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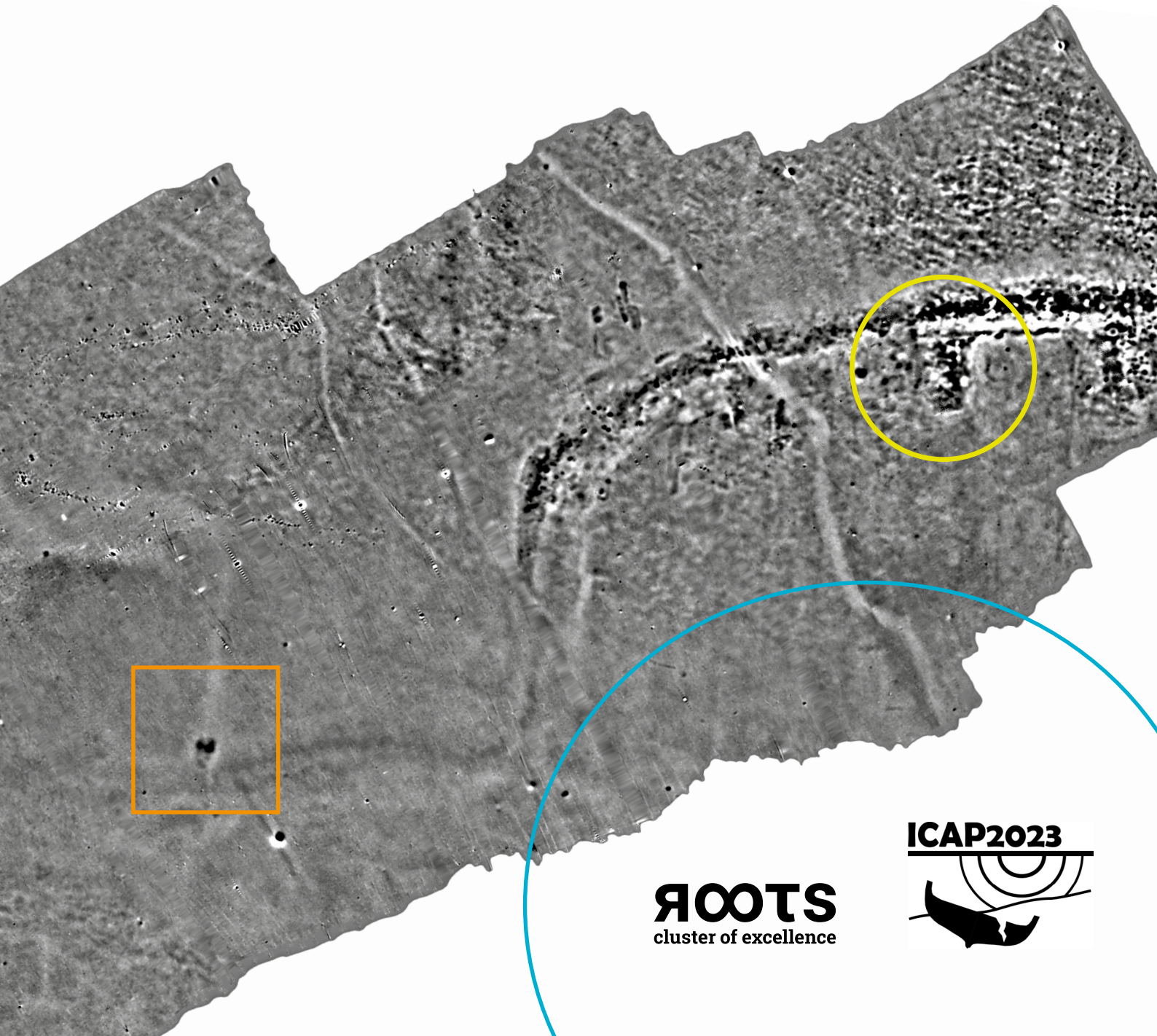
ADVANCES IN ON- AND OFFSHORE **ARCHAEOLOGICAL PROSPECTION**



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ICAP2023

ADVANCES IN ON- AND OFFSHORE **ARCHAEOLOGICAL PROSPECTION**

Proceedings of the 15th International Conference on Archaeological Prospection

Edited by Tina Wunderlich, Hanna Hadler and Ruth Blankenfeldt

Kiel (Germany), March 28 – April 1, 2023

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ADVANCES IN ON- AND OFFSHORE ARCHAEOLOGICAL PROSPECTION

Proceedings of the 15th International Conference on Archaeological Prospection

EDITORS

Tina Wunderlich
Institute of Geosciences, Kiel University, Otto-Hahn-Platz 1, 24118 Kiel, Germany
tina.wunderlich@ifg.uni-kiel.de

Hanna Hadler
Institute of Geography, Johannes Gutenberg University Mainz, Johann-Joachim-Becher-Weg 21, 55128 Mainz, Germany
hadler@uni-mainz.de

Ruth Blankenfeldt
Centre for Baltic and Scandinavian Archaeology (ZBSA), The Schleswig-Holstein State Museums Foundation
Schloss Gottorf, Schlossinsel 1, 24837 Schleswig, Germany
ruth.blankenfeldt@zbsa.eu

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Editorial

Tina Wunderlich [1], **Hanna Hadler** [2], **Ruth Blankenfeldt** [3]

1 Institute of Geosciences, Kiel University, Kiel, Germany, tina.wunderlich@ifg.uni-kiel.de
2 Institute of Geography, Johannes Gutenberg University Mainz, Mainz, Germany, hadler@uni-mainz.de
3 Centre for Baltic and Scandinavian Archaeology (ZBSA), Schleswig, Germany, ruth.blankenfeldt@zbsa.eu

The proceedings at hand offer the unique opportunity to collect the latest research in archeological prospection in 90 short articles. Results of measurements, improvements in data processing and visualization in these articles were presented and discussed at the 15th International Conference on Archaeological Prospection (ICAP2023) in Kiel, Germany March 28 – April 1, 2023). All submitted articles, regardless of poster or oral presentation, were subject to peer review. Two reviewers have read and commented the articles and their comments together with a decision of the editorial board were send to the corresponding author. After revision the articles were again checked by the editorial board and accepted for publication provided that the article was improved adequately.

The volume starts with articles from four keynote speakers, presenting the wide range of present-day research in archaeological prospection: (1) shedding light on the mobility patterns of hunter-gatherer groups in Northern Europe, (2) submersible ground penetrating radar (SGPR) providing amazing insights into the depositional structures in lake floor sediments, (3) seismic full-waveform inversion (FWI) enabling imaging of sub-meter scale archaeological objects, and (4) landscape reconstruction in ancient Olympia proving the existence of a so far unknown lake. In addition, in memory of Albert Hesse, a pioneer in archaeological geophysics, who passed away in 2022, one article reflects on his life and achievements.

As the hosting Kiel University also has a focus on marine sciences, a special session on marine and wetland prospection is presented. The respective articles deal with the localization of archaeological objects as well as landscape reconstruction on nowadays silted-up land, tidal flats or shallow water investigations. Numerous geophysical methods can be applied, but partly need adaptations with respect to instrument carriers and processing techniques.

The majority of articles focuses on case studies all over the world. Most of them use several geophysical or remote sensing methods in combination to yield a better characterization of the subsurface. Although naturally they focus on relatively local and site-specific targets, their experiences can also be applied to other sites, which makes this session a valuable contribution to archaeological prospection in general.

In contrast to single archaeological features the investigation of the past environment is the focus of the session on environmental studies and landscape evolution. Naturally, these studies cover larger areas and also have to deal with large amount of data.

New methodological developments and innovations include amongst others a semi-autonomous driverless system, true 3D Electric Resistivity Tomography (ERT) measurements or the investigation of the effect of rain on GPR measurements.

Last but not least, advances in processing and visualization techniques, partly connected with data from case studies are presented. Amongst others, the articles deal with tools for the combination of data from multiple sensors, noise reduction in GPR data, using seismic noise for subsurface imaging or deep learning for automatic hyperbola detection.

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Wolfgang Rabbel, **Ercan Erkul**, **Martin Thorwart**, **Dennis Wilken**, **Tina Wunderlich**
Institute of Geosciences, Kiel University, Kiel, Germany

Scientific Committee

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Christophe Benech (CNRS - Université Lyon 2, Lyon, France), **Adam Booth** (University of Leeds, Leeds, United Kingdom), **Hannah Brown** (University of Bradford, Bradford, United Kingdom), **Lawrence Conyers** (University of Denver, Denver, United States of America), **Joris Coolen** (Regional Association of Westphalia-Lippe (LWL), Münster, Germany), **Philippe De Smedt** (Ghent University, Ghent, Belgium), **Jörg Fassbinder** (University of Munich, Munich, Germany), **Annika Fediuk** (Eastern Atlas, Berlin, Germany), **Tomasz Herbich** (Polish Academy of Sciences, Warsaw, Poland), **Alois Hinterleitner** (Geosphere Austria, Vienna, Austria), **Stephen Kay** (The British School at Rome, Rome, Italy), **Roland Linck** (Bavarian State Office for the Preservation of Monuments, Munich, Germany), **Neil Linford** (Historic England, Portsmouth, United Kingdom), **Paul Linford** (Historic England, Portsmouth, United Kingdom), **Bente Sven Majchczack** (Kiel University, Kiel, Germany), **Ian Moffat** (Flinders University, Adelaide, Australia), **Nikos Papadopoulos** (Institute for Mediterranean Studies, Foundation for Research and Technology, Rethymno, Greece), **Roman Pašteka** (University of Bratislava, Bratislava, Slovakia), **Natalie Pickartz** (State Office for the Preservation of Monuments in Stuttgart, Ludwigsburg, Germany), **Michał Pisz** (University of Warsaw, Warsaw, Poland), **Wolfgang Rabbel** (Kiel University, Kiel, Germany), **Christoph Rinne** (Kiel University, Kiel, Germany), **Martin Roseveare** (Tigergeo Limited, Hereford, United Kingdom), **Martin Thorwart** (Kiel University, Kiel, Germany), **Immo Trinks** (University of Vienna, Vienna, Austria), **Gregory Tsokas** (University of Thessaloniki, Thessaloniki, Greece), **Volkmar Schmidt** (University of Münster, Münster, Germany), **Petra Schneidhofer** (Vestfold and Telemark County Council, Tønsberg, Norway), **Andreas Stele** (Bavarian State Office for the Preservation of Monuments, Munich, Germany), **Andreas Viberg** (Guideline Geo AB, Umeå, Sweden), **Dennis Wilken** (Kiel University, Kiel, Germany)

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1

KEYNOTE LECTURES

Pioneers in a changing world – investigating the elusive settlement and mobility patterns of north European hunter-gather groups from the end of the last Ice Age

Berit Valentin Eriksen [1*]

1 Centre for Baltic and Scandinavian Archaeology (ZBSA), Schleswig, Germany
* Corresponding author: E-mail: berit.eriksen@zbsa.eu

Abstract
Late Pleistocene hunter-gatherer groups had to cope with extensive climatic changes. When glaciers melted and water levels rose, large areas were flooded. Familiar landscapes disappeared whereas other areas were slowly made available for colonization. Human groups exploiting these pristine territories were few and their settlements scant. Tracking the movements of these elusive pioneers requires the collaborative effort of several scientific disciplines.

Keywords
archaeological prospection; Late Paleolithic; mobility; settlement patterns; taphonomy

Introduction

The focal point of this paper is the well-known statement that you cannot eat your cake and have it or translated into archaeological terms you cannot excavate your site and keep it. Field archaeology is highly destructive to prehistoric sites in a way that is inverse proportional to the degree of preservation: if very little is preserved – an excavation will destroy the rest. Thus, the conscientious archaeologist sometimes faces a dilemma encompassing an immediate need to excavate for rescue purposes, a desire to investigate carefully and meticulously for research purposes, and a request to protect and preserve prehistoric sites in situ for future generations. But are these really true alternatives in current prehistoric hunter-gatherer archaeology, and can field archaeology be non-destructive or even protective? This paper emphasizes that in contemporary archaeological research design it is mandatory to incorporate rescue archaeological considerations – especially with respect to sites characterized by a low general visibility.

Material

The paper will proceed from and address these issues with specific reference to north European Late Upper Paleolithic and Early Mesolithic archaeology. In an ongoing research project "Pioneers of the North" (funded by the German Research Foundation as part of the Collaborative Research Centre CRC1266 "Scales of Transformation") we investigate the timing and nature of hunter-gatherer colonization in relation to the environmental preconditions in Northern Europe during the period c. 15,000-9,500 BCE. Our geographic area of study includes the terrestrial part of the north European plain including southern Scandinavia, as well as the past landscapes that are now flooded by the North Atlantic and the Baltic Sea. Select examples highlighting the taphonomic difficulties pertaining to the preservation and accordingly localization of archaeological remains from these pioneers will serve as basis for the discussion.

Discussion

There are a few important premises guiding the discussion. Evidently, prehistoric hunter-gatherer groups surviving the arctic or subarctic conditions of the late Weichselian Ice Age must have been strongly dependent on the natural environment. Considering the environmental conditions and the marked seasonal variation in climate, flora, and fauna – we also must assume that mobility and settlement strategies may have been quite complex at the time (Eriksen 2002; Hamer et al. 2019). Thus, a broad geographic approach is crucial to our understanding of these aspects. If the geographical area of investigation is too limited, we will miss the overall context within which to interpret the patterning, and we may even miss vital aspects of the patterns themselves.

By reference to ethnographical observations pertaining to subrecent hunter-gatherer societies, the prehistoric hunter-gatherers in question are habitually described as being highly mobile, demographically fluctuating and exhibiting a more or less explicit seasonal behavior. Unfortunately, such a lifestyle frequently results in very few traces left behind, and hence a very low visibility of past settlement and mobility patterns. Well defined structural remains (fireplaces, tent rings, stone settings, etc.) are rare and inconspicuous by comparison to those left by later and more sedentary societies. Moreover, late Weichselian conditions for preservation are often problematic due to a variety of periglacial landscape factors (e.g., solifluction, aeolian erosion, lack of soil formation, etc.). Thus, Late Paleolithic living floors or cultural layers, if at all present, may be no more than a few millimeters thin, or they may appear as a more or less diffuse horizon of subsoil material with a scattering of archaeological remains.

Conclusions

Obviously, such elusive settlement remains are difficult to identify by traditional archaeological prospection (e.g., machine trenching) (Eriksen 1999). Depending on the resources available for fieldwork as well as the local topography and soil conditions, supplementary reconnaissance walks in ploughed soil, small test pits dug by hand, systematic corings, or even very narrow machine trenches may be used to clarify stratigraphic relationships and aid in the localization of sites (Eriksen 2001, 2006). However, as local archaeological authorities everywhere are subject to an increasing economic strain, with manpower often being a limiting factor, there also is a manifest need for faster and more efficient methods of investigation. In conclusion, it is argued that a combination of conventional archaeological field-methods and advanced geophysical prospection may hold a significant potential for negotiating this need (Corradini et al. 2020).

Acknowledgments

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Submersible ground penetrating radar (SGPR) – chances and limits for underwater investigations

Jens Hornung [1*]

1 Institute for Applied Geosciences, Technical University of Darmstadt, Darmstadt, Germany
*Corresponding author: E-mail: hornung@geo.tu-darmstadt.de

Abstract
Results of submerged ground penetrating radar (SGPR) measurements show spectacular detailed depositional structures of lake floor sediments, which could not be revealed with any other geophysical method yet. Due to its very high resolution, GPR is particularly suitable for archeological prospection on land surfaces and now on lake floors. A case study showed that a submerged archaeological site in Lake Constance (boulder mounds, the so-called "Hügelis") is interfingering with the sedimentary record. Depositional history reveals that the site must be human-made and dates back to the prehistorical period. 14C ages of sediment and wood poles proved Neolithic age of the more than 170 boulder mounds comprising over 80,000 metric tons of rock.

Keywords
archeology; Lake Constance; Neolithic boulder mounds; sedimentology; underwater ground penetrating radar

Introduction

Land based GPR is well established and successfully applied since years in archaeological prospection (e.g. Leckebusch 2001; Wallner et al. 2021), sedimentology (Franke et al. 2015), and engineering geology. Rarely, GPR systems were used already from boats on the water surface (Sambuelli et al. 2009; Baum et al. 2014; Fediuk et al. 2022). However, using GPR-systems underwater was not possible yet due to the lack of submersible systems. This study shows the high scientific potential of lake floor GPR surveys by constructing a submersible ground penetrating radar (SGPR) and applying it at the floor of Lake Constance (SW-Germany).

Materials and methods

A commercial GPR system (GSSI Inc., Model SIR 4000, 200MHz antenna) was modified to use it underwater (Fig. 1). A survey wheel running on the lake floor controlled the system and a dragged RTK buoy on the lake surface ensured underwater positioning.

The system emits a short electromagnetic pulse with a nominal center frequency of 200 MHz. The pulse is reflected at boundaries where the dielectric permittivity of the penetrated material changes. Such a boundary corresponds to geological layer changes as well as to boundaries, which were formed when the ground was disturbed or extrinsical material was brought in by human activities.

Submerged GPR (SGPR) penetrates deep when water and sediments have a low conductivity. Lake carbonates usually show a low conductivity whereas clay-rich sediments show high conductivities. Hence, the system works well in most sweet water lakes, but is limited in penetration depth in clay rich sediments. In saline lakes or in the sea SGPR will not show a sufficient penetration depth due to the high conductivity of the water.

Results

The SGPR system revealed sedimentary structures and architecture in the sub-littoral of Lake Constance. Data allowed reconstructing the depositional history and sediment fluxes (Wessels and Hornung 2019). Subsequently the potential for archeological prospection was recogni-

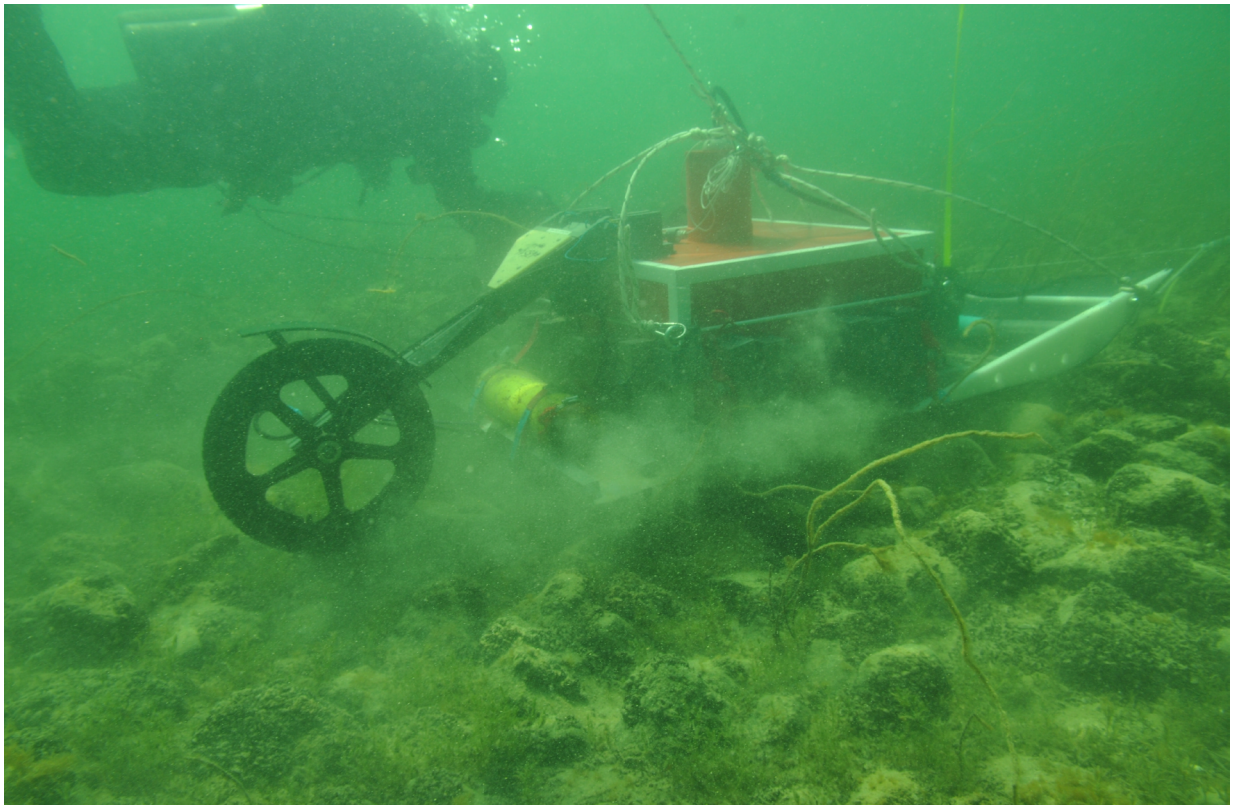

Fig. 1: Submersible ground penetrating radar (SGPR) in action on a Neolithic boulder mound in Lake Constance. Photo: AATG, Matthias Schnyder.

zed. In 2015, mysterious boulder mounds were discovered at the Swiss coastline of Lake Constance (IGKB 2015). The scientific question was to clarify if these mounds were the summits of a glacial moraine buried in the lake sediments or if the mounds were sitting on top of the sediment and hence were human-made. Figure 2 shows the SGPR section of one of the investigated mounds. The glacial moraine subducts 100m before the boulder mound and is overlained by different types of sediment reflected by different radarfacies types. The boulder mound is located on top of these sediments. Hence, it is not a summit of the glacial moraine – it is an independent structure, which interfingers with the topmost part of the lake sediments. Towards the lake, some boulders rolled or felt down the former slope. Then the deposition of lake sediments continued for almost another 100m covering also parts of the mound.

In conclusion, the boulder mound was human-made exactly at the transition from the littoral to the sublittoral. The mound was originally higher to let fall or roll down boulders towards the former lake slope. After the destruction of the mound deposition continued for a long time, hence, the mound should date back at least in prehistoric times. A subsequent underwater excavation revealed wood poles of an average of 3500 yrs. cal. 14C age BC and sediment dating of the layer with the fallen boulders supported this Neolithic age (Leuzinger et al. 2021).

