 2D odporových modeloch (pozri *Mušič et al. 2015*, 37–64) bolo definované amfibolitové podložie planiny s mohylami s vyšším elektrickým odporom a gravitačne transportovaný materiál s lepšou elektrickou vodivosťou (najmä naplaveniny a piesky) v nižšej, relatívne rovinatej oblasti na juhu. Tieto modely profilu ERT 1 nad stredne vysokou mohylou 31 (obr. 13) boli vytvorené na základe meraní z troch rôznych sústav elektród (pozri *Mušič et al. 2015*, 37–64). Následne bola metódou ERT skúmaná aj nízka mohyla 33 (obr. 13).

Keďže sa ako najvhodnejšia ukázala dipólovo-dipólová elektródová sústava, pri ERT meraní mohýl sme využívali najmä túto techniku. V modeli odporovej tomografie sú vysokoodporové anomálie predstavujúce zvyšky kamennej hrobovej komory (obr. 13: k) dobre oddelené od zvetraného amfibolitového materiálu s nižším odporom (obr. 13: b, c) nad pevným amfibolitovým podložím s vyšším odporom (obr. 13: d). Profily ERT naprieč mohylou 33, merané v dvoch na seba kolmých smeroch (obr. 13: ERT 2, ERT 2_1), jasne definovali zvyšky kamennej hrobovej komory v centrálnej časti mohyly (obr. 13: C, D).

Pohrebisko v Pivole

Magnetická metóda

Očakávali sme, že zachytíme magnetické anomálie z možných kruhových priekop, ale nie anomálie naznačujúce existenciu hrobových komôr (obr. 16). Týmto spôsobom sme doplnili výsledky georadarovej metódy, ktoré samy o sebe jednoznačne nepotvrdili prítomnosť obvodových priekop, ako aj výsledky výkopov, ktoré boli väčšinou zamerané len na skúmanie centrálnych hrobových komôr. V prípade mohyly 13, kde boli vytýčené tri zisťovacie sondy na detekciu kruhovej priekopy, sa podarilo identifikovať len zvyšky plášťa mohyly.

Georadarová metóda (Ground penetrating radar/GPR)

GPR metóda, využívajúca 400 MHz anténu, bola uprednostnená pri riešení výskumných otázok týkajúcich sa presnej polohy a veľkosti hrobových komôr vybudovaných z kameňa kladeného na sucho vnútri mohýl, ako aj ich zachovanej výšky (obr. 17–20). Na dôkladnejšie štúdium zloženia mohýl bola aplikovaná pokročilá metóda spracovania s topografickou korekciou (obr. 18; pozri *Goodman et al. 2006*, 157–161). Po aplikovaní prístupu zohľadňujúceho špecifiká jednotlivých prípadov sa výrazne znížil šum a drobné nepravidelnosti v zložení mohyly sa prejavili ako slabo viditeľná variabilita pozadia s ojedinelými zvyškami kamenných komôr z nasucho kladeného kameňa. Kvalitné georadarové dáta umožnili presnú 3D vizualizáciu, ako aj analýzy výsledkov meraní v 3D prostredí (obr. 20).

Po terénnych výskumoch sme sa často vracali k základným údajom, prehodnocovali sme ich a opätovne analyzovali, aby sme z nich vyťažili ešte viac poznatkov, pretože počas terénneho archeologického výskumu sme rozpoznali len niektoré objekty, ktoré neboli viditeľné alebo zrozumiteľné v primárnych výsledkoch geofyzikálnych meraní, alebo naopak. To je i prípad mohyly 13, kde až terénny archeologický výskum ukázal rozdiel medzi jednotlivými časťami kamenných zvyškov konštrukcie hrobovej komory a rozlíšil sutinu od konštrukcie z nasucho kladeného kameňa a jej drevené prvky (obr. 21).

Obr. 1. Najvýznamnejšie lokality staršej doby železnej medzi masívom Pohorje a riekou Dráva.

Obr. 2. Poloha archeologického komplexu Poštela (pri Maribore), s pohrebiskami v polohách Pivola a Habakuk na podklade DTM vytvoreného na základe LiDAR-ových dát (autor DTM D. Mlekuž)

Obr. 3. Hradisko Poštela a pohrebisko v polohe Habakuk. Plochy skúmané rôznymi geofyzikálnymi metódami, plytkými vrtmi a zisťovacími sondami (pozri obr. 2; autor DTM D. Mlekuž; podľa *Mušič/Črešnar/Medarić 2014*, obr. 2; *Mušič et al. 2015*, obr. 8).