Discussion

Hydroacoustic methods such as the 'subbottom profiler' are usually restricted to max. 1-3 m penetration into the sediment and show reasonable resolution to detect sedimentary or archaeological structures. Water-based seismic methods like the 'boomer' or 'pinger' method can reach significant penetration depths of several tenths of meters. However, resolution is not sufficient to resolve archaeological or sedimentary structures. As all acoustic methods rely on mechanical properties, they have problems to generate reflections when gas is present in the sediments, which is quite common in the subsurface of lake floors. Advantage of these methods is that they are independent of electrical properties of the sediment (e.g. conductivity)

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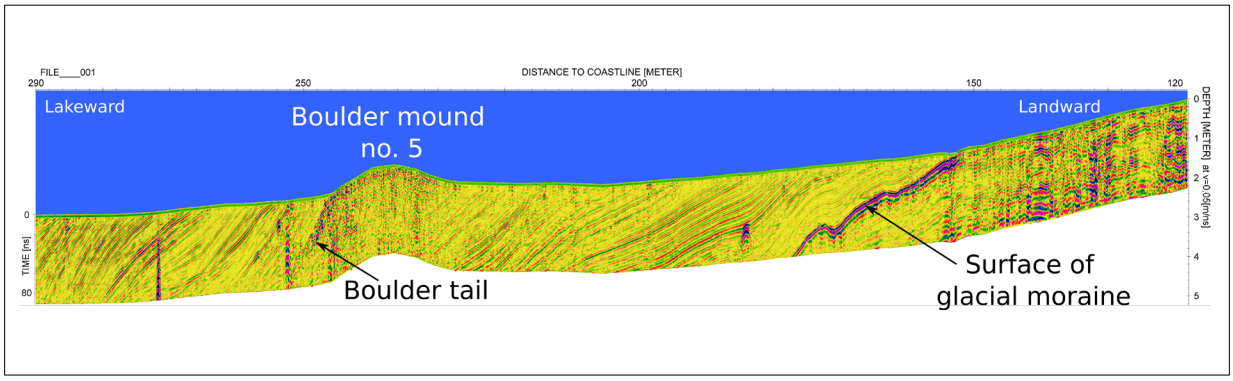

Fig. 2: SGPR section of the Neolithic boulder mound no. 5 in Lake Constance. Note that the mound is sitting inside and on top of the sediment and the glacial moraine is far beyond the mound. Boulders at the lakeward slope rolled or felt downdip and were covered with subsequent sediments. Deposition of lake carbonates continued after the boulder mound formation far out into the lake. Modified after Leuzinger et al. (2021).

and work even in clay-rich sediments and in salt water.

The GPR method overcomes resolution, insufficient penetration depth problems, and the electromagnetic waves can penetrate through layers with higher gas content. Additionally GPR may reveal material properties to some extend (Owenier et al. 2018; Fediuk et al. 2020). Probably electromagnetic properties revealed by GPR reflections can be used to distinguish rock boulders and wood trunks in lake floors.

For a long time lacustrine GPR surveys were restricted to the lake surface using non-metallic boats to float the antenna over the site. Due to significant energy losses in the water column, the application was limited to the shallow littoral zone e.g. 1-2 m water depth. The submersible GPR (SGPR) developed at the Darmstadt University of Technology is the first system, which can truly dive down to the lake floor and record detailed sections with sufficient penetration depth, superior resolution (cm-scale), and clarity of data.

Conclusion

Submersible GPR systems turned out to reveal crucial data about even small-scale sedimentary and archaeological structures in lake floors. Based on an integrated concept of lithofacies and radarfacies interpretation, it is possible to interpret depositional history, environment and palaeoclimate conditions from these data.

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Seismic full waveform inversion in archaeological prospecting

Daniel Köhn[1*], Manuel Zolchow[1], Rebekka Mecking[2], Dennis Wilken[1], Tina Wunderlich[1], Denise De Nil[1], Wolfgang Rabbel[1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 TEECsolutions, Isernhagen, Germany
* Corresponding author: E-mail: daniel.koehn@ifg.uni-kiel.de

Abstract
Seismic full waveform inversion is introduced as a novel high-resolution imaging tool in archaeological prospection. The full waveform inversion approach allows the high-resolution characterization of low-contrast sedimentary layers, high-contrast stone wall structures and air-filled cavities.

Keywords
archaeological prospection; full waveform inversion; seismic; subsurface characterization

Introduction

Archaeological prospection can rely on a wide spectrum of electro/magnetic and seismic methods with different areal coverage. Elastic properties of the sub-surface are traditionally estimated by first arrival travel time tomography (FATT) or the inversion of surface wave dispersion spectra. Both of these approaches focus on special properties of the wavefield and therefore have limitations in terms of resolution and applicability. By incorporating phase and amplitude information of the entire recorded wavefield, the seismic full waveform inversion (FWI) is able to improve the structural resolution significantly. Previous studies demonstrated the capability of FWI to resolve near surface structures related to problems in engineering geophysics (Tran et al. 2013) and archaeogeophysics (Dokter et al. 2017; Wittkamp et al. 2018; Schwardt et al. 2020). In this presentation, we review some of our FWI applications in archaeogeophysics with different degrees of complexity and fields of application. Archaeological excavations allowed a ground truthing of the resulting subsurface models.

Full waveform inversion approach

In seismic SH-FWI, the waveform misfit between modelled and field data is minimized in order to obtain high resolution models of the shear wave velocity vs and density distribution in the subsurface. To solve this non-linear optimization problem an appropriate objective function has to be defined. To mitigate common problems of applying 2D FWI to field data, like variable coupling at different receiver positions, we use the trace normalized global correlation norm GCN (Choi and Alkhalifah 2012; Dokter et al. 2017) to avoid these problems at least to some extent. This objective function can be minimized by iteratively updating the model parameters starting with an initial background model using a preconditioned conjugate gradient method (Dokter et al. 2017). To reduce the non-linearity of the inverse problem and mitigate the dominance of the low-frequency Love wave in favour of high-frequency data, a sequential FWI workflow of low-pass and band-pass filtered data with different bandwidth is applied (Köhn et al. 2019). Smoothness constraints are imposed by preconditioning the gradients with an anisotropic 2D Gaussian filter adapted to the local S-wavelength.

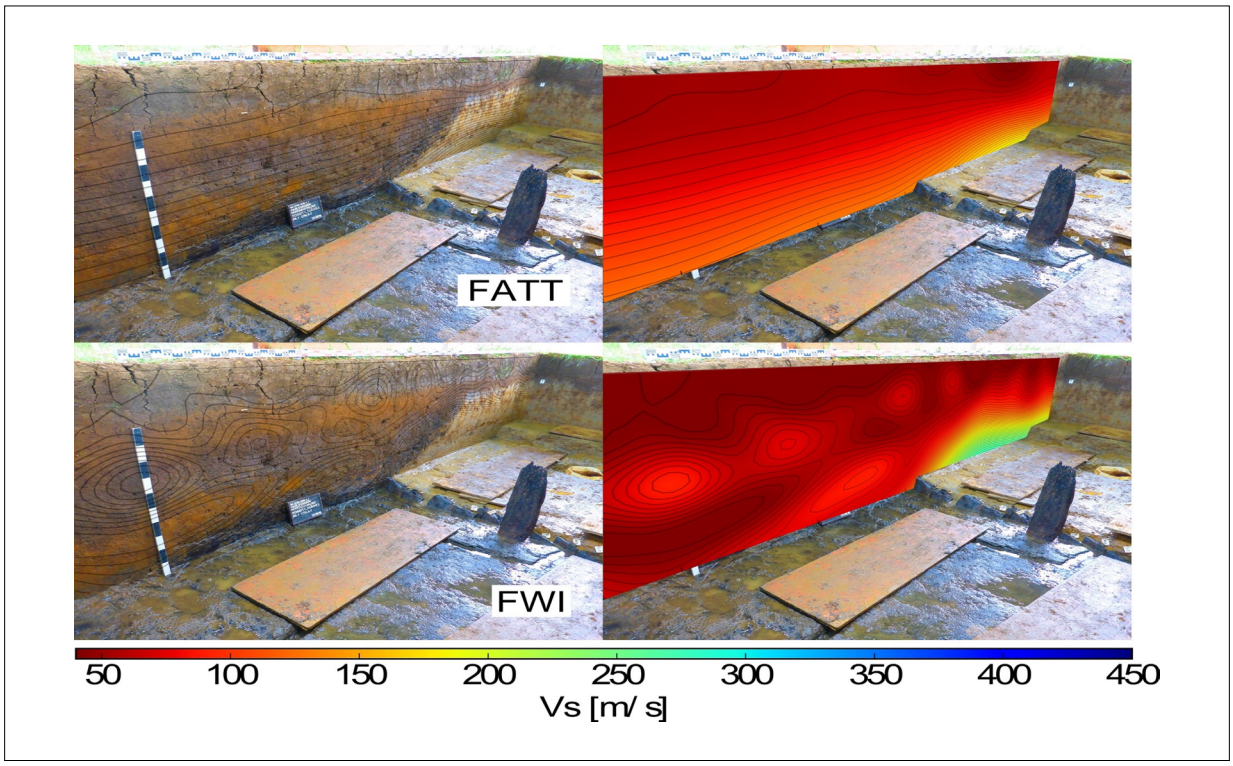

Fig. 1: Comparison of the Fossa Carolina canal structure from an excavation photo with FATT (top) and FWI results (bottom), respectively. The color bar is only related to the FATT/FWI results. Photo from Köhn et al. (2019).

High resolution mapping of a near-surface canal structure

To demonstrate the potential of our SH-FWI approach, we inverted a SH-transect across the medieval Fossa Carolina canal structure (also known as "Karlsgraben") in southern Germany (Köhn et al. 2019). Originally initiated by the Franconian king Charlemagne as a 3 km long canal to connect the Danube and Rhine River system, the construction was realized in 793 AD. The Fossa Carolina is one of the most important major hydraulic engineering projects in the Early Middle Ages. An archaeological excavation (Schmidt et al. 2019) from August 2016 allowed a ground truthing of the FWI result. Figure 1 shows a comparison between an excavation photo and S-wave velocity models derived by First Arrival Travel-time Tomography (FATT) and FWI, respectively. The upper 40 cm of the depth-cut show a weathering layer consisting of soil and vertical cracks. With increasing depth alternating, distinct yellowish and grey clay layers are visible. Near the bottom of the excavation, parts of a black organic-rich layer define the shape of the canal basement. The FATT result (top) shows a gradual increase of the S-wave velocities with depth but no clear correlation with the true grey and yellowish subsurface layers. A slightly stronger velocity gradient appears at the sharp layer transition of the canal basement, but its shape is not accurately mapped by the FATT. The subsurface resolution is significantly improved by the FWI (bottom). The canal basement shape in the FWI result is defined by dense velocity contours, which indicate a significant velocity gradient. In contrast to the FATT, some distinct low- and high velocity anomalies appear within the canal. In some parts, colours of the photo can be directly correlated with the velocity model. For example, some low-velocity contour lines of the FWI Vs-model nearly coincide with a yellowish clay layer at the bottom left of the excavation, the high velocity anomaly above correlates with a grey clay layer. In the weathering layer this correlation is not so obvious anymore, because the loose soil and deep-penetrating vertical cracks lead to a reduction of the shear modulus. As a result, some dominant near surface low-velocity anomalies, down to a depth of 40 cm, are introduced.

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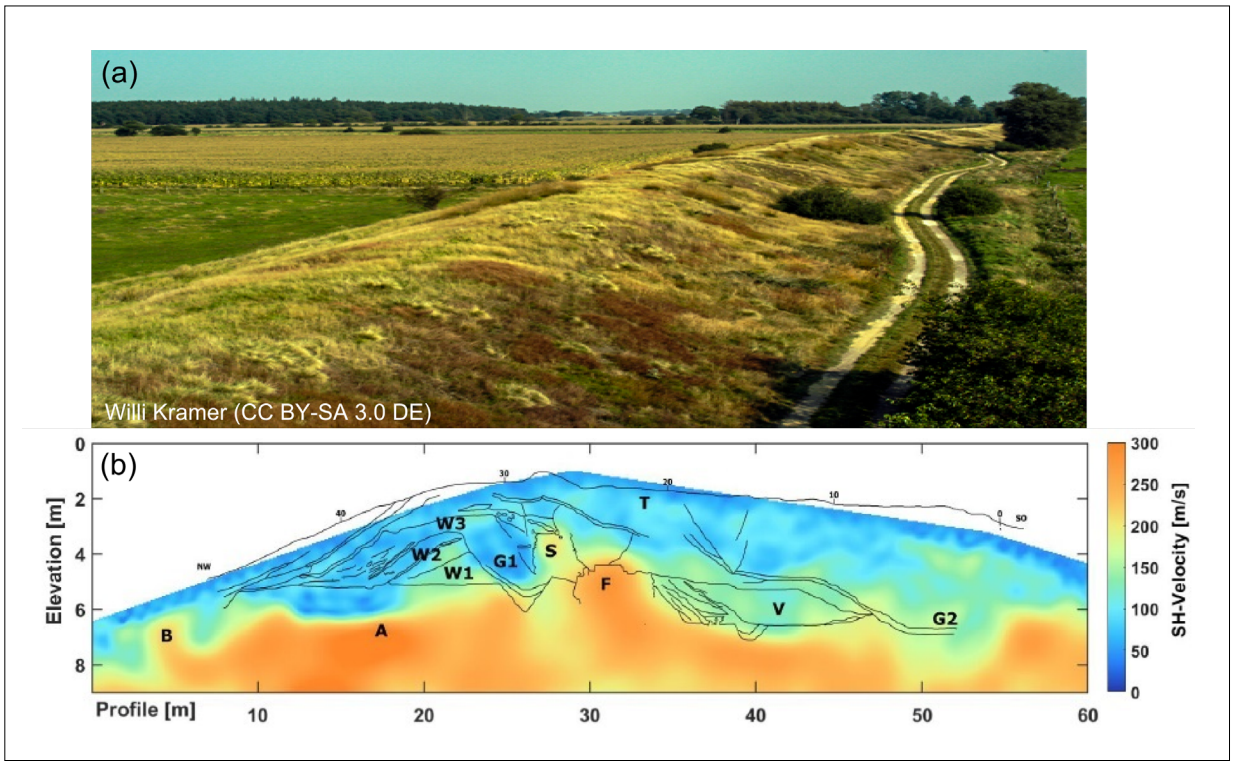

Fig. 2: Photo of the Danewerk (a) and ground truthing of the final FWI result in comparison with an archaeological excavation sketch (b) according to Andersen (1998). Prominent features: top layer (T), stone wall (S), wall foundations (F), early wall phases (W1-3), trench structures (G1-2), infilling (V),possible deeper foundations (A, B).

FWI in the presence of significant surface topography

Significant surface topography poses a problem for FWI applications, due to the required accurate numerical modelling of synthetic surface wavefields, affected by the free-surface boundary condition. To solve this issue, a spatially oversampled Cartesian Finite-Difference approach with a special treatment of the free-surface boundary condition (Pan et al. 2018) is applied. An example of a problem with significant surface topography is the UNESCO World Heritage site Danewerk, a prominent defensive fortification wall, extending from the Baltic Sea to the North Sea in Northern Germany (Fig. 2 a). Originally built at some time before AD 500, the fortification was improved over the centuries by a wooden fence, a cobble stone wall and a massive brick stone wall. From a geophysical prospecting perspective, this target is especially interesting, because the embedded stone walls lead to significant physical parameter contrasts in the subsurface. Ground truthing of the FWI results is based on an excavation conducted in 1991 (Andersen 1998). Figure 2 b) shows a comparison between the FWI result and an archaeological sketch. Prominent features are marked by letters. W1, W2, W3, denote the different early, construction phases of the Danewerk. Initially, it was a small wall consisting only of soil growing over the centuries in size. W1 belongs to the oldest part of the Danewerk construction, while W2 and W3 were added later. The early construction phases W1, W2, W3 consist of soil with intermediate S-wave velocities between 150 m/s - 200 m/s. S denotes the remains of the cobble-stone wall which is also visible in the FWI results with S-wave velocities of 200 m/s. The compact brick-stone wall, denoted by F, can be characterized by higher velocities of about 300 m/s. Two high-velocity anomalies A and B with up to 400 m/s could be related to basement structures consisting of cobble stones to avoid a further collapse of the Danewerk.

Detection of air-filled cavities

Another important field of application for the FWI is the detection of cavities. Figure 3a shows the Yigma Tepe, a monumental burial mound in the urban area of the an-

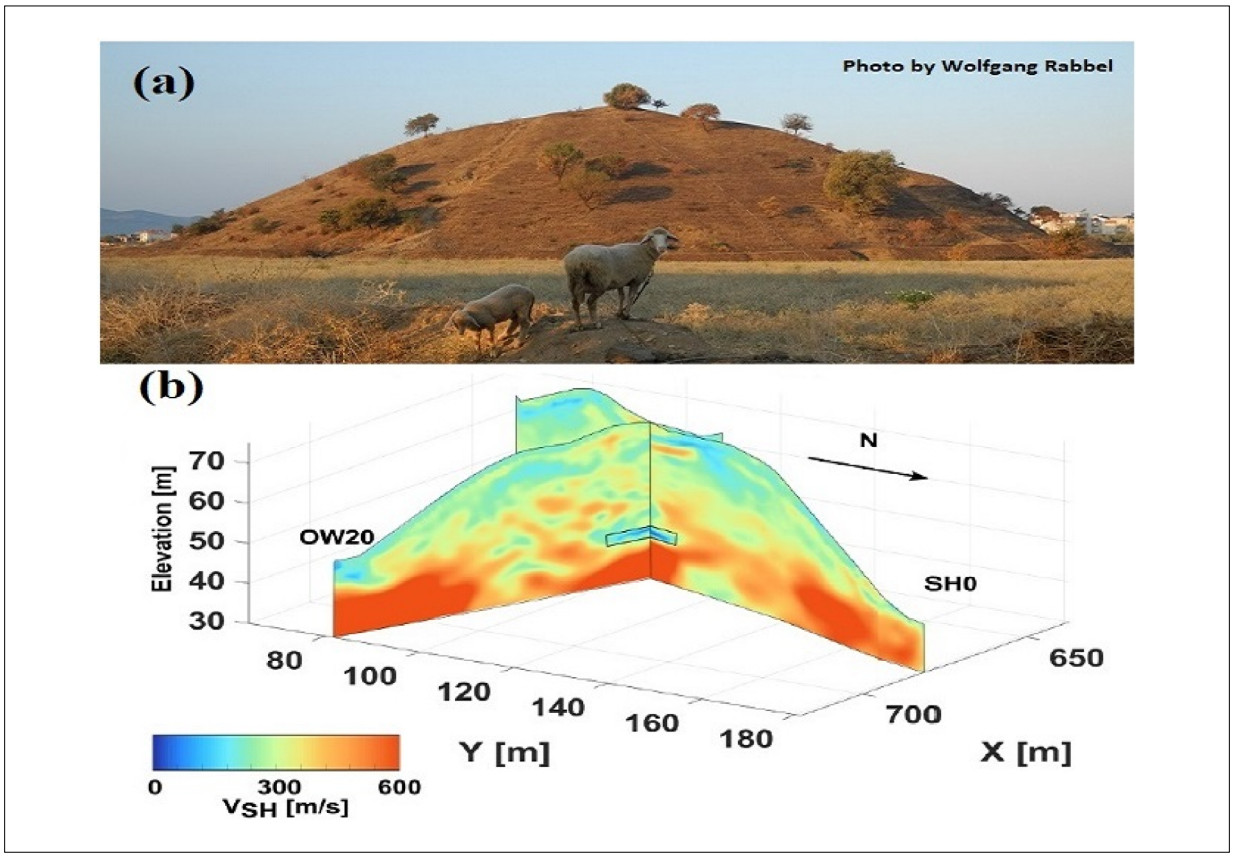

Fig. 3: Photo of the Yigma Tepe (a) and the 2D-FWI results of two SH-profiles along the mound (b).

cient city of Pergamon (Turkey). It is an almost circular structure with a diameter of 158 m and a height of about 32 m. The construction of the tumulus has been dated back to the Hellenistic period around 200 BC. The independent, reflection-focussed SH-FWI of two intersecting profiles across the tumulus (Mecking et al. 2021), revealed the complex internal structure of the mound and a prominent low-velocity anomaly at 30 m depth. This anomaly can be correlated with a system of partially collapsed excavation tunnels from the beginning of the 20th century. Notice also, that despite the 3D, heterogeneous subsurface structures, the 2D SH-FWI was able to resolve similar S-wave velocity anomalies at the intersection point of the two seismic profiles.

Conclusions

In this talk, we demonstrated the potential of 2D SH-FWI to resolve near-surface structures, either low-contrast sedimentary layers, high-contrast stone wall structures or air-filled cavities in a 3D heterogeneous subsurface. The applicability of the developed 2D SH-FWI workflow is not limited to archaeological problems, but can also be adapted in the fields of engineering, geotechnical and non-destructive testing.

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The "Lake of Olympia": geoarchaeological evidence of a lake environment in the vicinity of ancient Olympia (western Peloponnese, Greece)

Lena Slabon[1*], Lea Obrocki[1], Peter Fischer[1], Timo Willershäuser[1], Franziska Lang[2], Hans-Joachim Gehrke[3], Birgitta Eder[4], Erofili-Iris Kolia[5], Oliver Pilz[6], Dennis Wilken[7], Andreas Vött[1]

1 Institute of Geography, Johannes Gutenberg University Mainz, Mainz, Germany
2 Department of Classical Archaeology, Technical University of Darmstadt, Darmstadt, Germany
3 Department of Ancient History, University of Freiburg, Freiburg, Germany
4 Austrian Archaeological Institute, Athens, Greece
5 Ephorate of Prehistoric and Classical Antiquities, Ancient Olympia, Greece
6 German Archaeological Institute, Athens, Greece
7 Institute of Geosciences, Kiel University, Kiel, Germany
* Corresponding author: E-mail: lslabon@uni-mainz.de

Abstract
Our results yield evidence of a large lake environment that existed near the ancient site of Olympia which was so far unknown. The limnic sequence reveals considerable changes in the ecological conditions over time, based on Direct Push sensing, sedimentary and micropalaeontological analyses. Radiocarbon data show that the "Lake of Olympia" existed from the 8th/7th millennium BC until, at least, the 1st century AD. The existence of the "Lake of Olympia" next to the cult site of Olympia has considerable historical, archaeological and geographical implications (e.g., as waterway or water supplier).

Keywords
ancient Olympia; direct push sensing; landscape evolution; micropaleontological analyses; sediment cores

Introduction

The site of Olympia (western Peloponnese, Greece) was used as a venue for the Panhellenic games between Archaic times and the 4th cent. AD (Sinn 2004). It is one of the best investigated archaeological sites of this period with systematic excavations having begun in 1875 by the German Archaeological Institute (Heilmeyer et al. 2012). In contrast, our knowledge on the overall landscape development and our understanding of relevant changes of the drainage pattern and the associated sedimentary burial of the site is still limited. The site is located at the northern fringe of the Makrisia Basin at the confluence of the Kladeos and Alpheios rivers and shows a complex tectonic setting (Fig. 1). Based on previous studies downstream the Alpheios River and along the coast of the Gulf of Kyparissia, we were able to show that the area was subject to strong tectonic uplift of minimum 13 m to a maximum of 30 m since the mid-Holocene (Vött et al. 2015, 2019). In addition, we found that the so-called Olympia terrace, which accompanies long sections of the Kladeos and lower Alpheios rivers, documents multiple phases of high-energy flood events and associated phases of strong siltation with their triggering mechanism still being evaluated (Vött et al. 2011, 2019). Against this background, recent studies focused on the direct vicinity of the site to gain more information on site formation and the overall landscape development.

Here, we present results based on high-resolution Direct Push Electrical Conductivity measurements (DP-EC) in combination with sediment coring and micropaleontological studies.

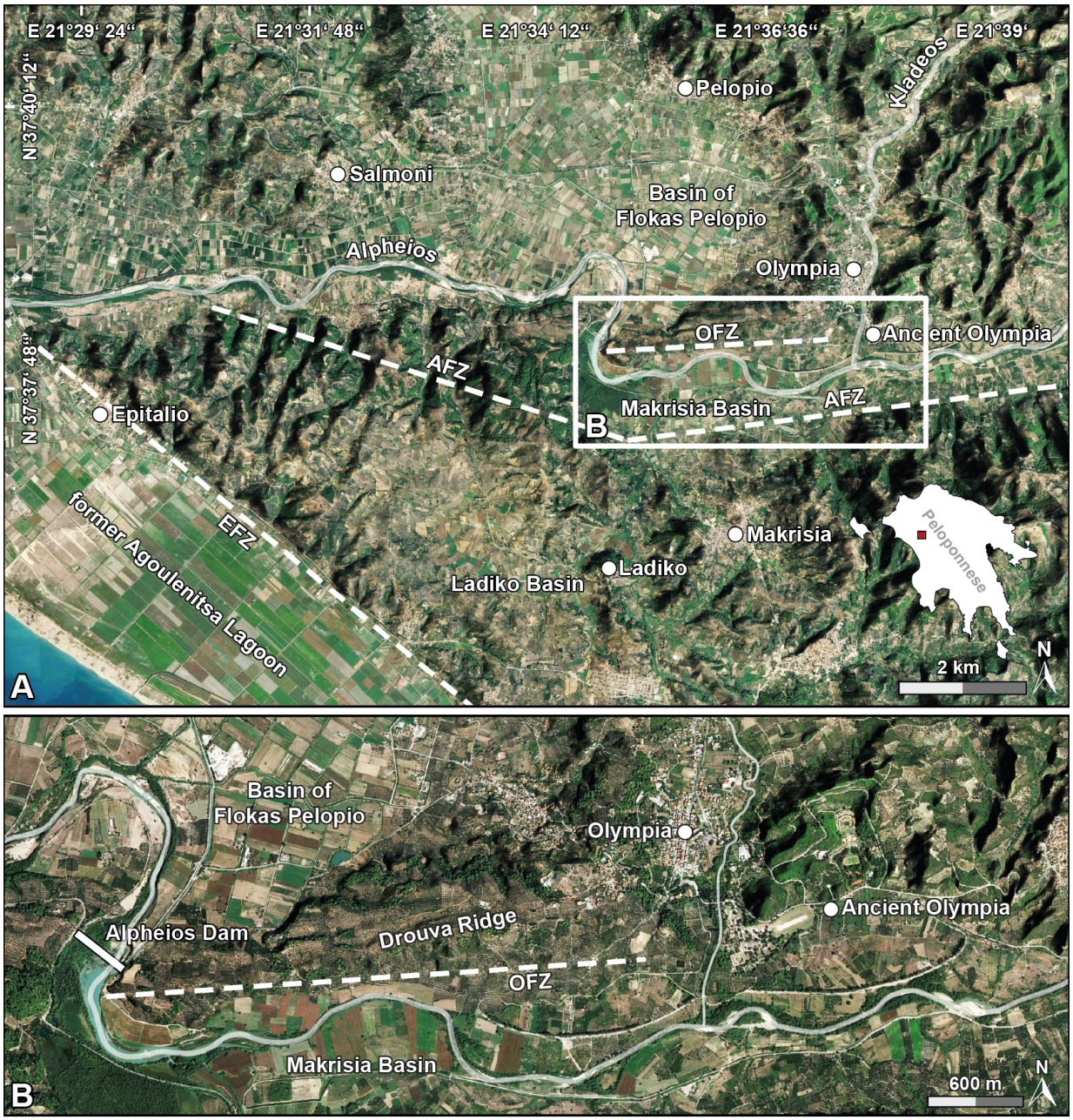

Fig. 1: (A) Topographical overview of the study area located in the western Peleponnese (Greece) showing the Olympia fault zone (OFZ), the Alpheios fault zone (AFZ) and the Epitalio fault zone (EFZ) (Vött et al. 2018, Papanikolaou et al. 2007) (B) Detailed view of the Basin of Makrisia showing the location of ancient Olympia (base map: Google, ©2023 CNES/Airbus, Landsat / Copernicus, Maxar Technologies).

Materials and methods

Direct Push (DP) sensing is a non-invasive method, which is applied increasingly in geoarchaeological research. DP-EC logging yields vertical centimeter-scale stratigraphic information since the electrical conductivity is mainly dependent on the predominant grain size. Higher conductivities usually correlate with finer-grained sediments and low electric conductivity values with coarser grained sediments. Detailed subsurface data obtained by DP-EC measurements help to concentrate coring activities to selected key sites. Compared to coring, DP sensing is more time-efficient and allows better investigation of non-cohesive sediments where boreholes often tend to collapse (Fischer

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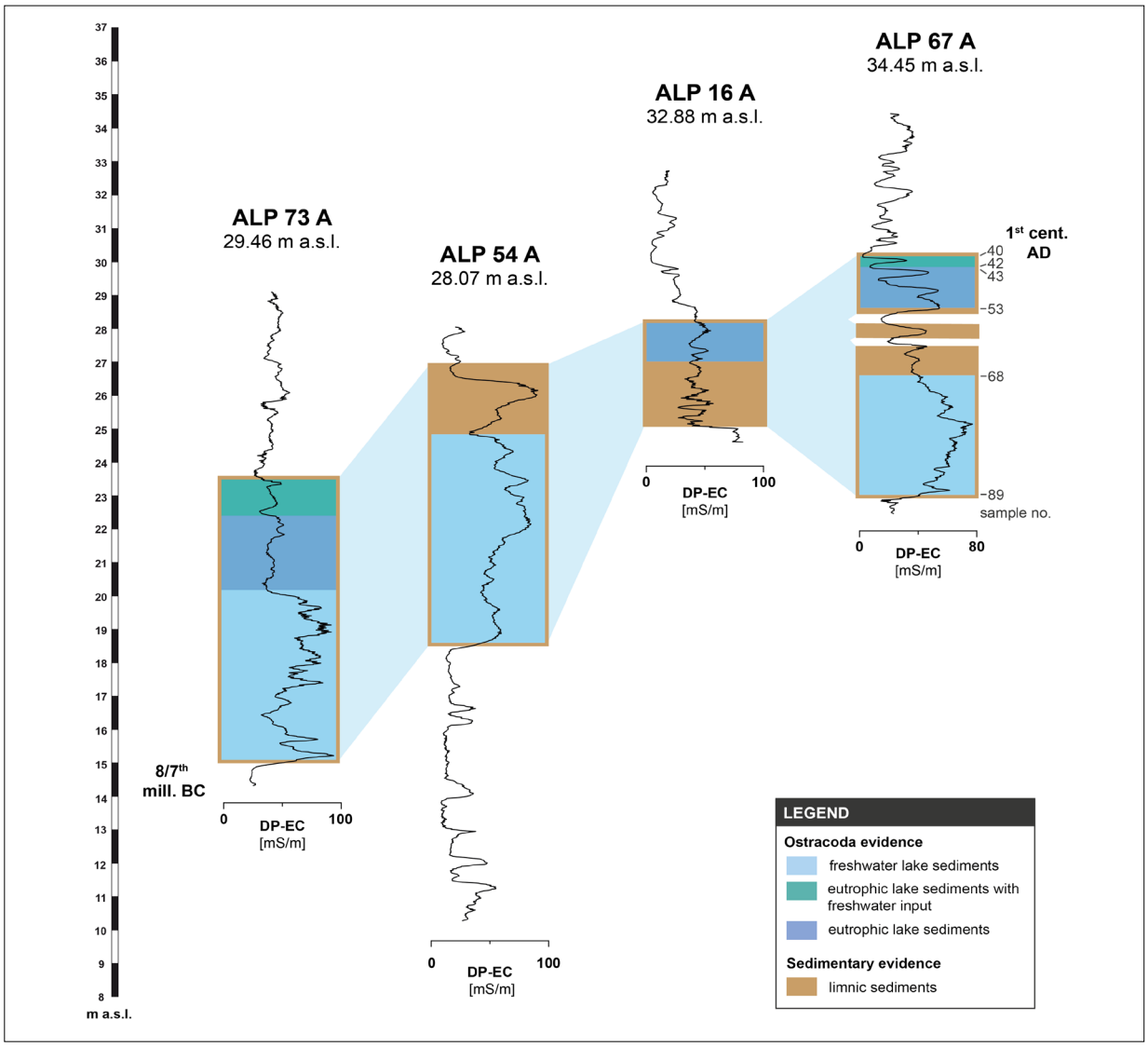

Fig. 2: Evidence of the "Lake of Olympia" based on sediment cores, DP-EC measurements and ostracod analyses. Our results allow differentiation between different lake phases. For location of coring and DP-EC sites, see Figs. 1 and 3.

et al. 2016). We use a Geoprobe SC520 soil conductivity probe mounted on a Nordmeyer RS 0/2.3 drill rig. The conductivity probe consists of four linear arranged electrodes operated with a Wenner electrode array that provides a vertical resolution of 0.02 m.

Micropaleontological studies were conducted in search of ostracod specimens within the limnic sediments. Ostracods are highly sensitive indicators for different kinds of environments. They occur in marine, brackish and freshwater environments such as lakes and ponds. We used microfossils as an important tool to reveal landscape changes and anthropogenic influences. Moreover, ostracods provide information on e.g., habitat structure and disturbance, salinity, land use effects and climate. Due to their size and generally high abundance, they are especially well suited for sediment core analyses, as only small sample sizes are required (Quante et al. 2022; Mazzini et al. 2022). We retrieved various samples from different depths and especially from core sections where fine-grained silt-dominated potentially limnic sediments were found. Samples were wet-sieved and taxonomically classified using Meisch (2000), Athersuch (1989) and Fuhrmann (2012).

ALP 67A	sample		Ostracods				Total number of ostracods	Number of different species
Facies	no.	depth [m]	freshwater	brackish	marine	others*		
V - eutrophic lake sediment with freshwater input	40	4.35	x	x		x	161	2
	41	4.45	x	x	x	x	51	2
	42	4.53	x	x			13	3
IV - eutrophic lake sediment	43	4.58		x		x	27	1
	44	4.68		x			2	1
	45	4.80		x		x	5	1
	46	4.89		x			5	1
	47	5.09		x		x	25	1
	48	5.14		x		x	74	1
	49	5.24		x			2	1
	50	5.36		x		x	3	1
	51	5.46		x		x	5	1
	52	5.57				x	2	-
	53	5.70		x			7	1
III - infill	59	6.45	x			x	4	1
	60	6.59					-	-
	65	7.35					-	-
II - freshwater lake sediment	68	7.77	x	x		x	7	3
	70	8.25					-	-
	72	8.65			x		1	1
	77	9.73	x			x	11	4
	80	10.25	x	x		x	173	6
	83	10.75	x			x	17	2
	88	11.37	x			x	75	4
	89	11.48	x	x	x	x	36	6
I - fluvial/ colluvial wdeposits	92	11.71		x			1	1

Tab. 1: Results of micropaleontological analyses of sediment samples from sediment core ALP 67A: Distribution, abundance and diversity. x means that taxa occur in the sample. * means genus and species indeterminate or fragment.

Results and discussion

Our results yield robust evidence of a large lake environment that existed near Olympia and that was so far unknown. The "Lake of Olympia", as we call it, covered large parts of the Makrisia Basin with the ancient site of Olympia directly located at its north-eastern shore. Geoscientific evidence for the existence of the lake comprises detailed sedimentary and stratigraphic data retrieved from numerous cores drilled in the entire basin, DP-EC logs collected at key sites and detailed micropaleontological analyses.

Figure 2 shows a transect of four DP-EC logs and associated sediment cores (ALP 73A, ALP 54A, ALP 16A and ALP 67A) located in the Makrisia Basin. The highlighted sections represent limnic sedimentary facies identified by significantly increased EC values related to fine-grained silt-dominated sediments. Micropaleontological analyses allowed further characterization and subdivision of the limnic sequences. Based on the occurrence and distribution of ostracod species, we are able to differentiate between different ecological conditions. In fact, periods of freshwater conditions, eutrophic conditions with significant

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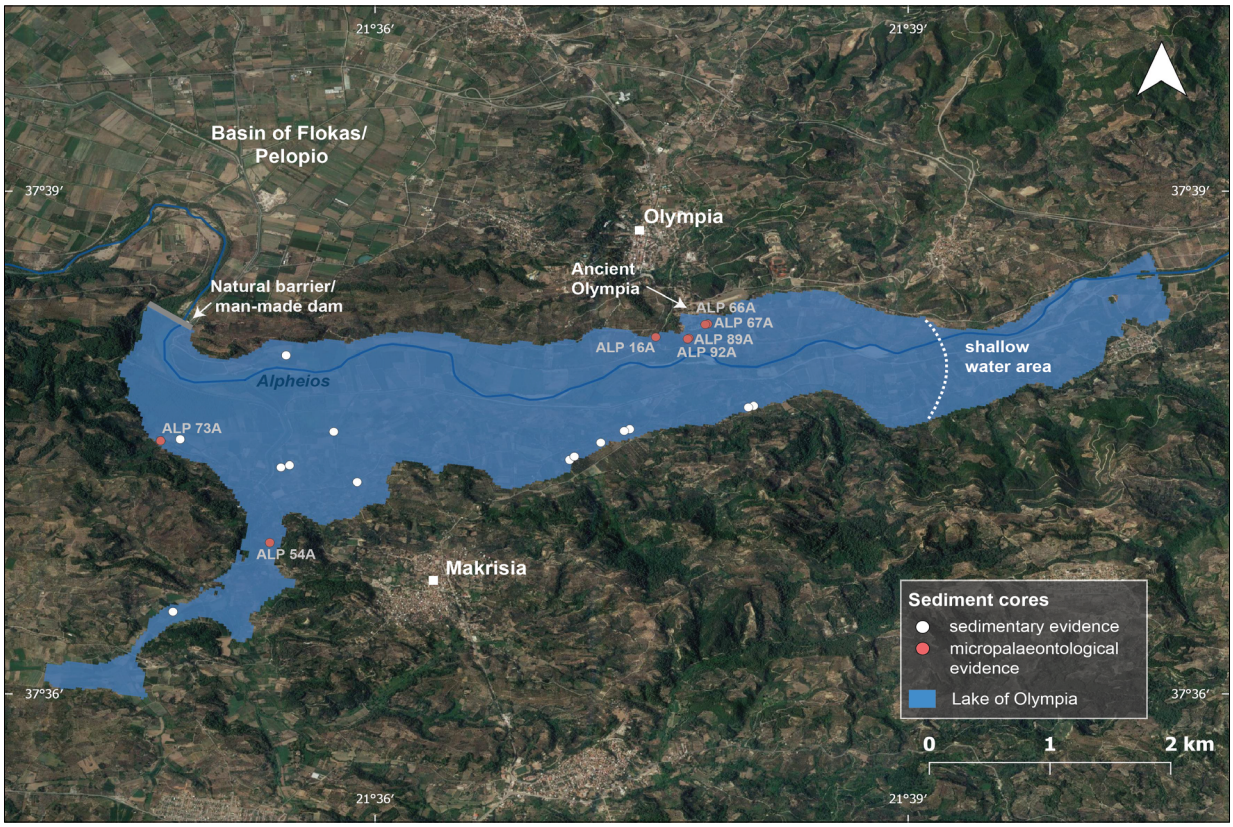

Fig. 3: Reconstruction of the extent of "Lake of Olympia" based on sedimentary (coring sites marked in white) and micropaleontological evidence (coring sites marked in red) (base map: Google, ©2023 CNES/Airbus, Landsat/Copernicus, Maxar Technologies).

freshwater input and strongly eutrophic conditions were identified.

Summarized results of the ostracod assemblage found for sediment samples from core ALP 67A are presented in Table 1. Ostracod species are separated into freshwater, brackish, and marine species depending on their preferred habitat. Based on the distribution of ostracods, the depositional sequence can be divided into five sedimentary facies. Three of these facies provide evidence of stillwater: facies II, facies IV and facies V. In facies II, freshwater species dominate; brackish to marine specimens occur only intermittent and in small numbers most probably brought in by birds. Within these facies, a high abundance and an increased diversity (number of different species) are discerned. The abundant freshwater species (e.g., *Candona* spp., *Ilycyprisbradyi*, *Limnocythereinopinata*) prefer stagnant or slow flowing water as habitat (Meisch 2000). In contrast, in facies IV, the brackish water species *Cyprideistorosa* is dominant and indicating strongly eutrophic conditions. Abundance is slightly reduced and diversity is low within these samples compared to facies II. In facies V, the total number of ostracods and their diversity are increased and freshwater species occur again; still, the samples are dominated by *Cyprideistorosa*. In facies I and III, both the total number of individuals and the diversity are significantly lower (no sample with > 1 different species). Based on sedimentological parameters, these facies are assigned as fluvial/colluvial deposits (facies I) and infill (facies III), respectively. Similar findings were found for other sediment cores (Fig. 3).

Based on sedimentary evidence from DP-EC logs, sediment cores and results of multi-proxy analyses in combination with the given topography, it is assumed that the maximum extent of the "Lake of Olympia" covered an area up to 6 km long and up to 2.5 km wide (Fig. 3). In Figure 3, coring sites marked in white provide sedimentary evidence of the lake, while coring sites marked in red provide additional microfossil evidence. However, the reconstructed scenario is based on the present-day terrain model and does not consider the tectonic activity in the area.

Based on radiocarbon data, the "Lake of Olympia" existed from the 8th/7th millennium BC until, at least, the

1st century AD. Hence, the lake period coincides with the use of the ancient site of Olympia as venue for Panhellenic Games. Preliminary results further show that the lake was repeatedly subject to massive changes of the lake level. This seems associated with phases of blocked discharge at the narrow breakthrough through the Drouva Ridge and subsequent catastrophic draining events forming, among others, the Olympia Terrace. The existence of a large waterbody next to the cult site of Olympia has considerable historical, archaeological and geographical implications. For example, it may be assumed that the "Lake of Olympia" was used as a waterway to reach Olympia and to provide adequate water supply. During summer months the visitors of the ancient Olympic Games used earthen cisterns that were fed by lake-controlled groundwater. The large cattle herds that were needed as supply for food and sacrifices may have grazed along the lakeshores and in shallow lake areas. Furthermore, shallow water conditions at the eastern fringe of the "Lake of Olympia" may have allowed the Alpheios River to be crossed by foot.

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2

ALBERT HESSE MEMORIAL

Albert Hesse: life and work (1938-2022)

Alain Tabbagh [1*], Michel Dabas [2], Christophe Benech [3]

1 UMR 7619, Métis, Sorbonne Université, CNRS, EPHE, Paris, France
2 UMR 8546 AOROC ENS, CNRS, Paris, France
3 UMR 5133 Laboratoire Archéorient, Maison de l'Orient et de la Méditerranée, Lyon, France
* Corresponding author: E-mail: alain.tabbagh@sorbonne-universite.fr

Abstract
Albert Hesse was one of the pioneers in archaeometry in France. He has developed the electrical methods, and more specifically the continuous electrical surveying methods and focused very early on urban archaeology and geophysics. This paper focusses on his work, showing specific interactive maps to highlight the position of his different surveys world-wide.

Keywords
archaeological prospection; archaeometry; earth resistance methods; electrostatic; statistics

Introduction

Summarizing Albert Hesse's life is not an easy task. Several obituaries have already been published in the different associations and places where he has worked and left an important contribution for the development of geophysical methods: ISAP (https://www.archprospection.org/albert-hesse/), GMPCA (https://gmpca.fr/actualites-de-l-archeometrie/71-actualites-de-l-association/1719-albert-hesse-nous-a-quittes-le-2-juillet-2022), CEA in Egypt (https://www.cealex.org/evenement/hommage-a-albert-hesse/) and ENS (http://www.archeo.ens.fr/Hommage-a-Albert-Hesse.html). He is for everybody of us the pioneer for the introduction of geophysical methods in archaeology in France in the 60s. His two first books: "Prospections géophysique à faible profondeur; applications à l'archéologie" (Dunod éd. 1966) and the "Manuel de prospection géophysique appliquée à la reconnaissance archéologique" in 1978 remain important milestones in his career and reference books for all of us, even if more up to date manuals have been published since.

Resumé of his life (from ISAP Newsletter65)

Albert was born in Casablanca and lived in Morocco during his childhood and adolescence. After his baccalaureate graduation (1956) he moved to his homeland to follow an engineering cursus at the "Arts et Métiers" higher education school from which he graduated in 1960. By the end of this cursus, he met Professor André Leroi-Gourhan who guided him to archaeology. Following the teachings of Professor Louis Cagniard, he chose near surface geophysics applied to archaeological prospection and was recruited by CNRS in October 1960. From October 1963 to March 1965 he did his military service in the Navy and followed this up as reserves officer in marine mines detection. He became "Docteur-Ingénieur" in 1964 and was the founder of the discipline of archaeological geophysics in France. He continued with this subject throughout his career in the CNRS, including at the "Centre de Recherche Géophysique" in Garchy (Nièvre) where he was director of the laboratory from 1982 to 1988. He retired by the end of 1999.

His commitment in scientific organization was substantial and constant:

- Supervised ten PhD thesis and taught archaeological prospection methods at University Paris 1 from 1980 to 2000.
- Organised student exchanges between Garchy and the University of Bradford (UK) from 1977 to 1988.
- Founding member (1976), general secretary (1976-1980) and President (1980-1987) of the GMPCA (initially "Groupe des Méthodes Physiques et Chimiques de l'Archéologie" and later "Groupe des Méthodes Pluridisciplinaires Contribuant à l'Archéologie").

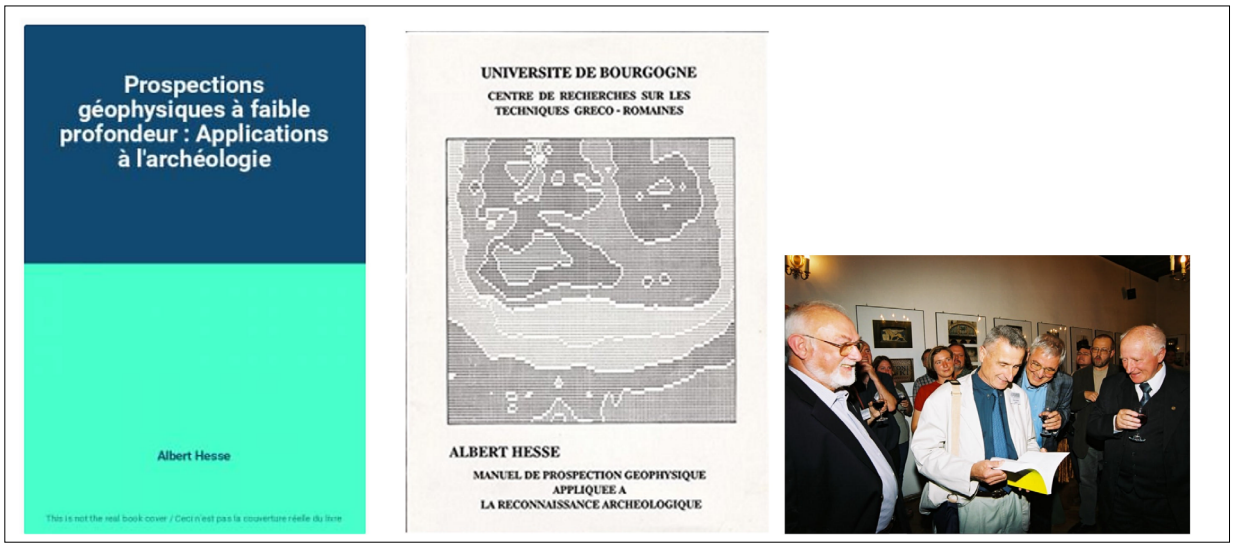

Fig. 1: Front pages of the reference book written by Albert Hesse. Himself at the center of the picture.