Obr. 4. Hradisko Poštela a pohrebisko v polohe Habakuk (A). Severná časť pohrebiska (B), skúmaná magnetickou metódou, metódou GPR, odporovou metódou a vybrané profily na 2D odporovú tomografiu (podľa *Mušič et al. 2018*, obr. 1; 4).

Obr. 5. Habakuk. Severná časť pohrebiska. A – tieňovaný DTM; B – analýza miestneho reliéfu (D. Mlekuž); C – výsledky magnetických meraní; D – „horizontálna stratigrafia“ skupiny mohýl s konštrukčnými relatívno-chronologickými fázami (následnosť: žltá – oranžová – červená – purpurová – modrá; čiernou vyznačené mohyly nie sú spoľahlivo datované; podľa *Črešnar 2017*, obr. 3; *Črešnar/Vinazza/Mušič 2019*, obr. 6).

Obr. 6. Habakuk. Severná časť pohrebiska, skúmaná metódou magnetického gradientu na DTM (A) a magnetogram gradientu celkového magnetického poľa (B). Magneticky „tiché“ miesta (a), plochy s rozličnou magnetickou susceptibilitou povrchovej vrstvy pôdy (b), centrálna časť mohylového pohrebiska s kruhovými priekopami okolo mohýl a niektoré približne štvorcové tvary možných centrálnych hrobových komôr (c), široký pás magnetických anomálií prírodného pôvodu (d; podľa *Mušič et al. 2018*, obr. 2).

Obr. 7. Habakuk, severná skupina mohýl. LiDAR-ová mapa s polohami plytkých pôdnych vrtov (A), výsledky magnetického merania po aplikovaní *low-pass* filtra (B), a výsledky meraní magnetickej susceptibility v ornici (× 10^{-3} SI) do hĺbky približne 5 cm, realizovaných v pravidelnej sieti 10 × 10 m (C). Najvyššie hodnoty magnetickej susceptibility boli namerané na relatívne rovnej ploche južne od skupiny mohýl (podľa *Mušič et al. 2015*, obr. 16).

Obr. 8. Habakuk, severná skupina mohýl. Priemerné hodnoty magnetickej susceptibility nameranej prístrojom *Kappameter KT-5* na povrchu (A) a v dvoch hĺbkových intervaloch plytkých vrtov (B – 0–30 cm; C – 30 cm až pevné podložie v hĺbke približne 50–60 cm). Hodnoty susceptibility sa líšia, najnižšie sú na povrchu a najvyššie v niekoľkých polohách v poslednom hĺbkovom intervale. Domnievame sa, že to nie je vplyvom podložia, pretože susceptibilita amfibolitu (okolo 0,2–0,25 × 10^{-3} SI) je nižšia než namerané hodnoty. Predpokladáme, že všetky hodnoty nad 2,5–3 × 10^{-3} SI by mohli byť archeologického pôvodu. Ich hlavným zdrojom sú obyčajne aktivity súvisiace s vysokými teplotami. Napríklad v južnej časti nekropoly bola na základe merania magnetickej susceptibility (ako doplnok k magnetickému meraniu a nízkofrekvenčnej elektromagnetickej metóde) objavená rituálna uloženina zo staršej doby železnej, obsahujúca veľké množstvo fragmentárnej keramiky a zvieracích kostí (podľa *Mušič et al. 2015*, obr. 17).

Obr. 9. Habakuk, severná skupina mohýl. Mapa magnetických meraní na DTM odvodenom z LiDAR-ovej mapy pre náhodne zvolený 3D pohľad magnetickej odpovede mohýl po aplikovaní *upward continuation* algoritmu (A). Pokročilé metódy spracovania magnetických meraní: *vertical derivatives* (B), *upward continuation* s prepočítanými magnetickými anomáliami na úrovni 0,75 m (C) a 1,5 m nad skutočnou výškou magnetického profilu (D), *reduction to the pole* a *upward continuation* 0,3 m nad skutočnou výškou magnetického profilu (E). Centrálne časti mohýl, obkolesené kruhovými priekopami s priemerom korelujúcim s mohylou (a), širokým pásom relatívne silných magnetických anomálií geologického pôvodu popri východnom okraji topografickej vyvýšeniny s mohylami (b), magneticky „tichá" plocha (c), a plocha s rozličnou magnetickou susceptibilitou pravdepodobne archeologického pôvodu (d; podľa *Mušič et al. 2018*, obr. 3; 10).