- Member of the Standing Committee of the Archaeometry International Symposium from 1980 to 1999.
- Member and Secretary (1997) of the Pre and Proto-History section of the "Comité Technique des Travaux Historiques et Scientifiques" (CTHS).
- Associate Editor of Archaeometry (1993-1998) and of Archaeological Prospection (1994-1999).
- Member of the editorial board of the French journals "Paléorient", "Revue d'Archéométrie" and "Histoire et Mesure".
- Member of the scientific council of Mont Beuvray from 1985 to 1990.
- ISAP founding member (2003) and then honorary member (2004).

Contribution

His scientific approaches covered archaeometry as a whole. He always intended to introduce measurements to quantify observations, probably as a consequence of his theoretical background as an engineer of Arts et Métiers - see for example his dissertation about the uncertainties in electrical methods in his 1966 book or his article about "Count or Weight? Absolute or relative values?" (Hesse 1999). For him, archaeological prospection was a synthetic approach not limited to geophysical investigations (which provide information about the buried features), but also using surface and aerial observations (cf. his work with kites with B.-N. Chagny in Saï or the sherds counting in Turkey for the location of amphorae production), statistical analysis of the spatial distribution of remains (his sister was a mathematician), document studies (cf. his work for the Heptastadium in Alexandria), ….all things now facilitated by the use of GIS. He was from a generation which was not using computers at the beginning but was able to draw isocurves maps manually and has always thought about the meaning of each measurement taken in the field (generally written on a piece of paper). This distance from the computers and their stammering introduction into archaeological geophysics made him reluctant to new technologies at first, but has helped understanding how and which measurements should properly be taken into consideration. A philosophy of sparsity, we could summarize nowadays in a period of massive acquisition of data. Those who had the chance to work with him in the field have taken advantage of this teaching. Another point I also learn (MD) from him is to always look in other directions than the one the archaeologist is asking you (the site is there, OK, but what is behind you?). This vision has proved to be very useful in lot of situations. The last important point I learned was that (geophysical) measurements was one thing, but all other clues have to be included to solve a problem. One of these, was to consider the whole landscape and even to feel it barefoot! Painting was one of his passions which probably helped him in understanding a landscape.

As an exploration geophysicist (or we prefer the term surveyor), he chose to work on a large variety of chrono-cultural areas, at first in the Eastern Mediterranean,

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Fig. 2: Albert Hesse painting in Alexandria (Egypt).

Near and Middle East and Egypt, but also in India, Java, Mexico, Honduras, West Indies, Burundi … and Europe. These projects were carried out within the framework of 'French abroad missions' and were of high scientific and human interest. However, his efforts to convince the metropolitan archaeology decision–maker to invest in prospecting methods were less fortunate. So that he wrote in1998: "Who can believe that everything can be detected and is readable by shovel trenches, while there exist numerous examples of identification by measurements of features that were not evidenced by excavations?"

We have developed with a GIS, a list of all places where he has made reports and/or publications (with their hyperlinks for download).

The laboratory of Garchy was the perfect place to develop the geophysical methods for archaeology: direct access to large fields where artificial features have been buried (but also real archaeological features in a close vicinity), a "dream" team (AT for the theoretical developments, Jeannette Tabbagh for computing and Alain Jolivet for mechanical and electronic design) and finally the possibility to host lot of students in a remote place with all facilities. Knowing his hospitality, lot of students from different part of the world and especially from Bradford University have benefited from this situation.

His major contributions to the development of geophysical techniques were related to earth resistance methods that are very simple in their principles and robust against the different sources of noise. He proposed solutions to overcome climate influences, to correct for anisotropy effects resulting from the orientation of current lines, and overall urged the development of designs for the use of continuous measurements while profiling. Several systems based on specific resistivity meters developed in Garchy (RMCA designed by A. Jolivet) were tested from the first one behind a small tiller or later on by a tractor. In 1995

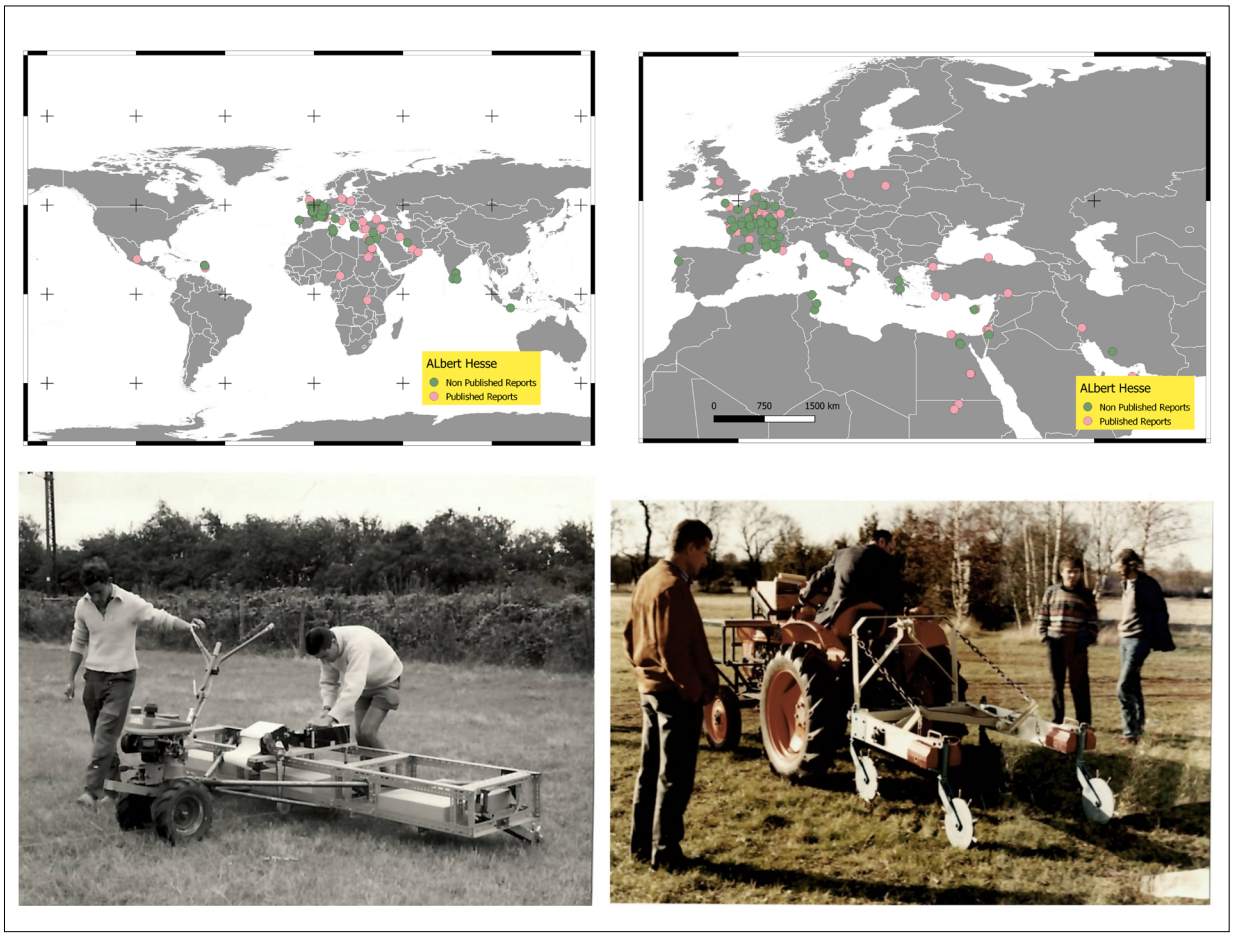

Fig. 3: Locations of the surveys achieved by Albert Hesse throughout the world (top left) and zoom in the Euro-Mediterranean area (top right). Resistivity measurements while moving: in line Wenner system in 1964 (left bottom), and the RATEAU square array prototype (right bottom) with Alain Jolivet, Michel Dabas and Georges Ducomet (1987).

at Wroxeter (England), a hand-towed (and home made by Albert) cart was designed to measure continuously the electrical resistivity in a pole-pole configuration. The system proved successful (Dabas et al. 2000) and was very light. It fulfills the main wish of Albert to survey with the minimum weight and size system!

Beyond archaeology, the resulting technical progress even met a fruitful application in precision agriculture with the very heavy duty systems designed by Geocarta (ARPs). Albert has had indeed a strong interest in soil science and established very early cooperation with research institutions in this field (INRA, Institut National de Recherche Agronomique). Every geophysicist knows that detectability of archaeological targets is a result of the contrast in physical properties between the target and its surrounding, the soil in Archaeology. Albert has understood very early the importance of soil.

The use of geophysical techniques in urban contexts was one of his major interests since the beginning of the 70s. First limited to the earth resistance technique it was later supplemented with two complementary methods, the electrostatic one which is an extension of the resistivity technique and ground penetrating radar (GPR).

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A complete list of his publications (62 in total) can be found here: http://www.archeo.ens.fr/IMG/pdf/bibliographie_albert_hesse-added-md.pdf

Also interactive maps can be found here: www.chronocarto.eu

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3

MARINE AND WETLAND PROSPECTION

Prospecting in the marshland: the Sumerian city Fara-Šuruppak (Iraq)

Jörg W.E. Fassbinder [1*], **Sandra E. Hahn** [1], **Marco Wolf** [2]

1 Geophysics Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität (LMU) München, Munich, Germany
2 Institute of Near Eastern Archaeology, Ludwig-Maximilians-Universität (LMU) München, Munich, Germany
* Corresponding author: E-mail: fassbinder@geophysik.uni-muenchen.de

Abstract
Fara-Šuruppak was a major Sumerian city of the third millennium B.C. By magnetometer prospecting we discovered and traced a casemate city wall that enclosed the city. On the west bank of the Euphrates river we identified a large harbour complex of Fara-Šuruppak. The magnetogram revealed the existence of channels, a bridge, hydraulic constructions and agricultural fields.

Keywords
data interpretation; Fara-Šuruppak; magnetometer prospection; mudbrick features; Sumerian city

Introduction

Fara-Šuruppak, situated along one of the ancient river courses of the Euphrat in south-central Iraq, dates back to the Jemdet Nasr period around 3000 BC with a continuous occupation until the end of the Ur III period around 2000 BC. Besides Eridu, Kish, Uruk, Ur, Nippur, Umma, Lagash and Larsa, to name only a few, Fara-Šuruppak was among the most prominent city-states of Sumer. Šuruppak is named as the seat of the last dynasty before the Flood in the Sumerian King List. Its mythical king is said to have built a ship ("Noah's Ark") to evacuate his people. First explorations and excavations were undertaken under the direction of Walter Andrae by the Deutsche Orient-Gesellschaft in 1902 and 1903 (Heinrich and Andrae 1931). In 2017, the Institute of Near Eastern Archaeology of the LMU-Munich started the "Fara Regional Survey Project (FARSUP) (Otto et al. 2020) in cooperation with University Al-Qadisiyah (Abbas Al-Hussainy). Magnetometer prospecting was commenced in 2018 and continued in 2022. The site is devoid of vegetation and thousands of deep looting pits cover the majority of the mound. We therefore focused our magnetometer prospecting on a few selected areas on the mound and the less looting-affected outskirts of the city. The highlights of the survey so far are the discovery of the city wall, evidence of a large harbor complex, traces of ancient agriculture, watercourses and a bridge, among others. The revealed layout of a unique building complex in the center of the mound, likely a temple, complements the ancient excavations by Walter Andrae (Hahn et al. 2022).

Approach

The pear-shaped tell of Fara-Šuruppak is nowadays extremely destroyed by the thousands of looting pits. Large trenches, up to 900m long, 5m wide and still up to 3 m deep, are the remains of Walter Andrae's excavations in 1902/03, intersecting the tell into several areas from east to the west. The survey was conducted with total field cesium-vapour magnetometers in uncompensated "duo sensor" configuration with the Scintrex SM4G-Special and the Geometrics G858 magnetometer. As with geophysical survey at similar locations of Mesopotamia e.g. Uruk (Fassbinder et al. 2005; Becker et al. 2019), Larsa (Darras et al. 2021) or Charax-Spasinou (Lambers et al. 2019), the sites are not only difficult to access, but one also has to cope with a soft and sometimes muddy ground. Large-scale prospecting by a wheeled devised system or with a motor-

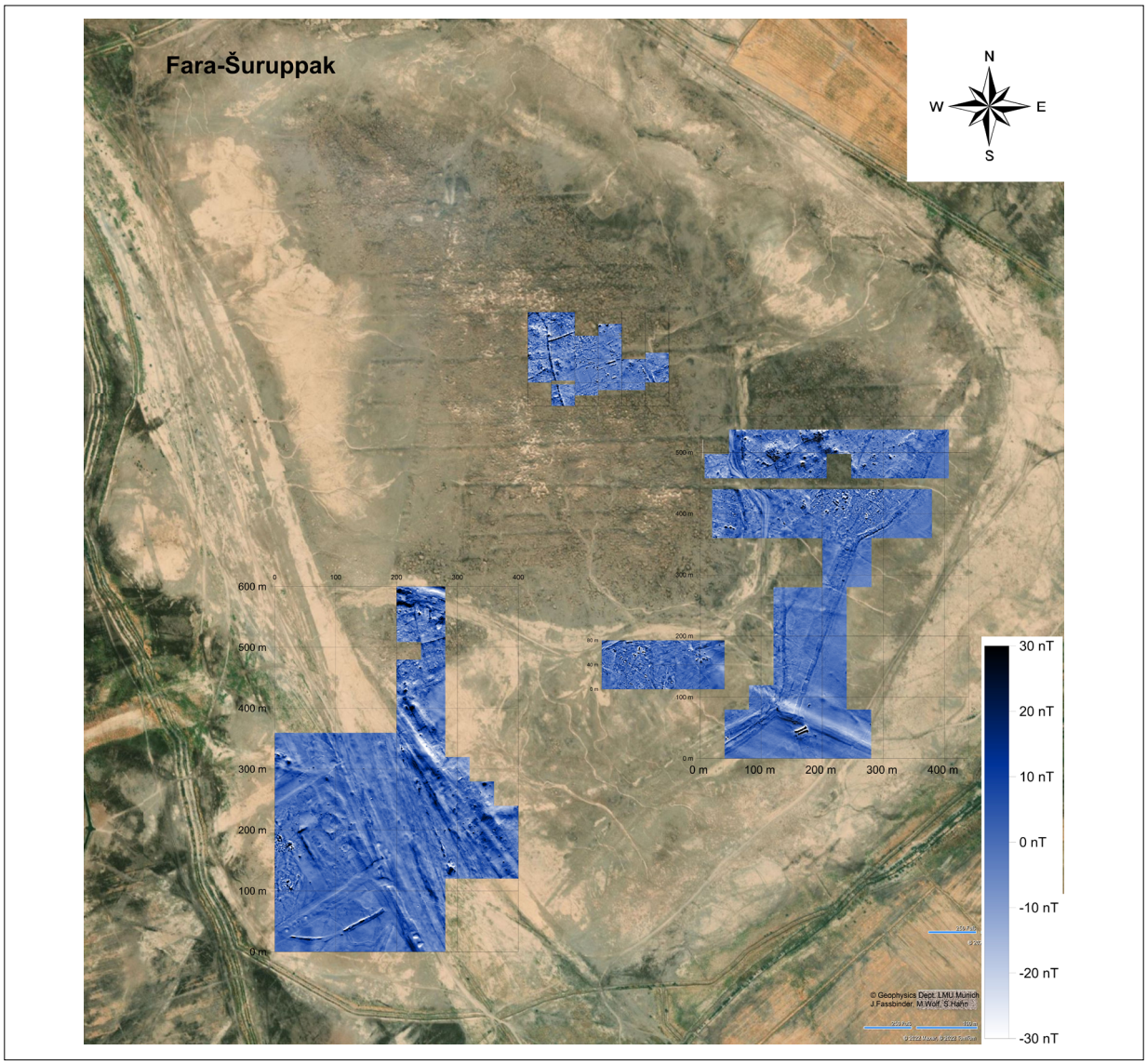

Fig. 1: Fara-Šuruppak. Satellite image of the mound (dark brown) and the adjacent area with the outskirts and ancient river courses fused with the magnetogram image (blue). (base map: Google, ©2023 CNES/Aibus, Maxar Technologies).

ized vehicle is utterly impossible. Driving off-road, particularly on footpaths, is unfeasible or would severely damage the archaeological site. Except from a partially solidified area in the center of the mound, we therefore first concentrated our survey first on the lower and flat area of the site.

Results

The first important finding of our magnetometer survey was the indisputable proof of the existence of a city wall. With the results of 2018 – 2022, we were able to trace its remains on a length of ca. 900 m (see Figs. 1-3). The wall, up to 12 m wide, resembles a casemate wall (Fig. 2), which is very similar to some sections of the city wall in Uruk. So far, we have not yet found a city gate. In the east, next to the city wall, we detected traces of an ancient agriculture fields, intersected by dams and an extremely high magnetic anomaly, probably of a bridge or a sluice, similar to the finding of the French prospecting team in Larsa (Darras et al. 2021). Between the elevated part of the mound and the lower plain, we were able to trace city quarters, shapes of houses and a canal separating the area to the east and south from the main mound. Roads, pa-

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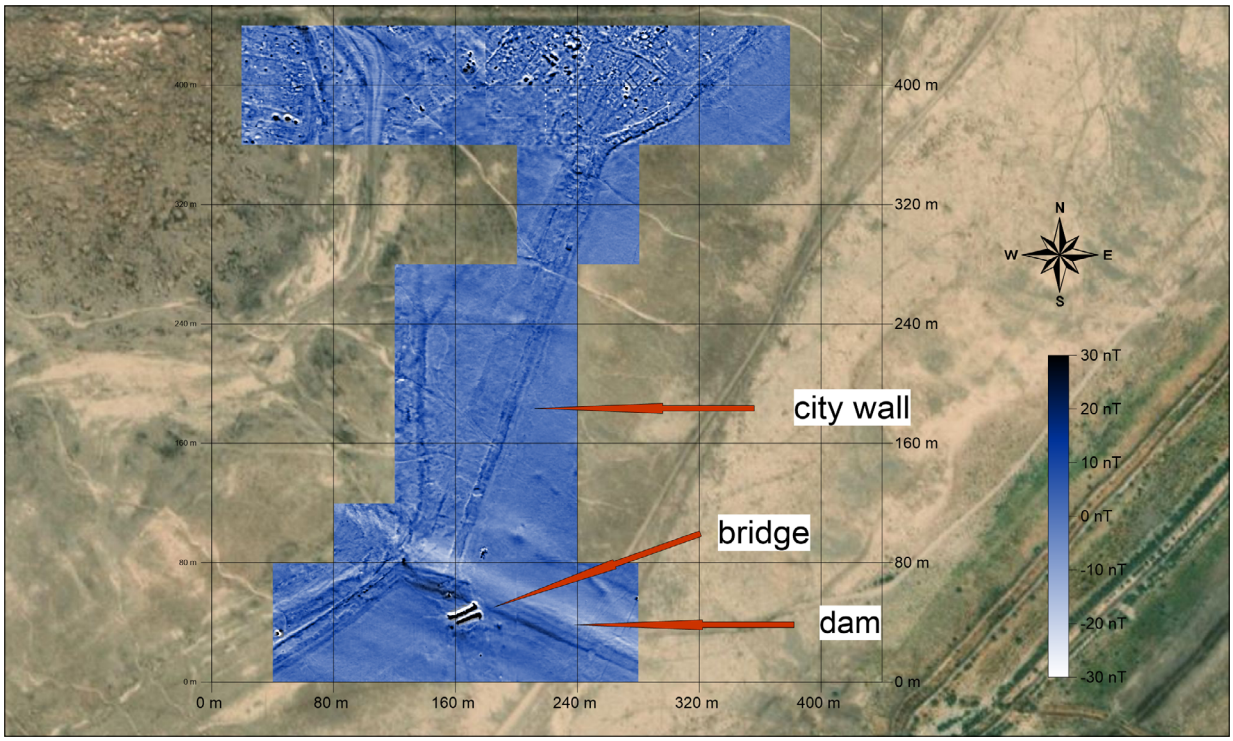

Fig. 2: Fara-Šuruppak. The South East survey area covers a large section of the city wall; outside we detect agricultural fields, dams, as well as one of Mesopotamia's rare bridges (base map: Google, ©2023 CNES/Aibus, Maxar Technologies).

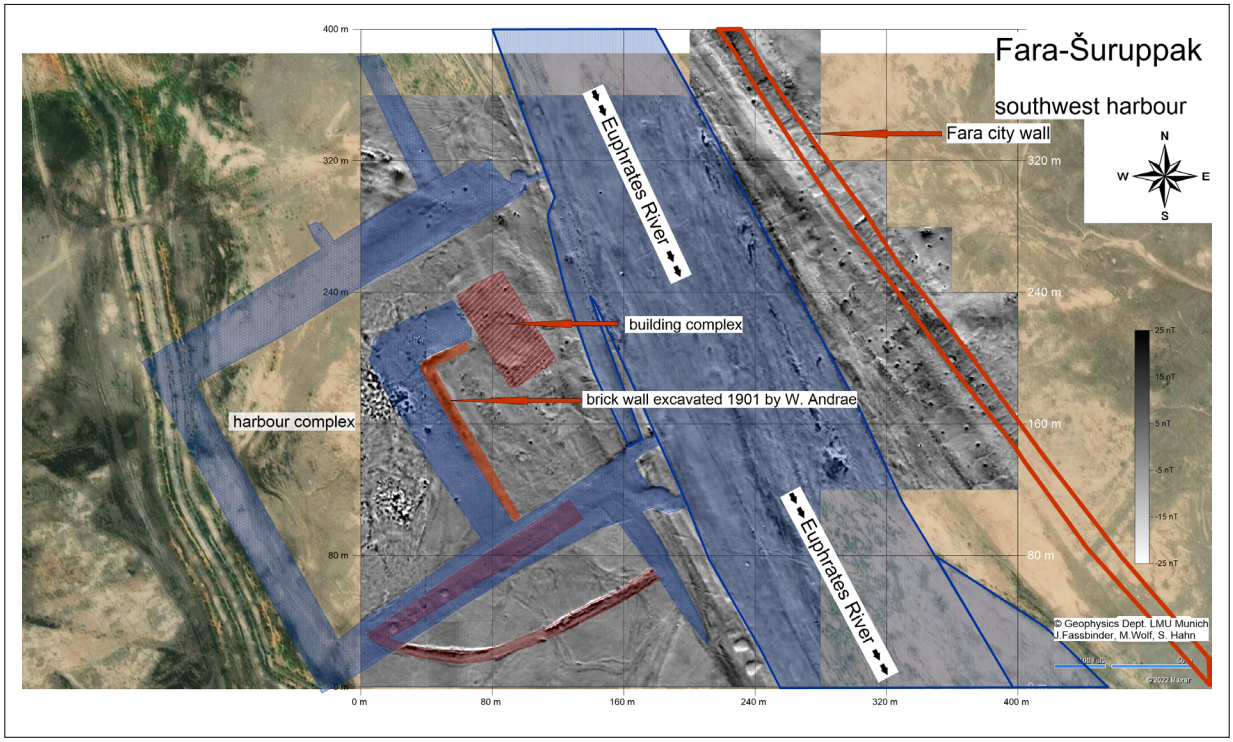

Fig. 3: Fara-Šuruppak. Opposite the western part of the city and the ancient Euphrates River locates the harbour. Canals, dams and hydraulic features enclose the port itself; a massive wall, probably quay boarders the T-shaped harbour basin in the center (base map: Google, ©2023 CNES/Aibus, Maxar Technologies).

thways and towpaths along the main channel are characterized by their linear positive (dark) anomalies.

On the west bank of the ancient Euphrates palaeochannel branch we find a large elevation of about 200x250 m, which is enclosed by canals and connected to a T-shaped basin in the center of the area to the south (Fig. 3). Andrae's excavation unearthed here a massive wall but could not explain its function. The magnetogram image reveals that this wall very probably belongs to the quay of an inland harbour.

Discussion

Archaeological prospecting in the sediments and old marshes from southern Mesopotamia offers a thankful field for the application of magnetometry and Earth Resistivity Tomography (ERT) (Parsi et al. 2018). Sundried mudbricks, sometimes tempered by pottery shirts or fired bricks, provide a high-contrasting magnetogram image and dynamics of $> \pm 30$ nT compared to the total field. In addition, the remains of riverbeds and canals as well as the ancient agricultural fields leave clear traces in the magnetic image.

Conclusion

The salient characteristic of the sites and cities in southern Mesopotamia is the environmental conditions under which they were build. Contrary to what the numerous results of magnetometer prospection at other archaeological sites in wetlands and marshes around the world might suggest, the majority of building constructions, mainly made from sundried mudbricks, the ancient river courses, the Euphrates River, canals, sluices, hydraulic constructions and traces of ancient farming provide us with an extraordinary magnetic contrast for successful prospecting. Excavations of channels, watercourses or large hydraulic constructions would be not only a time-consuming, expensive and unattractive approach for archaeologists but are also not in the focus of traditional digs. Archaeological geophysics, particularly magnetometry, is therefore an even more important tool, as it provides indispensable contributions to the general understanding of the organization and infrastructure of such sites.

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Seismic imaging of medieval dike remains in the Wadden Sea (North Frisia, Germany)

Bente Sven Majchczack[1*], Jan Philipp Schwarz[1], Dennis Wilken[1], Klaus Ricklefs[2], Wolfgang Rabbel[1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Research and Technology Center Westcoast, Kiel University, Büsum, Germany
* Corresponding author: E-mail: bmajchczack@roots.uni-kiel.de

Abstract
Dikes protected cultural lands along the Wadden Sea coast in medieval North Frisia. Remains of dikes must be found to reconstruct the drowned and lost landscapes. Certain imprints in sediment layers due to former load can be linked to eroded dikes. Sediment echosounding provides sections of these imprints and reveals dike courses. Medieval dikes have been traced at Hallig Südfall and south of Sylt.

Keywords
dike; Middle Ages; sediment echosounder; tidal flats; Wadden Sea

Introduction

In the study area (Fig. 1) of the North Frisian Wadden Sea (Germany), we investigated the remains of medieval dike systems in the tidal flats sediments using marine reflection seismics (sediment echosounder, SES).

Dikes and terp settlements were built in North Frisia from the 12th century onwards to protect newly colonized marshland from the North Sea (Meier 2004). Severe storm floods of the 14th century led to breakage of dikes. Large parts of the cultural landscape were inundated and turned into tidal flats (Hadler et al. 2021). Research of the 1920s discovered occasionally exposed remains of a dike with tidal gates, drainage systems and terps in the area of Hallig Südfall (Busch 1923). An initial study (Wilken et al. 2022) revisited this site to test geophysical prospection methods in the tidal flats. Although the dike remains recorded in 1921 were eroded thereafter, it was possible to trace the dike by magnetic gradiometry and image its characteristic imprint in the underlying sediments through marine reflection seismics. This imprint represents a known phenomenon already visible on the original dike remains (Busch 1936).

In the study presented, we probed SES data collected primarily for geological investigations in the same area for similar imprints to identify the further course of the dike and possibly other, unknown dike systems in the larger North Frisian tidal flats.

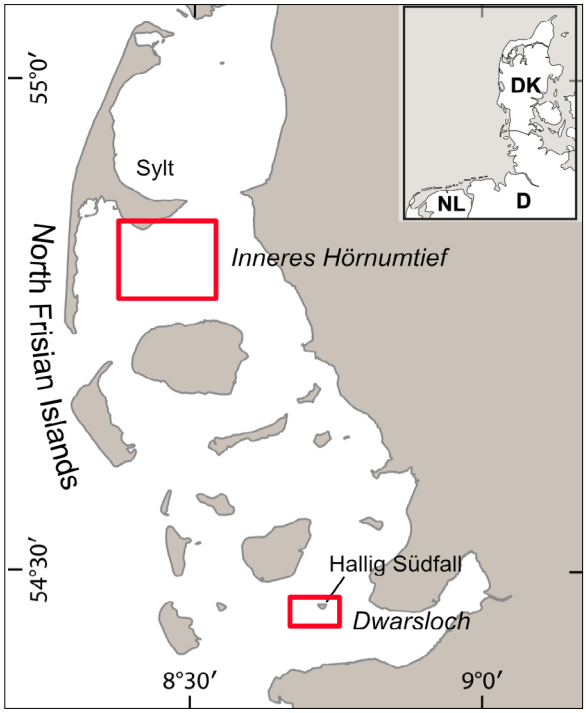

Fig. 1: Map of the North Frisian Islands (Germany) with outline of the two case study areas of the Dwarsloch tidal channel near Hallig Südfall and the Inneres Hörnumtief tidal channel near the island of Sylt.

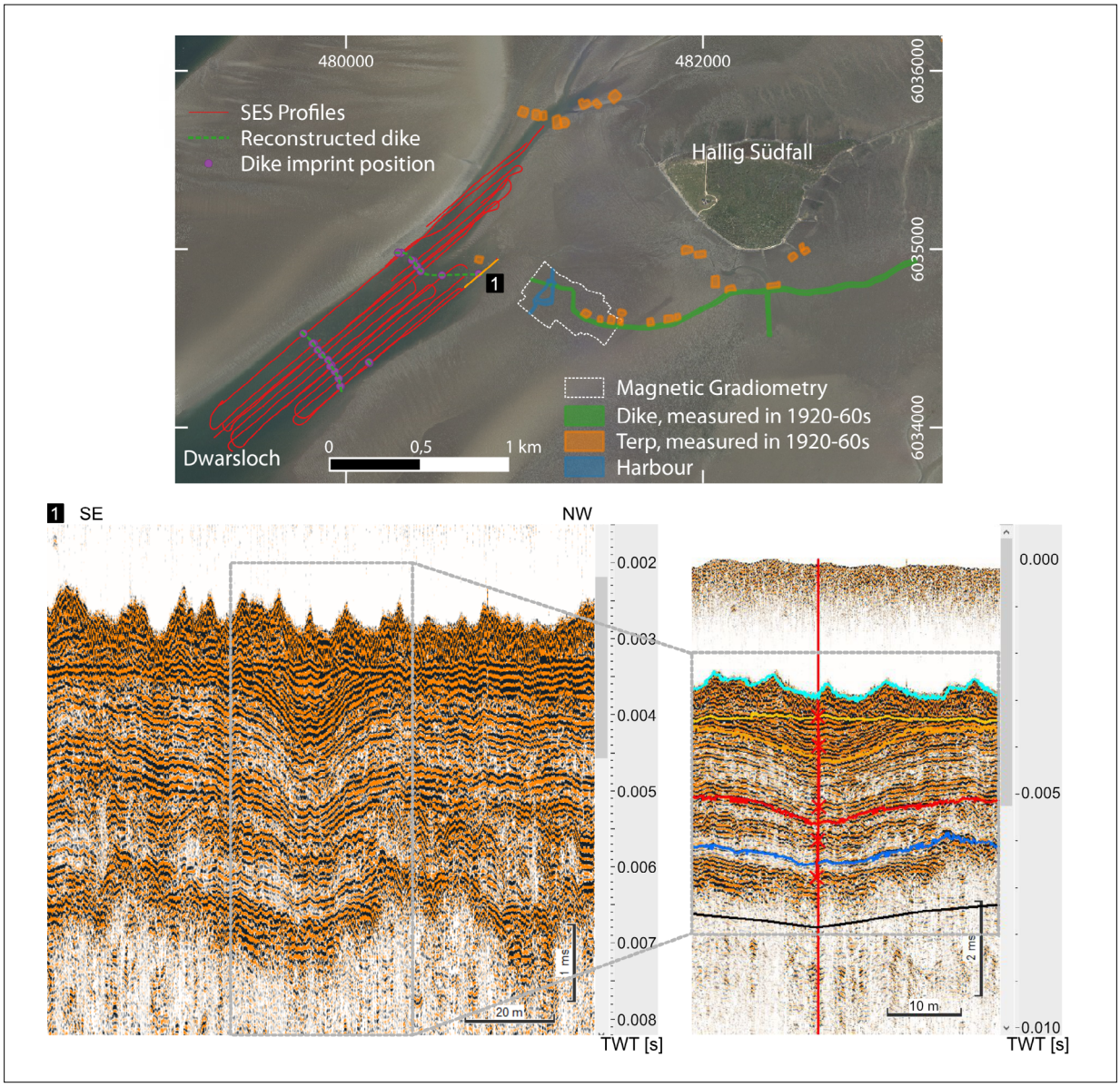

Fig. 2: Above: Aerial picture of Hallig Südfall (district of North Frisia, Germany) with drawing of dikes and terps as seen and measured in the 1920-60s and in magnetic gradiometry data (from Wilken et al. 2022), as well as sediment echosounder profiles in the Dwarsloch tidal channel with markings for dike imprints in the profiles and dashed outline of the newfound dikes. Aerial picture: LKN Schleswig-Holstein, 2018. Below: Seismic profile measured in the Dwarsloch with characteristic dike imprint. To the right, the profile section with the dike imprint is enlarged with reduced vertical exaggeration and drawing of discernible reflecting horizons.

Materials and methods

In the initial study, we used a high resolution two-channel SES with a center frequency of 4 kHz and a theoretical vertical resolution of about 0.1 m, positioned by RTK-DGNSS (Wilken et al. 2022). The SES data collected by K. Ricklefs in 2018-2021 in the tidal channels Dwarsloch southwest of Hallig Südfall and Inneres Hörnumtief southeast of Sylt used an INNOMAR2000 SES with a secondary frequency of 6 kHz and RTK-DGNSS positioning. The raw data was converted to the 16 bit SEGY data format and analyzed with Kingdom2018. The theoretical vertical resolution is 0.05 m, a maximum depth penetration of 15-20 m was reached in the Dwarsloch and 10-15 m at Hörnumtief. Both tidal channels were covered with long parallel profiles with a spacing of 50-100 m.

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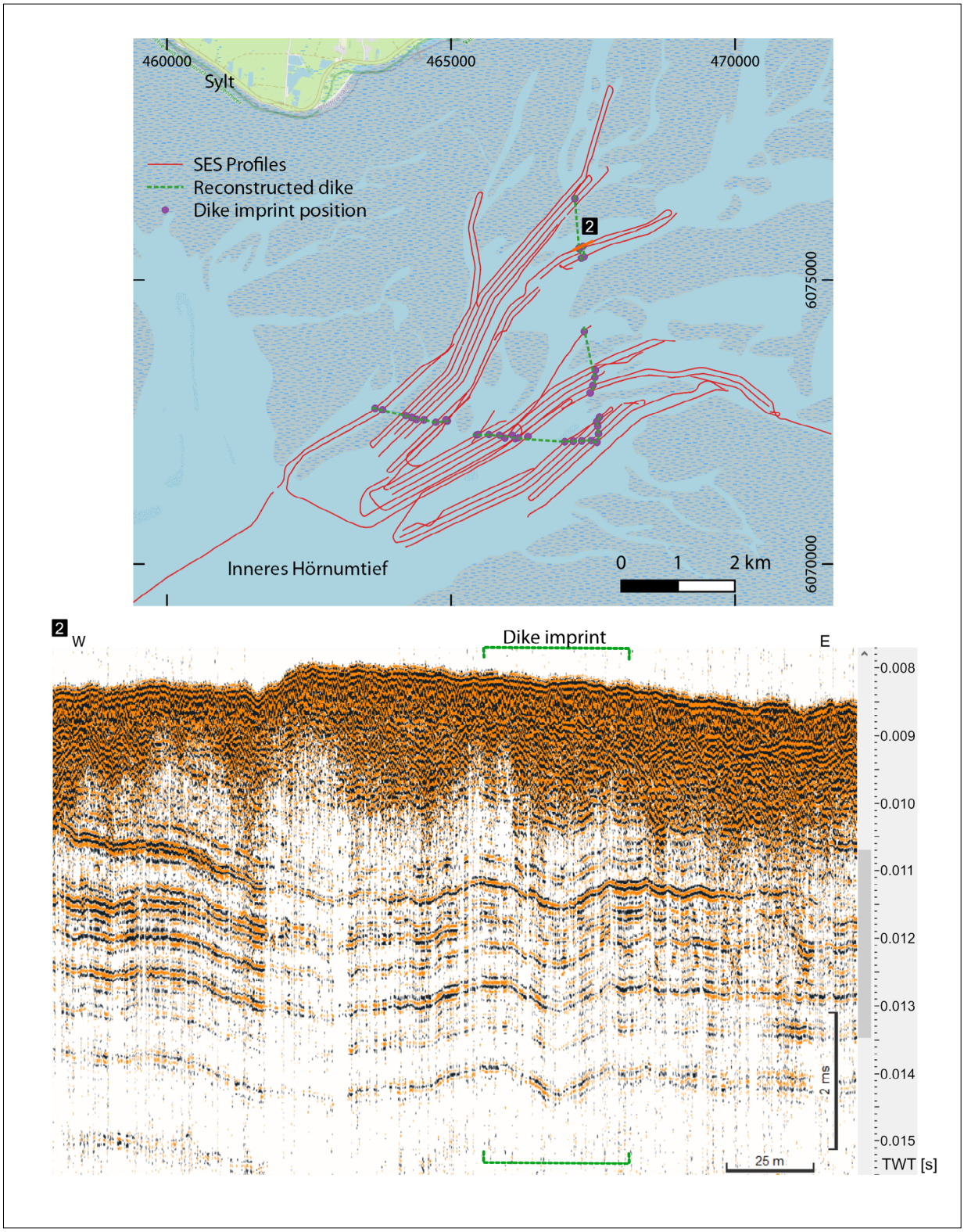

Fig. 3: Above: Map of the Inneres Hörnumtief tidal channel south of the island of Sylt (district of North Frisia, Germany) with drawing of sediment echosounder profiles, markings for dike imprints in the profiles and dashed outline of the newfound dikes. Map data: OpenStreetMap. Below: Seismic profile measured in the Inneres Hörnumtief with characteristic dike imprint.

The characteristic dike imprints derive from the pressure distribution underneath the original dike, leading to compression and deformation of the underlying sediment. The width of the imprint increases from shallow to deeper layers, while the imprints' height (of the deformation in regard to the overall course of the reflecting layer) decreases, therefore the dike imprints are only detectable in the upper 10 m of the stratigraphic sequence. This pattern distinguishes the dike imprints from geological features such as backfilled tideways. Dike imprints can only be found in pre-medieval, not redeposited layers, which can be clearly distinguished from younger tidal flat sediments. The SES profiles are screened visually for these characteristic structures. To gain a confident interpretation, possible dike imprints have to be aligned and found in at least five parallel profiles.

Results

The SES profiles measured in the tidal channel Dwarsloch lie parallel in extension to the measurements of the initial study (Fig. 2) and show a stratigraphy that can be matched with corings from the adjacent area (Wilken et al. 2022). The transition between young tidal flat sediments and pre-medieval, laminar strata is distinctive. In extension to the course of the previously recorded dike, all SES profiles show equally comparable dike imprints, describing a course towards the west with a bend to the northwest. In the upper layers, the maximum dimensions of the symmetrical, rounded imprint are 37 m in width with a depth of 27 cm, which is comparable to the initial study (Wilken et al. 2022).

A second row of dike imprints was found approximately 730 m further to the southwest. This previously unknown dike course ran roughly parallel to the south of the late medieval dike line in a northwestern-southeastern direction, indicating the existence of a younger polder seaward.

In SES profiles along the branches of the tidal channel Inneres Hörnumtief (Fig. 3), a number of structures have been found with striking resemblance to the dike imprints found in the Dwarsloch, albeit the conditions are not ideal with less visible original laminar layers and more redistributed sediment. Fewer parallel profiles were measured and higher boat speed und waves caused some noise. Possible dike imprints are found at 32 positions, but only few are clearly distinctive. Nonetheless, the confident imprints do align to an angled dike course. Best results are obtained in the northeastern, shallow parts channel branches with evidence of a north-south running dike. The dimensions of the imprints are comparable to the medieval dikes measured in the Dwarsloch.

Discussion

Seismic sounding on the confirmed archaeological site of a late medieval dike has shown that dike imprints can be measured in the subsurface. Starting from there, it was possible to find similar structures in further SES data. The known dike course could thus be extended, providing new evidence for the reconstruction of the medieval cultural landscape. But when screening further SES data, it is very hard to find confident imprints: the data quality is often poor due to noise from deeper waters or stronger engine thrust against the tide; many natural depressions appear as dike imprints; possible imprints do not recur in parallel profiles. Nonetheless, screening for possible dike imprints without a presumption based on archaeological data resulted in the case of the Inneres Hörnumtief. Upon further research, the newfound possible dike course fits well to existing medieval dike remains on Sylt and might resemble the unknown course of the Stinum-dike, which is believed to have been destroyed in 1362 (Kühn 1989).

Conclusion

The application of SES in the tidal flats and channels of North Frisia provides a useful method to track eroded medieval dikes along their imprints. The necessary preconditions are a suitable, undisturbed stratigraphy without deep erosion, a high resolution, several parallel profiles and calm conditions for measurements. Tracking dike courses from a known structure as a starting point is helpful to gain a high confidence for an interpretation as an anthropogenic structure in contrast to backfilled channels. In the cases of Dwarsloch and Inneres Hörnumtief, it was possible to track medieval dikes, which were previously only known in general, but not in their exact course and extent.

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Underwater geophysical prospection in ancient Olous, Crete

Dimitrios Oikonomou [1*], Angelos Plageras [1], Nikos Papadopoulos [1], Kleanthis Symirdanis [1], Gianluca Cantoro [1], Athanasios Argyriou [1], Meropi Manataki [1], Christos Polykretis [1]

1 Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranean Studies, Foundation for Research and Technology, Rethymno, Greece
* Corresponding author: E-mail: doikonomou@forth.ims.gr

Abstract
We employ electrical resistivity tomography and magnetic gradiometry methods to the ultra-shallow submerged and littoral archaeological site of Olous. This allows reconstruction of the built environment that nowadays lie below the sea bottom, thus completing the respective archaeological evidence.

Keywords
ancient Olous; archaeological prospection; ERT; multisensor magnetic gradiometry; shallow marine and littoral geophysics

Introduction

Elounda is located on the eastern coast of Lasithi, Crete, near the regional capital of Agios Nikolaos. Archaeological findings in ancient Olous attest to the fact that the area was inhabited at least since the Archaic period. Minoan tombs have been found in the wider area, while recovered scriptures from Hellenistic times reveal the existence of a great harbor city during that time expanding in the Isthmus region that connects the Kolokytha peninsula with Elounda Bay (Apostolakou et al. 2009). A significant part of the city lies nowadays under water since the isthmus was narrowed due to sea levels variations. Previous geophysical investigation in the area (Symirdanis et al. 2016) showed promising results and useful information about the efficiency of the electrical resistivity tomography in locating submerged archaeological remains.

The geophysical survey was focused on the shallow part of the sea and the littoral area of Schisma Eloundas. It was carried out during in a period of time between the summer of 2019 and the winter of 2022. The main target of the investigation was the mapping of buried underwater and inland archaeological remains and structures in the broader archaeological area of ancient Olous, in an effort to complete the picture of the built environment of the submerged city.

Methodology and instrumentation

For the scope of the investigation the electrical resistivity tomography (ERT) method was implemented in two different ways. Concerning the dynamic mode, the dipole-dipole array with one meter spacing between the electrodes was used to collect data along 27 lines, covering approximately 10,000 m^2 of marine area in the southern bay. The static variation of the ERT method applied in two grids, along multiple parallel transects of one-meter distance, in the northern bay using the pole-dipole electrode configuration with one-meter electrode distance. A high-resolution bathymetric model was produced in order to be integrated along with the conductivity of the sea water in the 3D robust inversion algorithm (Loke et al. 2020) that was used for data processing. The bathymetry was also incorporated in the algorithm for locating the position of the electrodes in the dynamic mode (Oikonomou et al. 2019).

More than 11,900 m^2 in the very shallow areas of both sides of the Isthmus that connects the Kolokytha peninsula with the Elounda Bay, were investigated with magnetic gradiometry. A multichannel system consisting of five gradiometers placed on a frame in 50 cm crossline separation was assembled, while the resolution of the measurements along each track was about 10 cm.

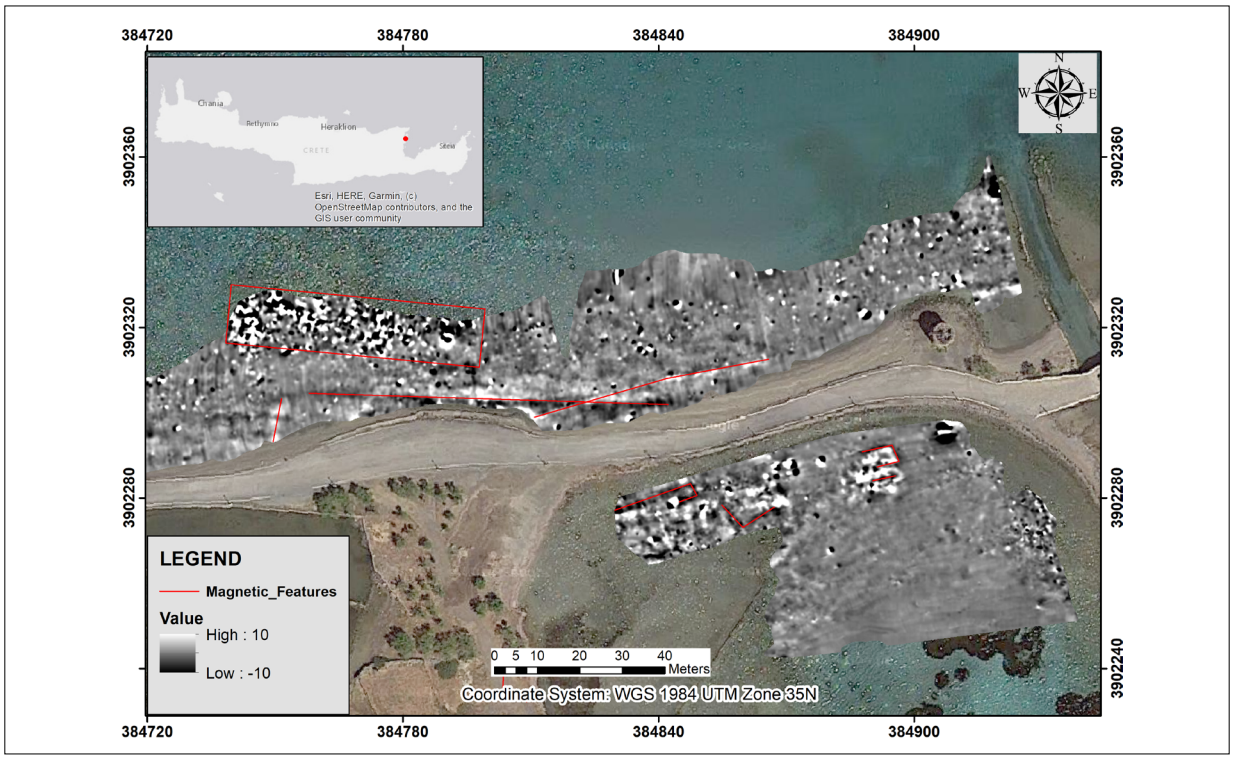

Fig. 1: Diagrammatic interpretation of the magnetic results at the north and south areas of Olous Bay (base map: Google, map data ©2013 Google). Units are nT. Axis units are in meters.