Obr. 10. Habakuk, severná skupina mohýl. 3D zobrazenie GPR signálov zaznamenaných 400 MHz anténou na topografickej mape odvodenej z LiDAR-ových snímok v troch hĺbkových intervaloch. a – 0–0,5 m; b – 0,5–1 m; c – 1–1,5 m. Relatívne silné GPR odrazy boli namerané nad aj medzi mohylami (pohľad zo severozápadu; podľa *Mušič et al. 2015*, obr. 11).

Obr. 11. Habakuk, severná skupina mohýl. Zdvihnutý amfibolitový blok pevného podložia (A), elektricky vysoko vodivý materiál (gravitáciou transportovaný materiál/kolúvium/masívny zosuv [D]), strmá vertikálna hranica (zlom?) medzi pevným podložím a jemnozrnným, gravitáciou transportovaným sedimentom (piesok/naplavenina [F]; podľa *Mušič et al. 2015*, obr. 13; 14; 20).

Obr. 12. Habakuk, severná skupina mohýl. Plocha preverená odporovým meraním (A). Celkovo boli najvyššie hodnoty odporu namerané na mierne vyvýšenej plošine s mohylami (B: a), čo je najlepšie viditeľné na 3D zobrazení (C: a). Možné kamenné komory sa nedajú zreteľne identifikovať v dôsledku heterogénneho zloženia plášťov mohýl s vysokým obsahom kamennej sutiny. O niečo vyššie hodnoty odporu, než má miestne podložie, sú zachytené na južnej strane na relatívne plochom teréne, ktorý mohol byť zmenený činnosťou človeka, hoci prírodný pôvod sa nedá úplne vylúčiť (B: b; C: b; podľa *Mušič et al. 2015*, obr. 10).

Obr. 13. Habakuk, severná skupina mohýl. Mohyla 31 (B): 2D ERT model profilu ERT 1. k – zvyšky kamennej komory s vysokým odporom (300–750 Ωm); p – veľmi vysoký odpor plášťa mohyly (vyše 1500 Ωm) blízko povrchu a nízky odpor vnútra mohyly pod úrovňou 0,5 m pod povrchom (60–150 Ωm); j – pravdepodobne kruhová priekopa mohyly vyplnená materiálom s vysokým odporom; b – jemnozrnný materiál s vysokým obsahom vlhkosti (do 100 Ωm); c – vodou nasýtený amfibolitový substrát (100–200 Ωm); d – vysoký odpor naznačuje čiastočne zvetrané amfibolitové podložie. Mohyla 33: 2D ERT model profilov ERT 2 (C) a ERT 2_1 (D), meraných v navzájom kolmých smeroch (A). k – zvyšky kamennej komory s veľmi vysokým odporom (700–8000 Ωm), pravdepodobne sa strop komory stlačil, čo sa dá usudzovať k konkávnej strednej časti mohyly nad komorou; p – plášť mohyly s vysokým odporom (vyše 1000 Ωm) siaha do hĺbky 0,5 m pod povrchom, oveľa nižšie hodnoty odporu (150–400 Ωm) sú vo vnútornej časti mohyly; j – obvodová priekopa okolo mohyly, ktorá bola neskôr vyplnená materiálom s vyšším odporom, transportovaným gravitáciou z mohyly, polohovo korešponduje s kruhovou magnetickou anomáliou; x – kamenné štruktúry s vysokým odporom, 0,7 m široké a 0,3 m vysoké, zostávajú bez interpretácie; b – zvetrané zvyšky amfibolitového podložia (200–700 Ωm; podľa *Mušič et al. 2018*, obr. 4–6).

Obr. 14. Pohrebisko Pivola (plochy A, B a C) s plochami preskúmanými rôznymi geofyzikálnymi metódami, plytkými vrtmi a malými výkopmi (pozri obr. 2). A – bývalý les, nikdy nekultivovaný, s dobre zachovanými mohylami; B – bývalá vojenská základňa, pretvarované mohyly; C – poľnohospodárska oblasť, mohyly takmer zničené (LiDAR-ová mapa D. Mlekuž).

Obr. 15. Pohrebisko Pivola. Plochy v severnej časti pohrebiska na poľnohospodárskej pôde s takmer zničenými mohylami v Pivole (A), skúmanými magnetometriou, GPR a odporovou metódou (B; LiDAR-ová mapa D. Mlekuž).