Fig. 2: Diagrammatic interpretation of the 3D inversion results at the East Grid of ancient Olous at a depth of about 0.75 m below the sea bed (base map: Google, map data ©2013 Google). Units are Ohmm. Axis units are in meters.

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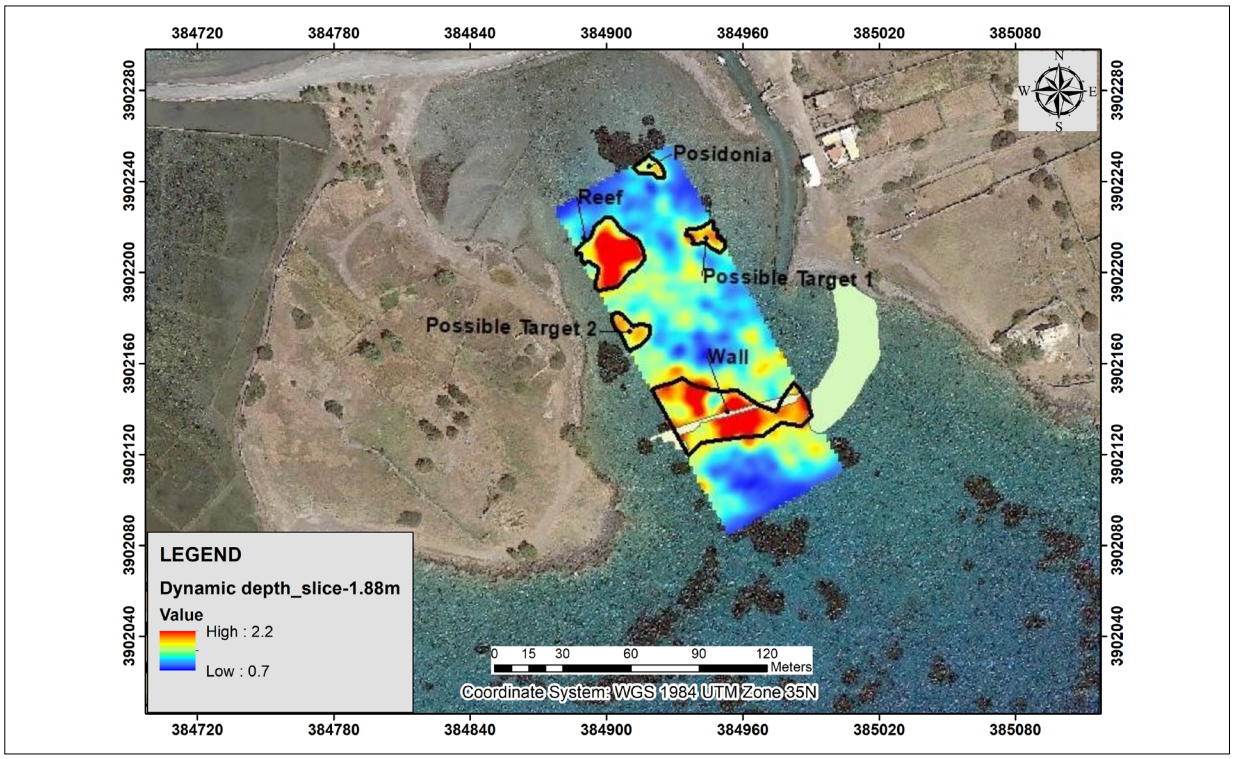

Fig. 3: Diagrammatic interpretation of the 3D inversion results of the Dynamic ERT method at the southern bay of ancient Olous at a depth of about 2 m, with the rectification of the identified wall for the archaeological survey (base map: Google, map data ©2013 Google). Units are Ohmm. Axis units are in meters.

Results

The processed magnetic map in both bays managed to reveal relatively small variations of the magnetic gradient. The geometry and their orientation aligned with visible structures on the sea bottom enhance the possibility that these features represent archaeological structural elements (Fig. 1). Concerning the static ERT results, many interconnected linear resistive targets were revealed. These targets are highly probable to form some sort of buried underwater structure, such as a public building or walls. Some of the targets could be verified in situ since they could be identified by archaeological inspection though diving. Finally, some resistive targets related to the presence of beach rock were also identified (Fig. 2).

Furthermore, the results of the 3D inverted dynamic ERT lines in the southern Olous Bay showed quite promising results. The horizontal depth slices managed to pinpoint the lateral and vertical continuation of a possible fortress wall, part of which has already been identified and mapped by the underwater archaeological diving survey. The slices show a much longer and wider wall than what was originally believed. Moreover, a cluster of Posidonia plants and a visible reef were also identified in the slices. The existence of two further buried resistive targets in the respective depth slices could also indicate respective anthropogenic structures since there is no relevant evidence that could support the geological origin of these bulky resistive anomalies (Fig. 3).

Conclusion

The results of the underwater geophysical survey at ancient Olous are quite promising, since both magnetic and electrical resistivity tomography managed to reveal interesting archaeological features providing useful information on the ancient city of Olous. The fact that those two methods can be successfully applied in shallow marine environment for mapping submerged archaeological remnants is very important, introducing an extra tool for archaeological surveys in this demanding environment.

Acknowledgments

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ClepsYdra: translating submerged archaeological remains from shallow water to digital environment with geoinformatics

Nikos Papadopoulos[1*]

1 Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranean Studies, Foundation for Research and Technology, Rethymno, Greece
* Corresponding author: E-mail: nikos@ims.forth.gr

Abstract
Coastal and shallow submerged archaeological sites face risks due to sea level rise and erosion. The documentation of visible remains will be completed through satellite and aerial remote sensing methods. Geophysical prospection methods will map the continuation of the structures below the sea bed. Multi criteria decision support algorithms will assess the risk threatening the shallow submerged archaeological sites.

Keywords
applied geophysics; assessment cultural heritage; photogrammetry; satellite remote sensing; underwater archaeology

Introduction

The study and documentation of Cultural Heritage (CH) is rapidly developing, at times favoring or even pushing the progress of technologies and equipment in place for the digitalization of items and landscapes. At the same time, the survival of CH is constantly threatened by factors related to the accessibility of the artefact, its location and context as well as the chronology. Nowadays it is possible to document in high detail the surroundings, making a step further to "look" beneath the soil and produce images of buried (Sarris 2015) and submerged (Galanidou et al. 2020) structures to assist and complement archaeological research in a timely and costly efficient manner.

Although the availability of mapping methods for the documentation of CH in deep-water is nowadays well established, significant developments have also been made to reconstruct the archaeoenvironment in the coastal and shallow aquatic environment transition zone with geophysical and geoarchaeological methods (e.g. Pydyn et al. 2021; Wilken et al. 2019; Cvikel et al. 2017). However, there is still space for methodological improvements to document archaeological sites in shallow water environment which are at risk of being excluded from the archaeological discourse on coastal area exploitation.

To this direction, the research project ClepsYdra: "Translating Submerged Archaeological Remains from Shallow Water to Digital Environment with Geoinformatics" has the ambition to maximize the accessibility to information regarding the current-state of now-submerged sites by minimizing the lack of protocols, procedures and equipment for shallow-water CH investigations, developing ways to explore and promote these under-studied submerged contexts. ClepsYdra is funded by the Hellenic Foundation of Research and Innovation and it will run for a period of two years. It is joining the efforts of two international research centers (Foundation for Research and Technology Hellas and Italian National Research Council) with the Greek Ephorate of Underwater Antiquities to understand the cultural landscape of shallow submerged archaeological sites in eastern Crete.

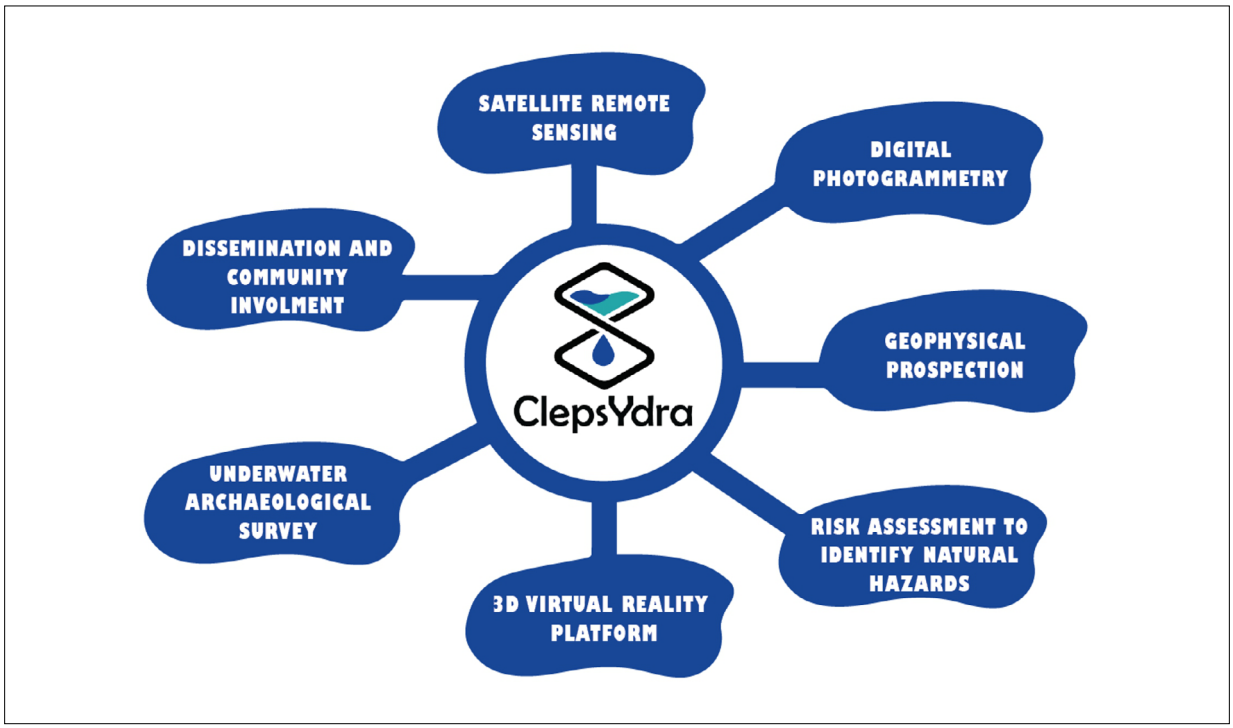

Fig. 1: Integration of the different research modules to fulfil the scientific objectives of ClepsYdra.

Objectives and methodology

Time is definitely the most essential and distinctive connotation of CH, which in combination with space and human interventions, are responsible for the conservation of archaeological remains. Its present and future survival is often compromised or threatened by various factors, mostly driven by natural phenomena. This is particularly evident when the space in which these artifacts are hosted today is hostile or it renders the documentation process a complex and expensive task. This is the case of archaeological sites close to the modern coasts, which were once in dry land and are now submerged because of the sea-level change across time.

The objectives of ClepsYdra include: a) Extensive 3D digital documentation of submerged and underwater buried archaeological evidences for five statistically representative case studies. b) Construction of a new low-cost open-hardware device for the digital documentation of shallow water contexts in automated and systematic manner. c) Application of non-destructive research methods (satellite / terrestrial remote sensing, aerial photography, underwater photogrammetry, traditional and digital 3D archaeological documentation) to capture the current state of selected sites, despite their difficult accessibility and incomplete visibility with naked eye. d) Modification, adaptation and improvement of geophysical methods and protocols to account for the shallow water context. e) Systematic merging and summarization of the above data for the enhancement of the archaeological understanding and interpretation, towards the analysis of the paleoenvironment in coastal and shallow submerged archaeological sites. f) The active and growing involvement of local community in the understanding, promotion and protection of CH (Fig. 1).

The main technological advancements include the: a) development of an algorithm for calibration of drone-aided photographs to account for the two medium problem and the creation of a custom made sailing platform for automated navigation and photo-capturing in single medium, b) development of algorithms for joint inversion of resistivity and seismic data, c) development of algorithms within a Multi-Criteria Decision Analysis (MCDA) model to assess the overall risk assessment of the CH sites that are found on the merged inland and littoral zone.

In order to achieve the project's objectives, statistically relevant sample sites have been identified, including some commonalities, logistics facilities and peculiarities. All the

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Fig. 2: Location of the ClepsYdra case studies in eastern Crete. The background base satellite map is taken from Google Earth (©2010 DigitalGlobe, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, ©2010 European Space Imaging).

sites have similar chronology dated in the Roman Times and are located in the eastern part of Crete which is gradually sinking based on established geological and tectonic models (Mourtzas et al. 2016). Thus, the sample includes four shallow submerged and (partially) sand-buried sites in the Eastern part of the island of Crete including an important Roman settlement (Koufonisi islet), two pluri-stratified -prehistoric to Roman- sites (Gaidouronisi islet, and Stomion bay) and one ancient harbor (Hierapetra). (Fig. 2).

Expected results

ClepsYdra aims towards a better understanding of the cultural landscape and the closer contact of the coastal and marine archaeological sites of Crete with the wider public. It will propose an integrated approach for the documentation of the shallow submerged archaeological sites combining: a) underwater archaeological investigation and geophysical imaging, b) satellite, aerial, low-altitude and underwater mapping with digital photogrammetry, c) risk modelling and assessment, all together providing a unique tool to understand the Cretan marine archaeology, especially of the Roman times which were until recently underexplored. It will also put the bases for a protocol or a sequence of procedures for the successful implementation of integrated methods in similar shallow marine archaeological environments. Underwater archaeology will also gain a new set of tools for approaching coastal sites in a holistic manner that will allow to easily combine results from submerged sites with those of land archaeology. These tools will also give the advantage of a relatively rapid data collection that is crucial for remote sites along the coast where weather conditions (mostly wind) and in situ difficulties (waves, water turbidity and others) are not always ideal for fieldwork activities. The amount of information derived by the integrated application of new and improved methods will be concentrated in a new set of information regarding the risks to which each site is exposed. Indeed, the capability to fuse all these in an all-in-one geoinformatics package arises by offering the opportunity to evaluate the natural hazards and the overall risk assessment of the CH sites found inland, while extending this with submerged structures at the littoral zone as well.

Acknowledgments

The research project "ClepsYdra: Translating Submerged and Buried Cultural Heritage from Shallow Water to Digital Environment with Geoinformatics" (Project Number: 3339) is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Faculty Members & Researchers".

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Multidisciplinary shallow underwater geophysical prospecting at Delos island

Angelos Plageras[1*], Dimitrios Oikonomou[1], Nikos Papadopoulos[1], Athanasios Argyriou[1]

1 Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment, Institute for Mediterranean Studies, Foundation for Research and Technology, Rethymno, Greece
* Corresponding author: E-mail: plageras@geo.auth.gr

Abstract
Geophysical imaging methods have been applied to reconstruct the cultural dynamics in the two different submerged sites in Delos island. The geophysical results provided useful information for understanding the complexity of the submerged archaeological sites.

Keywords
archaeological prospection; Delos island; ERT; multisensor magnetic gradiometry; shallow marine geophysics

Introduction

The island of Delos is located at the center of the Cyclades archipelago in the Aegean Sea of Greece. It was one of the most important parts of the ancient Greek world, known as a religious site, the treasury of the Athenian Alliance, and as trading port. The island hosts temples honoring the birthplace of the twin gods Apollo and Artemis and therefore, it is rightfully considered as one of the most important archaeological sites worldwide.

The increased attention to coastal zone management contributed to the development and implementation of shallow-water mapping approaches for capturing current environmental and archaeological conditions (Simyrdanis et al. 2015, 2016; Papadopoulos 2021). The geophysical survey took place during early September of 2021 and its purpose was to map the extent of the settlement limits through offshore geophysical investigation and to locate possible archaeological relics buried below the sea bottom in two different submerged sites in the northeastern (Stadio) and northwestern (Skhardanas) bays of the island.

Methodology and instrumentation

The digital bathymetry models in both bays were completed through a combined implementation of the Ohmex SonarMite BTX single beam echo sounder and RTK-GNSS measurements to survey the deeper and the shallower parts. The bathymetry models in Stadio and Skardhanas covered ca. 21,000 m^2 and ca. 24,000 m^2 respectively.

For the survey purposes, two different geophysical techniques were used. The electrical resistivity tomography (ERT) method was used in two variations: the static mode in Stadio Bay and the dynamic mode in Skhardanas Bay. The choice of different ERT survey variants in the bays was based on the depth of the bays. Thus, the maximum depth of about 12 meters in Skhardanas was actually prohibitive to use productively the static mode, whereas the maximum 4 meters water depth in Stadio facilitated the used of static ERT mode. The multisensor magnetic gradiometry method was used in the shallow part of Stadio bay, whereas ground penetrating radar was concentrated in a small section along the coast of Skhardanas.

For the dynamic survey, a 10-channel resistivity meter was used, along with a special cable equipped with 13 graphite electrodes with one meter spacing between them. The cable was pulled using a boat along 37 predefined lines, employing the dipole-dipole array covering 10,385 m^2 of marine area. At Stadio Bay, the pole-dipole electrode configuration employing a fixed submerged cable position was used to complete the ERT survey in two

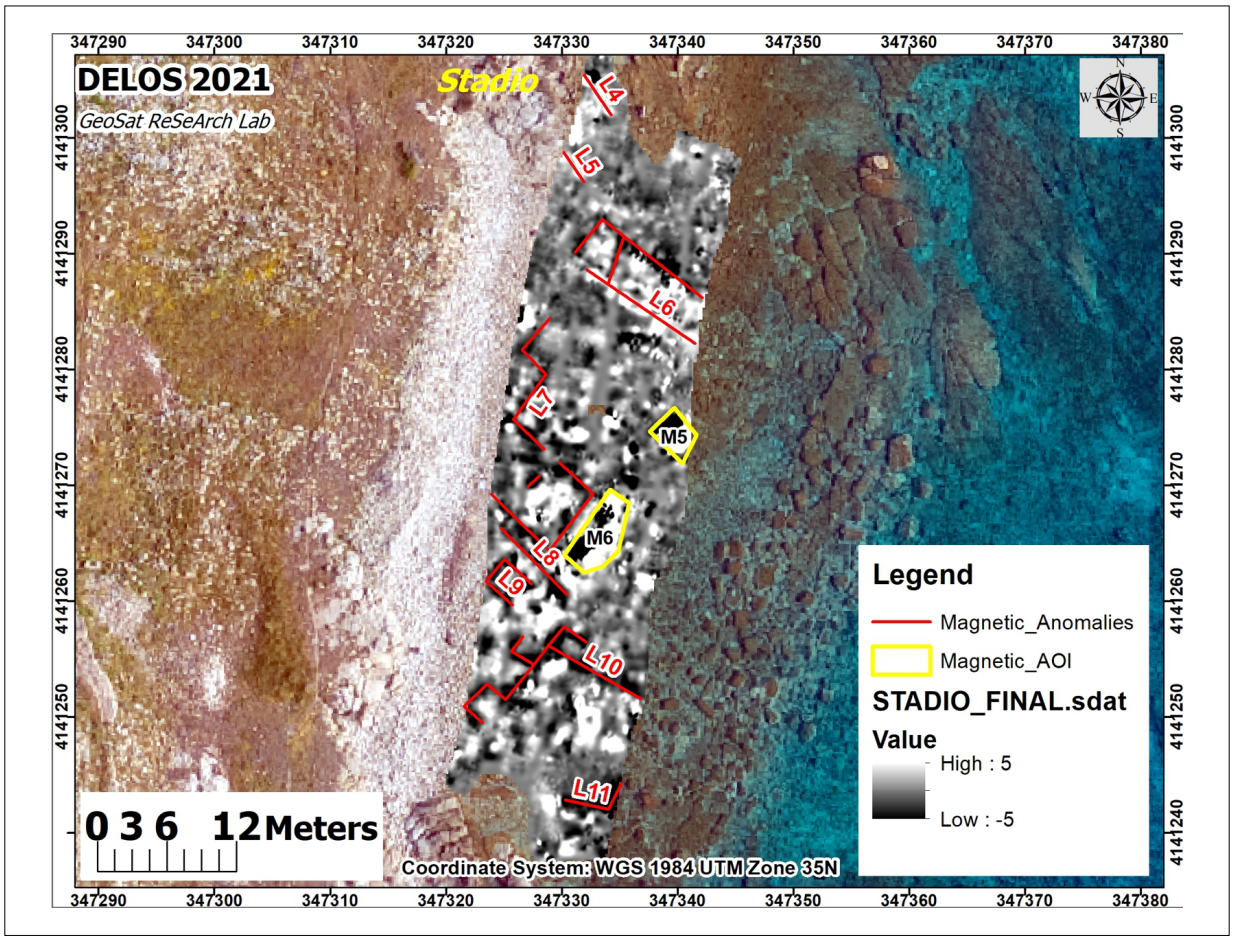

Fig. 1: Diagrammatic interpretation of the magnetic anomalies at the northern section of Stadio Bay (orthophoto: Moretti et al. 2015). Units are in nT/m. Axis units are in meters.

separate grids. The unit electrode distance along the lines was one meter and multiple combinations of N separations (distance between the current and potential dipoles) were utilized to increase the signal to noise ratio and to map the deeper stratigraphy, while the crossline distance was also set equally to one meter. The ERT survey was completed along multiple parallel transects in an effort to map the resistivity properties below the bottom of the sea within a 3D context. The tomographic data were processed with 2-D and 3-D robust inversion algorithms, incorporating the sea bottom topography and the conductivity of the sea water (Loke et al. 2020), allowing for the extraction of vertical and horizontal slices describing the resistivity variation below the sea bottom.

A multichannel magnetic gradiometer system equipped with five SENSYS FGM600 gradiometers was used to log the gradient of the vertical component of the magnetic field, covering an area of 1,443 m^2 at the very shallow part in Stadio Bay. The five magnetometers were mounted on a non-magnetic cart with 50 cm separation. and the spatial sampling resolution of the measurements along the track was about 10 cm. The whole system was mounted on a specific frame made of fiberglass for carrying the sensors, the RTK-GNSS and the electronic box.

Results

The geophysical results were rectified on the aerial photo of the site (Moretti et al. 2015). More specifically the magnetic gradiometer map in Stadio showed strong magnetic anomalies related to scattered metal fragments and the rocky outcrop on the seabed. Despite these external interferences, the magnetic results showed a number of linear and rectilinear anomalies related to submerged archaeological features in the coastal and ultra-shallow part of the bay (Fig. 1).

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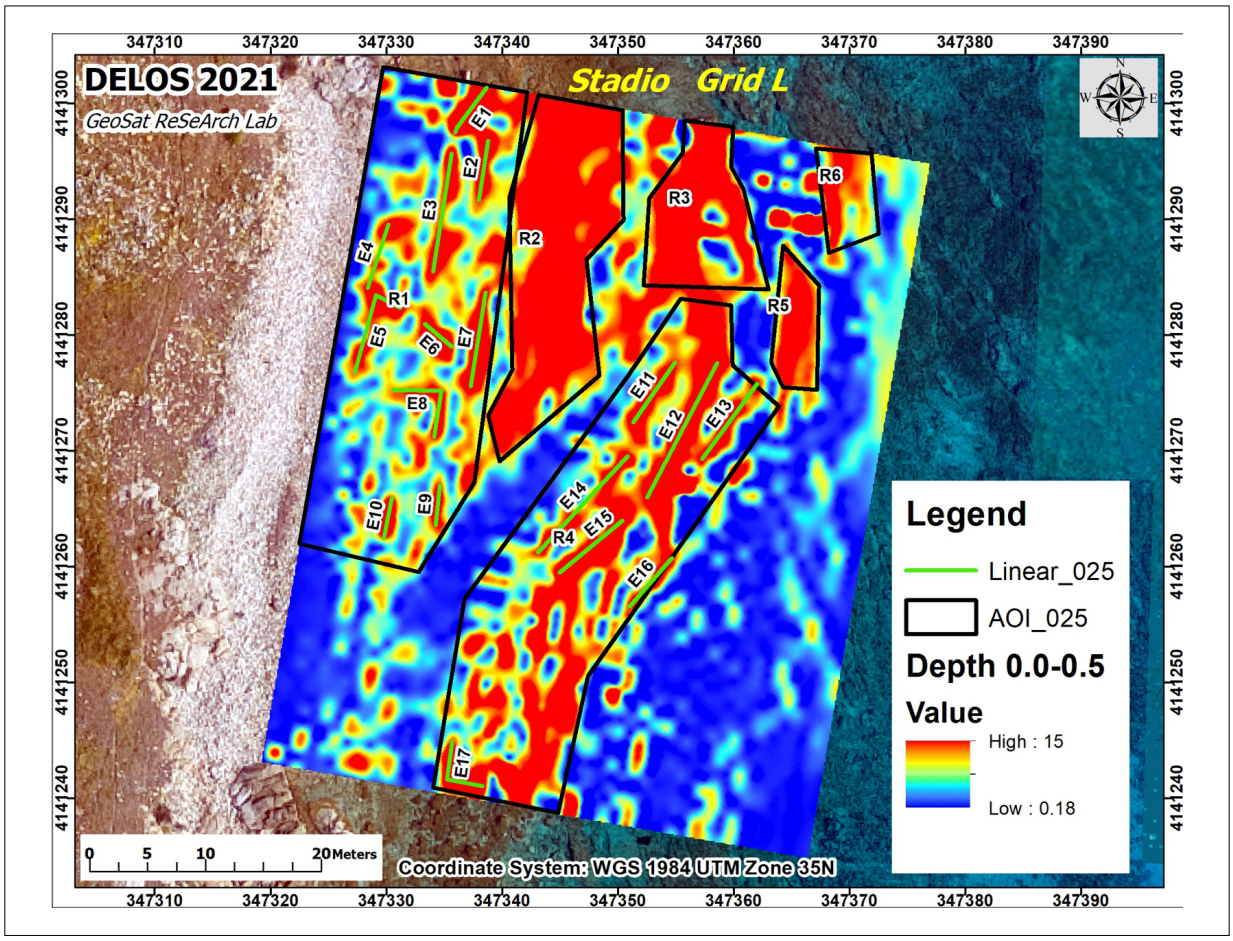

Fig. 2: ERT depth slice of the northern grid in Stadio Bay (orthophoto: Moretti et al. 2015). Indicative linear resistive anomalies (E1 –E17) are marked with green lines. Units are in Ohmm. Axis units are in meters.

The ERT depth slices in the overlapping regions show a relatively good correlation with the magnetic maps. Furthermore, ERT gives additional information on the distribution of structural remains in the deeper sections of the bay and the boundary of the settlement that is presently submerged, completing in this way the picture of the habitation pattern (Fig. 2).

Concerning the Skhardanas Bay Dynamic ERT data set, the 2D inverted lines failed to provide any information of archaeological value, since most of them were surveyed in a depth greater than 2 m. However, this data set provided valuable geological information, such as the existence of two faults in the area. On the other hand, the pseudo3D depth slices created from the ultra-shallow lines pinpointed many targets of possible archaeological interest, as well as a cultural layer that was already visible (Fig. 3).

Conclusions

The possibility of applying well-known geoinformation methods, such as ERT and magnetic gradiometry to un-(or under-) explored archaeological shallow-water contexts was very important from a methodological point of view and for the results obtained. Indeed, although the adaptation of commonly used tools to depths shallower than 2 m presented some challenges and required the creation or customization of equipment, the results support such efforts and provide useful information for understanding the complex archaeological site of Delos. The innovative aspect of this work arises from the adaptation and development of well- established and consolidated techniques (ERT and magnetic gradiometry) to a shallow water context. At the same time, this approach surely needs refinement and will benefit from inputs from different and complementary disciplines. In general, the

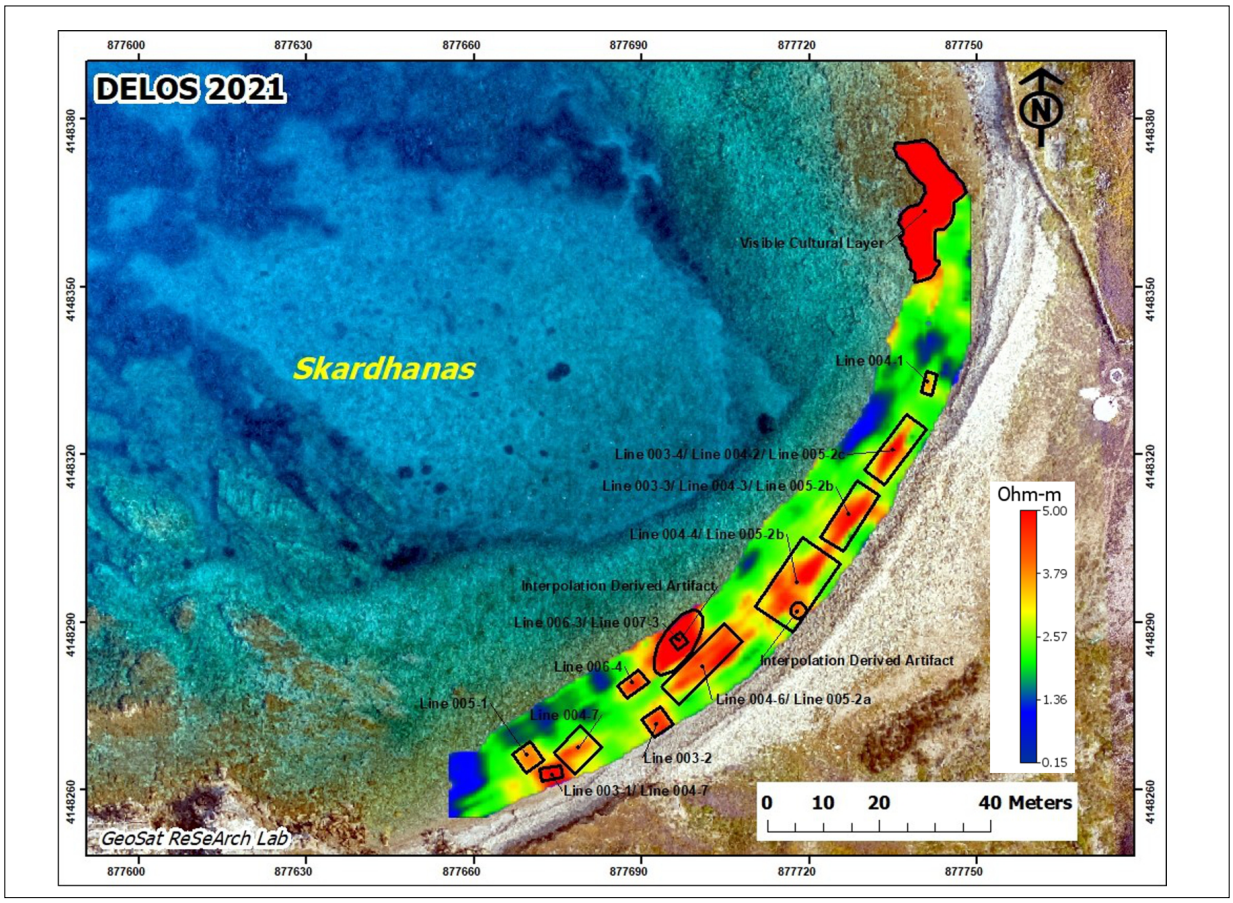

Fig. 3: Resistivity slice for depths of less than one meter below the seabed, extracted from the 3-D quasi model of the ultra-shallow dynamic ERT lines in Skardhana (orthophoto: Moretti et al. 2015). Diagrammatic interpretation of the resistive features probably related to submerged archaeological structures. Axis units are in meters.

manifold marine geophysical campaign at Delos provided promising results in the sections that were investigated. The high resolution geophysical approach was able to indicate a number of candidate targets, thus completing to a certain degree the picture for the submerged built environment of the archaeological site.

Acknowledgments

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Deal with steel: investigating the wreck of the heavy cruiser *Admiral Scheer*

Dennis Wilken [1*], Fritz Jürgens [2], Ercan Erkul [1], Wolfgang Rabbel [1], Ulrich Müller [2]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
* Corresponding author: E-mail: dennis.wilken@ifg.uni-kiel.de

Abstract
In this paper, we present, for the first time, a World War II warship imaged underground, in a silted up harbor. Only reflection seismic measurements and electrical resistivity tomography allowed prospecting of the target at challenging depths from 4 m to 12 m below surface.

Keywords
archaeological prospection; battleship; ERT; seismics; World War II

Introduction

Individual, large (German) naval units, like battleships, such as the *Bismarck* or the *Graf Spee*, experience great public interest, while their sister ships are rather unknown. This also applies to the *Admiral Scheer*, the sister ship of the battleship *Graf Spee*, which, due to a long and intensive period of service (1934 to 1945), is one of, if not the most successful, ship in the German Navy history. One month before the end of the Second World War, it capsized after a bombing raid on the port of Kiel. The wreck of the ship was subsequently filled in with sediments and debris, sharing the fate of the entire naval harbor basin.

The *Admiral Scheer* was built as the second of three armored ships of the 'Germany' class at the Wilhelmshaven shipyard. The ship was commissioned on November 12th, 1934 and was named in honor of Admiral Reinhard Scheer. It is noteworthy that ships of this class were the first larger German naval units whose hulls were welded and not riveted and which were powered using diesel instead of traditional steam engines. Despite their small size (186 m in length), the ships were heavily armed with six 28 cm guns. Therefore, the three ships of this class were known as pocket battleships. After several missions between 1936 and 1945 the *Admiral Scheer* was called back to Kiel on March 18th 1945. On the evening of April 9th 1945, during a bombing raid, five 'tall boy' bombs were dropped on the ship. The hull on the starboard side was damaged and the ship capsized in the shallow harbor (Figure 1, top right). In July 1945, British forces began to dismantle those parts of the wreck that were still above water. Pictures published in the local newspaper *Kieler Nachrichten* show that the entire stern as well as the tank turret and parts of the machinery were recovered. The harbor basin was then filled in the early 1950s with sea sand and debris and a drainage channel was dug. This channel describes a slight curve, which is often associated with the outlines of the wreck.

Materials and methods

The *Admiral Scheer* represents an important piece of German naval and Kiel's regional history and is a unique investigation target due to its size and depth of burial on land within an urban environment.

The presented investigation began with the evaluation of the Allied aerial photographs, showing the ship overturned to starboard. Later photos show that the stern and front sections were removed. The preserved midship area was removed down to the water level. Based on buildings visible in the photos and still present

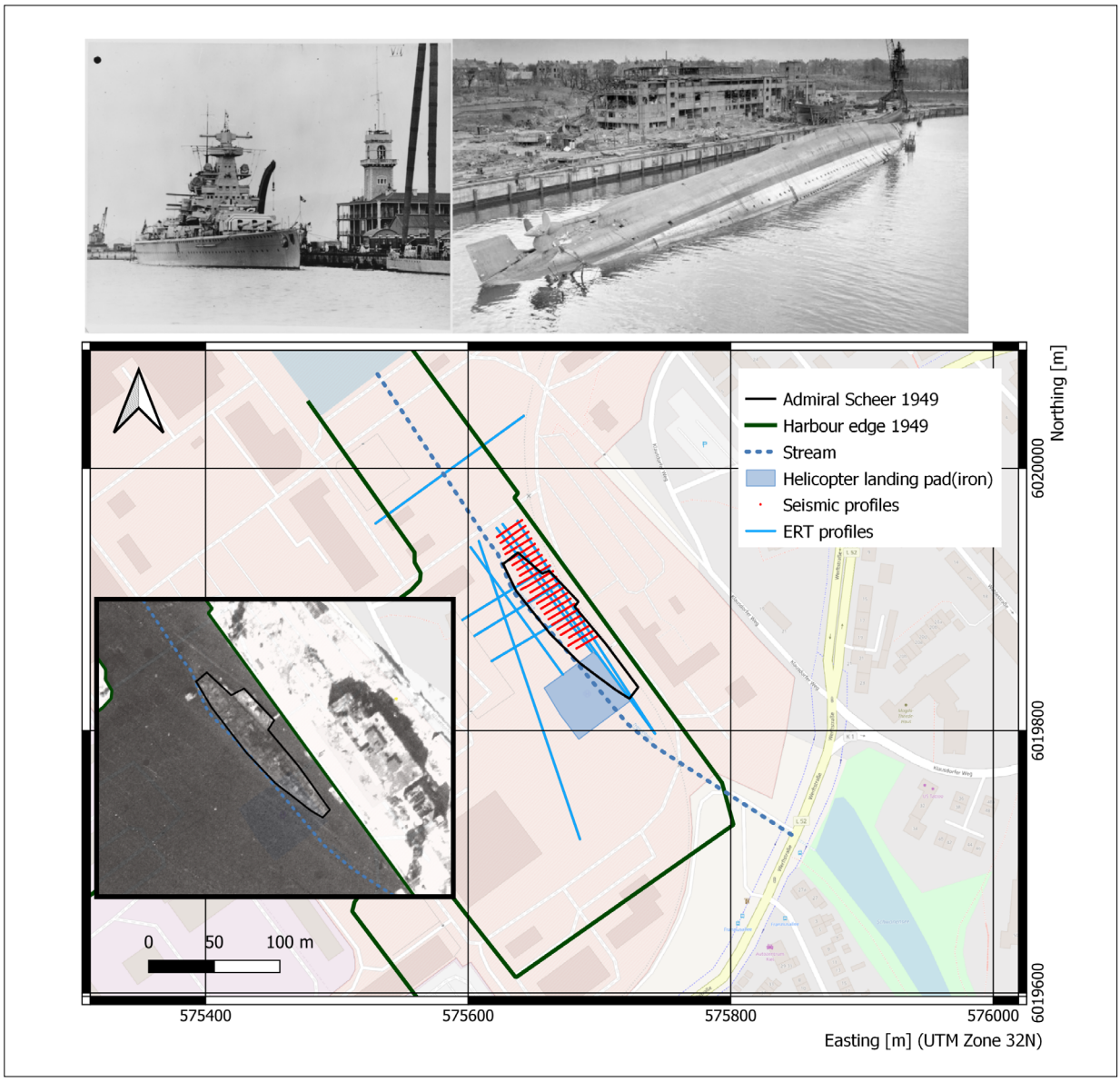

Fig. 1: Photographs of the ship and investigation area. Top left: the *Admiral Scheer* (NH 59664 Naval History & Heritage Command). Top right: the capsized *Admiral Scheer* (Imperial War Museum). Below: Map showing the locations of the measuring profiles in relation to the old harbor basin. The approximate location of the wreck based on an aerial picture from 1949 (inset of map) is outlined in black.

today, an approximate positioning was obtained for the remains of the wreck (Fig.1). These remains are expected to be located at a depth of four to twelve meters. An object like the *Admiral Scheer* consisting of steel, with water filled cavities at such depths, poses a real challenge for geophysical prospection (e.g. Passaro 2010 & Passaro et al. 2009), especially on land. Above that, the accessible area is bounded to the east by a railway and to the west by the drainage channel. The range of feasible geophysical methods is thus greatly reduced. The classical methods of archaeological prospection, magnetic gradiometry, ground penetrating radar (GPR), and electromagnetic induction (EMI) were tested but could, if ever, only scratch at the surface of the wreck. Magnetic measurements only show a large dipole anomaly and are affected by the railway and urban power cables. Therefore, seismic reflection and electrical resistivity tomography (ERT) measurements were used, offering the greatest potential to reach most parts of the wreck. Shear-wave reflection seismics were conducted on 19

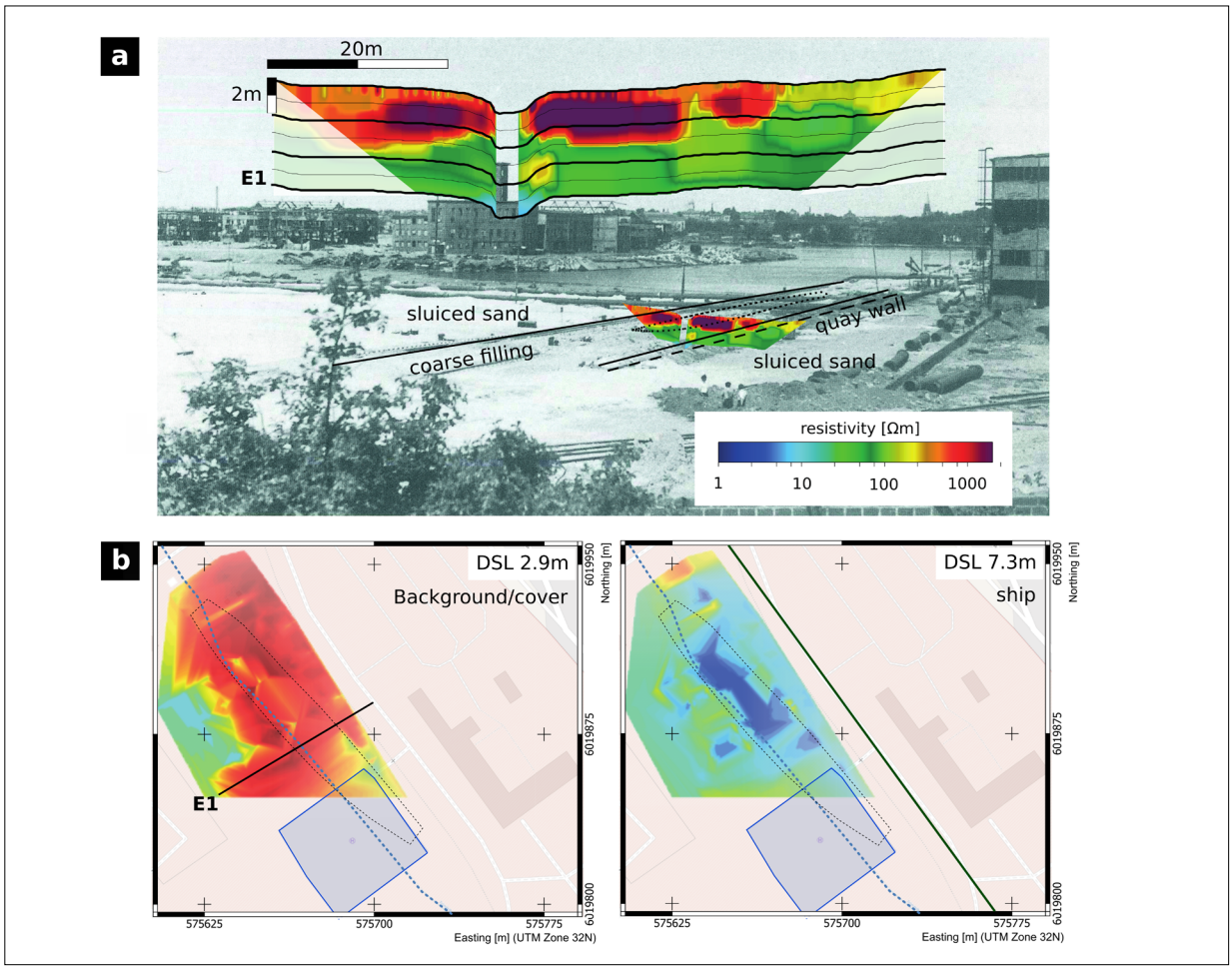

Fig. 2: a) Photograph of the Deutsche Werke Kiel (Koop/Schmolke 1993, 212) and ERT tomogram of profile E1. b) Two example ERT depth slices representing top material of harbor basin filling and wreck remains.

profiles with a crossline distance of 5 m (Fig. 1), each including 24 10 Hz S-wave geophones spaced at 1 m inline distance in SH orientation. Sledge hammer blows were placed between the geophones. Data processing included bandpass filtering, trace normalization and time gain, f-k filtering, and the creation of time slices. Time to depth conversion was implemented using an average shear wave velocity of 120 m/s.

Nine ERT profiles were measured with the RESECS2 (Geoserve) multi-electrode system, with 48 to 96 electrodes depending on the profile length. Electrode spacing was 1m and measurements were conducted in three configurations (dipole-dipole, Wenner-alpha and Schlumberger). All profiles were inverted with the same inversion parameters using Res2DInv.

Results

Figure 2a shows the old navy harbor basin after its refilling. The picture shows clear differences in the refill material. Above the wreck, the material appears coarser in the image, which is also reflected in the ERT data as high-resistivity area. Figure 2b shows electrical resistivity depth slices interpolated from profiles E1-E9. The example slices show the extent of the coarser filling material in the area of the wreck (down to more than 3m of depth) and at greater depths resistivities far below the resistivity encountered in the harbor entrance on E7 (representing soil saturated with groundwater), which we therefore address as an anomaly caused by the wreck.