Obr. 16. Pohrebisko Pivola, severná skupina mohýl. Magnetická mapa na digitálnom výškovom modeli. Silné bodové magnetické anomálie sú spôsobené mnohými železnými predmetmi roztrúsenými v poľnohospodársky obrábanej pôde (A). Priekopy okolo mohýl, identifikované na magnetograme, sú označené bielymi šípkami (B; podľa *Teržan/Črešnar/Mušič 2015*, obr. 8).

Obr. 17. Pohrebisko Pivola, severná skupina mohýl. A – plochy preskúmané GPR na DTM odvodenom z LiDAR-ovej mapy so žltými kruhmi indikujúcimi polohu a veľkosť mohýl; B – výsledky GPR meraní v hĺbkovom intervale 70–80 cm (LiDAR-ová mapa D. Mlekuž).

Obr. 18. Pohrebisko Pivola, severná skupina mohýl. Topografická korekcia výsledkov GPR metódy so 400 MHz anténou (A a B). Obrázok ukazuje excentrickú polohu hrobových komôr a zreteľné rozdiely v stave zachovania. Komora mohyly 13 (A – Kv_3) je dobre zachovaná (pozri obr. 17; 19; 20), zatiaľ čo komora mohyly 17 (B – Kv_6) je takmer úplne zničená hlbokou orbou (pozri obr. 17). Po topografickej korekcii je plášť mohyly so silným zvýraznením GPR signálov (tmavomodré plochy) tiež v pôvodnej polohe (podľa *Mušič/Črešnar/Medarić 2014*, obr. 4).

Obr. 19. Pohrebisko Pivola, severná skupina mohýl, mohyla 13. GPR časové rezy v hĺbkovom intervale od 0,5 m do 0,9 m (a–d) a odporové meranie (e). Výrazné georadarové odrazy z kamennej hrobovej komory a vysoké hodnoty odporu v centrálnej časti mohyly sú jasne viditeľné (A). Veľkosť takmer úplne zničenej mohyly bola určená na základe zoslabenia GPR signálov a významne nižšieho odporu v priestore plášťa mohyly (B, naznačené kruhmi).

Obr. 20. Pohrebisko Pivola, severná skupina mohýl, mohyla 13. GPR časové rezy v hĺbkovom intervale 60–70 cm (1) reprezentujú výrazné odrazy z hrobovej komory z nasucho kladeného kameňa v centre mohyly (A), zoslabenie GPR signálu vo vodou nasýtenom plášti mohyly vybudovanom z piesočnatej hliny (B) a chaotické odrazy zo štrkopiesku na modernom poli v blízkom okolí (C). Zobrazenie GPR amplitúdy (2) a 3D zobrazenie (3; podľa *Mušič/Črešnar/Medarić 2014*, obr. 6; *Teržan/Črešnar/Mušič 2015*, obr. 13; 16).

Obr. 21. Pivola, mohyla 13. Zobrazenie troch následných fáz výskumu hrobovej komory na georeferencovaných kolmých fotografiách a na počítačovej grafike vyhotovenej na základe týchto fotografií. Pri objavení bola hrobová komora zakrytá a vyplnená kamennou sutinou (A), po ktorej odstránení sa objavili dve väčšie koncentrácie spálenej zeminy a spálených ľudských ostatkov (B). Po odstránení výplne sa odhalili detaily dôležité pre pochopenie konštrukcie komory – dve jamy na zvislé drevené stĺpy vo východnej a západnej stene. Popri vnútorných stenách komory a na jej dne boli odkryté zvyšky zvetranej vrstvy, ktoré indikujú existenciu drevenej konštrukcie (C).

Text translated by Branko Mušič and Matija Črešnar
English proofreading by Patricia Groenewald
Súhrn preložila Lucia Benediková s využitím DeepL.com (free version)

Assist. Prof. Branko Mušič
University of Ljubljana
Faculty of Arts
Department of Archaeology
Centre for Interdisciplinary Research in Archaeology (CIRA)
Aškerčeva 2
SI – 1000 Ljubjana
branko.music@ff.uni-lj.si
https://orcid.org/0000-0003-1713-4550

Dr. Barbara Horn
Gearh d.o.o.
Radvanjska cesta 13
SI – 2000 Maribor
barbarahorn01@gmail.com

Assoc. Prof. Matija Črešnar
University of Ljubljana
Faculty of Arts
Department of Archaeology
Centre for Interdisciplinary Research in Archaeology (CIRA)
Aškerčeva 2
SI – 1000 Ljubjana
matijacresnar@ff.uni-lj.si
https://orcid.org/0000-0002-7856-6384