Figure 3 top right shows an example seismic profile together with an outline of a cross-section of the tilted

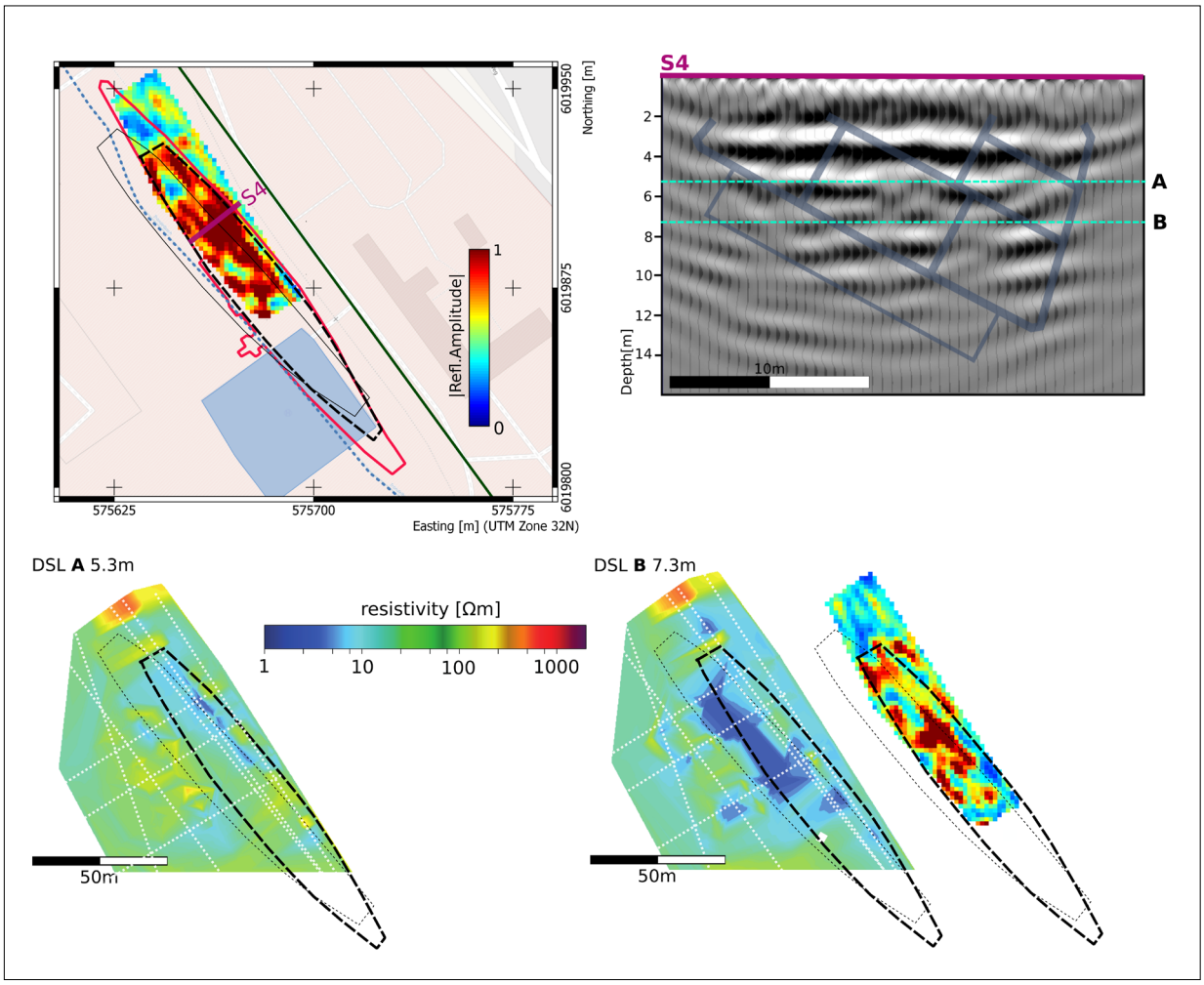

Fig. 3: Top left: Outline of the Admiral Scheer, based on aerial photographs (dotted line). The image also shows an exemplary seismic depth slice and the adjusted position of the wreck based thereon (dashed line). Top right: examplary profile S4 with the depths of the depth slices and an outline of the wrecks cross-section indicated. Below: two depth slices from ERT (DSL A) and ERT and seismics (DSL B).

ship based on original blueprints. The top left image shows an exemplary seismic depth slice calculated from all profiles at a depth of 5.3 m, with the position of the wreck based on an aerial photo superimposed (dotted line). The reflection amplitudes of the seismic profiles clearly reflect the shape of the wreck and therefore allow its position to be corrected (dashed line).

Discussion

The results show that ERT was able to distinguish the coarse harbor refill above the wreck from the sluiced sand around, providing its extent and thickness. In the deeper parts one low resistive area becomes visible, probably reflecting the wreck's mixture of steel, water-filled cavities and debris. This anomaly is slightly shifted westwards in comparison to the seismic results, probably due to side effects caused by the nearby drainage channel. In the seismic profiles, the reflections coming from the wreck are clearly visible, allowing the shape of the ship to be traced quite accurately (Fig. 3). Nevertheless, spatial resolution of both methods is not sufficiently high to distinguish individual parts of the ship; profile density would need to be increased towards 3D ERT (like in e.g. Rabbel et al. 2015, Günther et al. 2006). In terms of seismic prospection, Full Waveform Inversion (FWI) approaches could lead to an increased imaging resolution (e.g. Köhn et al. 2019), probably allowing for an interpretation of the wreck's substructure.

In summary, the measurements prove that the aerial photo from March 29th 1949 represents the state in which the *Admiral Scheer* was buried. Large parts of the hull and superstructure have been preserved in the buried harbor basin until today, covered by more than three meters of sand and debris.

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Barge or tjalk? A wreck investigation in the tidal flats of North Frisia

Dennis Wilken [1*], Fritz Jürgens [2], Dirk Bienen-Scholt [3], Bente Sven Majchczack [4], Ruth Blankenfeldt [5]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
3 Archaeological State Department Schleswig-Holstein, Schleswig, Germany
4 Cluster of Excellence ROOTS, Kiel University, Kiel, Germany
5 Centre for Baltic and Scandinavian Archaeology (ZBSA), Schleswig, Germany
* Corresponding author: E-mail: dennis.wilken@ifg.uni-kiel.de

Abstract
We present a case study on the applicability of geophysical methods to map shipwrecks in the coastal zone. We present results of magnetic gradiometry, electromagnetic induction, and photogrammetry.

Keywords
archaeological prospection; EMI; magnetic gradiometry; shipwreck; tidal flats

Introduction

East of the island of Südfall in the German tidal flats, a shipwreck was observed by wanderers and first investigated by archaeologists in 1998 (Archaeological survey of Schleswig-Holstein 2009) (Fig. 1a). Local oral tradition speaks of a cargo sailing vessel that capsized during a storm around 1900. The ship was loaded with tidal gates and was on its way from Husum to the Halligen (tidal islands).

1998 find description

The 1998 archaeological investigation reports frame heads and planks of a ship's side over a length of 11 m (Fig. 1b). They describe the remains of a flat-bottomed vehicle, probably the remains of a barge or lighter. The original length could not be determined. The width of the preserved wreckage is about 5.2 m. The very wide keelson plank (0.65 m) was striking. The flat bottom is 0.55 m below the surface of the tideland. Typical iron fittings of one or more tidal gates on the ship's floor as well as several iron fragments in the wreck and its surroundings were reported. Due to the general conditions, the wreck was not uncovered, so that observations are limited to exposed components.

The shipwreck was re-investigated during a campaign in September 2022 and prospected geophysically (magnetic gradiometry and electromagnetic induction) and archaeologically (in situ inspection and drone photography). The investigation and upcoming analysis tried to answer the following questions:

1. How does the wreck appear in gradiometry and frequency domain electromagnetic induction (FDEMI)?
2. Is there more wood remaining than the visible frame heads and planks?
3. How does the observed metal influence the data?
4. What is the size of the wreck?
5. And in conclusion, what type of ship might it be?

Materials and methods

A magnetic gradiometer survey was performed using an array of six fluxgate gradiometers (Foerster fluxgate differential vertical component magnetometers) with an internal vertical sensor distance of 0.65 m, a horizontal sensor spacing of 0.5 m and a sampling frequency of 20 Hz. Accurate positioning was achieved by RTK (Real Time Kinematic) DGNSS (Stonex S9i). The arithmetic mean was subtracted from the data of each profile. The resulting values were

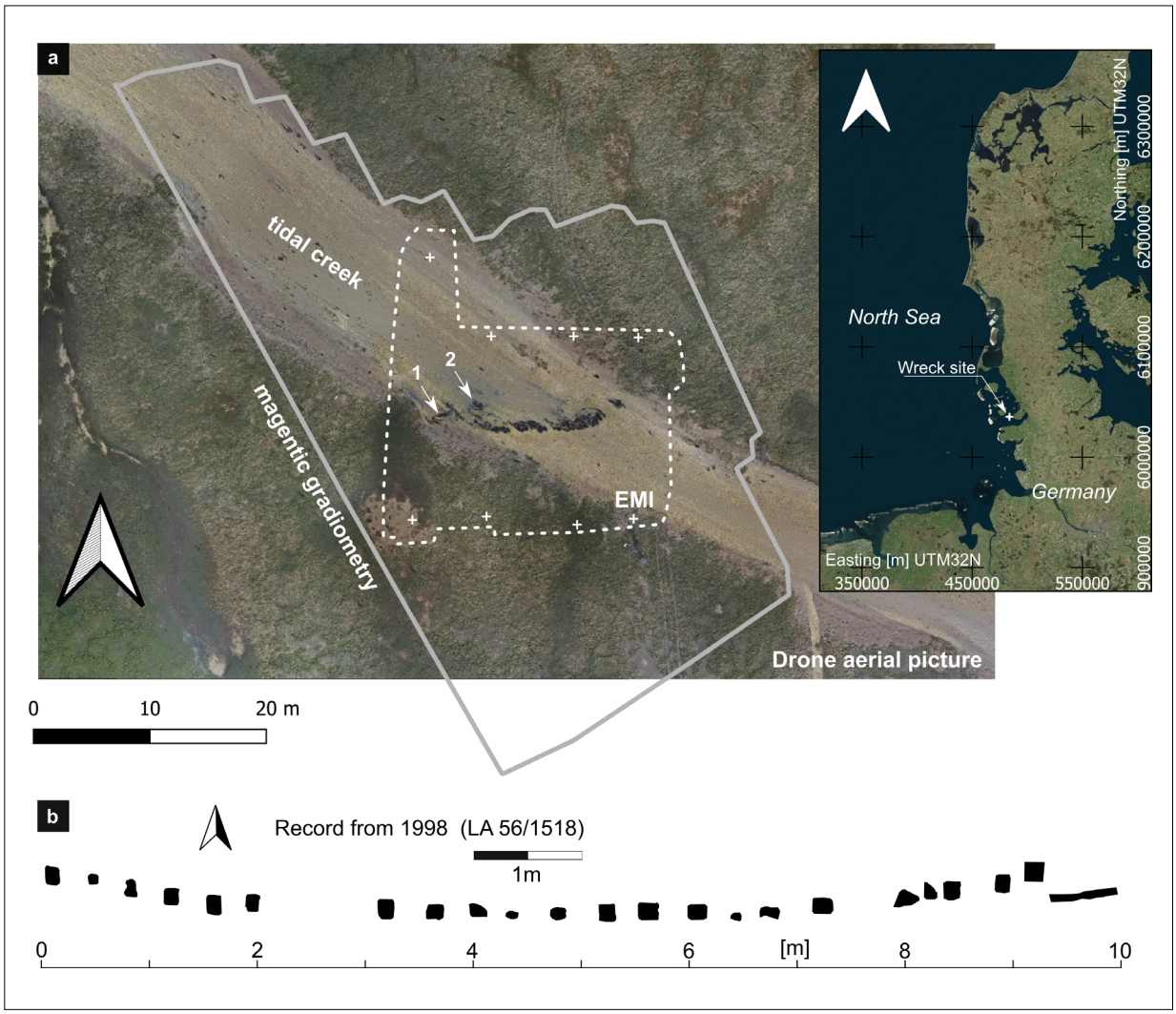

Fig. 1: a) Right : map with the position of the wreck site. Left: drone aerial picture of the site together with magnetic gradiometry and EMI investigation areas (solid grey, dashed white outline). b) Re-drawing of the finds from 1998 after Archaeological survey of Schleswig-Holstein (2009).

binned inline and interpolated cross-line (using linear interpolation) in order to form a data grid of 0.2 m bin size.

In a second attempt, we used the FDEMI (frequency domain electromagnetic induction) CMD Mini-Explorer by GF Instruments. The device consists of one transmitter and three receiver coils. The planes of the coils were oriented horizontally (horizontal coplanar, HCP). The distance between the transmitter and receivers were 0.32, 0.71, and 1.18 m. Further details on the method and its usage in tidal flats can be found in Wilken et al. (2022a). Beyond EMI mapping, we performed 1D conductivity inversions on profiles and on a small area to investigate the sensitivity to the wreck remains.

Furthermore, a high resolution aerial image of the area was performed by drone photography using a DJI Mavic 2 pro with additional RTK GPS module (Fig. 1a).

Results

The wreck can still be traced over a length of about 11 m, aligned east-west and lying on an even keel. Currently, only bulkheads on the southern long side are visible of the ship's construction, which correlates with the observations of the survey in 1998. While at that time the dimensions of the frames were measured 10 x 15 cm, this

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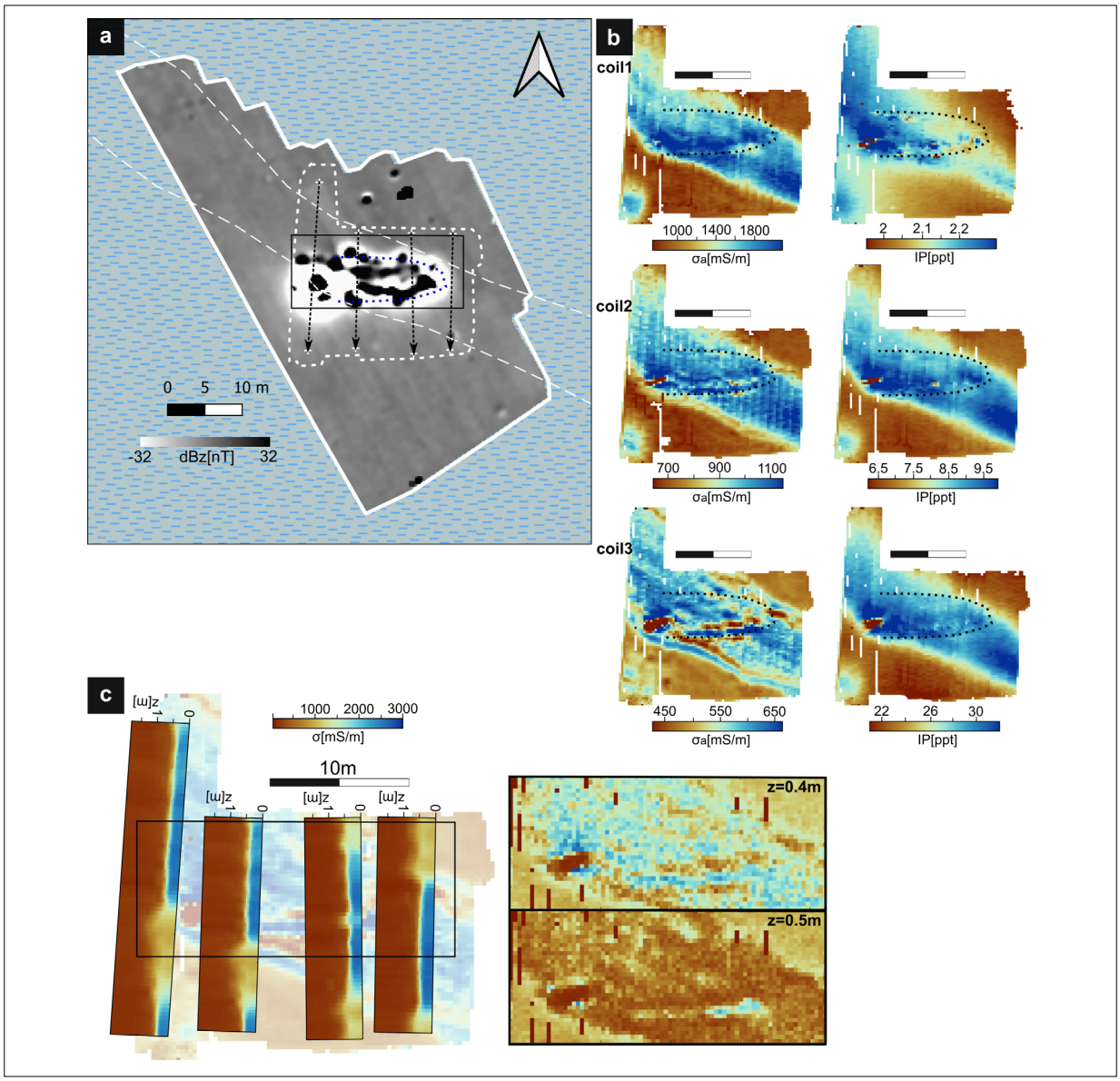

Fig. 2: a) Magnetic gradiometry map. Dashed white lines indicate the EMI area and the tidal creek. Black solid line and dashed lines indicate the area and profiles of 1D EMI conductivity inversions. b) Apparent conductivity and In-Phase (IP) maps of the three different coil separations. c) Inverted conductivity profiles (left) and depth slices through pseudo 3D conductivity cube (right).

could not be confirmed in the recent survey due to poor preservation and heavy growth of seaweed. The frames point relatively vertically upwards in the midship area, but make a bend in the bottom, the so-called Kimmung. This shows that it was a flat-bottomed vessel, which allowed a high cargo volume and safe dry-docking at low tide.

At the western end of the wreck lies a massive wooden structure ("1" in Fig. 1) that can be addressed as the stern knee. This is the connection between the keel and the stern, i.e. the bow and the stern of the ship respectively. According to current information, it is not possible to say which of the two ends of the ship it is. However, due to the tilted position of the stern knee, it can be said that the bow or stern has snapped off due to their heavy weight.

Another massive component, which lies further in the center of the wreck ("2" in Fig. 1), is presumably the keel. In 1998, the width of this keelson plank was given as 65 cm.

Figure 2 shows the results of the geophysical measurements. In Figure 2a the magnetic gradiometry map is shown in the 32 nT range, showing the outline of the

wreck in terms of magnetic signal. Figure 2b shows the apparent conductivity and In-Phase (IP) maps of the three different EMI coil separations. The outline of the magnetic feature is shown as black dotted line, framing visible signals from the wreck. Figure 2c shows example profiles and depth slices of the conductivity. The most striking structure visible in the profiles is the waterbody of the tidal creek with typical conductivities of up to 3000 mS/m. Wreck features appear strongest, where surface finds are still present in the water column.

Discussion

Regarding the observed keelson plank, unfortunately a mast shoe or other relics of a sailing vessel could not be documented, so that it cannot be said with certainty whether it was a lighter or a sailed vessel such as a tjalk. The dating of the ship is still fraught with questions. Due to the rather poor preservation of the wood, no wood sample has been taken for dendrochronological age determination. However, it is noticeable that the frames are at least partly made of iron or reinforced with it. This type of construction indicates that the ship was built at the end of the 19th/ beginning of the 20th century (Menzel 1997).

The gradiometry furthermore allows a containment of the whole wreck even for its northern, submerged side. Though an estimation of the ship's total length and width is possible being about 20 m by 6 m. This length is in the typical range of a tjalk. On the western side of the wreck, a strong magnetic anomaly as well as an IP and conductivity anomaly is observed, highlighting the stern knee and its wooden and (submerged) metal components. If this is the stern of the ship, large metal components could indicate a rudder hinge.

Due to the strong influence of the tidal creek on the EMI data, it shows only few indications of wreck remains beyond the surface finds. Although IP data of e.g. medium coil separation show weak indication of the northern edge of the wreck. The construction wood itself, if remaining in the subsoil, is not observed as clear as for example in Wilken et al. (2022a), who showed a clear signal of wooden wreckage in a more sandy tidal flat area, that is dry during low tide. In the present case more silty subsoil and water running down the tidal creek recommends a combination of gradiometry and EMI. A geophysical prospection and a feasible recording methodology of such archaeological features are of high interest in tidal flat areas, as erosion by tidal creeks and storm surges endangers the heritage of the area (Wilken et al. 2022b).

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4

CASE STUDIES

Analysis of the evolution of a Roman urban space by GPR survey

Christophe Benech [1*], Aurore Boulais [2], Laurence Brissaud [3], Mohamed Amine Jouini [4]

1 UMR 5133 Laboratoire Archéorient, Maison de l'Orient et de la Méditerranée, Lyon, France
2 Université de Grenoble Alpes, Grenoble, France
3 Musée et sites gallo-romains de Saint-Romain-en-Gal, Saint-Romain-en-Gal, France
4 Université Lumière Lyon 2, Lyon, France
* Corresponding author: E-mail: christophe.benech@mom.fr

Abstract
We identify the previous phases of a building by means of GPR of a Roman quarter. We analyze the data from excavations and geophysics in a complementary way to understand the evolution of an urban space.

Keywords
domestic space; gallo-roman site; GPR; urban space evolution; urbanism

Introduction

The site of Saint-Romain-en-Gal is located on the right bank of the river Rhône and is one of the districts of the ancient city of Vienne, located in the in the department Isère in France. The sinking of the river around the second century BC allowed for the development of a peri-urban sector relatively sheltered from the fluctuations of the Rhône. The first traces of occupation, in the form of rural occupation, date back to around 40 BC. A vast residential district then developed, but also commercial and artisanal sectors, as well as a vast monumental complex covering more than 8 ha. In just over two centuries, the plain of Saint-Romain-en-Gal therefore became a flourishing and dynamic peri-urban district. This exceptional dynamic was accompanied by ambitious development programs with a profound and sometimes rapid evolution of the urban space (Brissaud et al. 1995).

This evolution has been known at certain places on the site, where more or less extensive excavations have made it possible to propose partial restitutions of the previous states (Brissaud and Prisset 1995). These surveys made it possible to show the profound changes experienced in certain plots, whether in the spatial organization of private space or even in the change in function of some of these spaces.

The objective of the here presented geophysical archaeological prospecting was therefore to investigate areas already excavated in order to assess what information could contribute a GPR survey to understand the evolution of the urban space of Saint-Romain-en-Gal. For this, two sectors whose previous states are partially known by archaeological excavations (Prisset 2006), were tested in order to validate the results obtained with the radar and to assess the complementarity of the two approaches (Guarino 2018).

The first case study is focused on the last state of occupation of a house and a warehouse dated to the 2nd century AD. The first one, the *Maison de Sucellus*, is a domus of 1500 m² area, comprising a peristyle with three branches as well as a series of rooms whose function remains difficult to define because the remains have been leveled below the ground surface. However, we can identify the presence of a reception room overlooking a portico, which opened onto the garden with a rectangular basin with an apse. The second building, called the *Pillar Building*, is made up of a large courtyard framed by two rows of rooms. It is separated to the west from the *Maison de Sucellus* by a wide dividing wall. Excavations have shown that in the 1st century this same space was occupied by a single residence, the *Maison au Vivier*, located in the east-



Fig. 1: GPR survey in the rooms of the *Maison de Sucellus* at Saint-Romain-en-Gal (France). © C. Benech.

ern part with rooms organized around a large rectangular basin. The western part is occupied by the garden located 2 m below the house. This lower lying area was filled during the construction of the *Maison de Sucellus*.

The second case study concerns a space occupied in the last state of occupation by a market dated to the 2nd century AD. In the previous state, this space was occupied by a private house. Unlike the previous case, we therefore have a complete change of function between the two phases of occupations.

Materials and methods

Ground-penetrating radar prospecting was carried out using a Stream X multi-antenna radar array (IDS GeoRadar). It consists of 8 antennas spaced 12 cm apart, which allows for high-resolution recordings over a width of 72 cm in a single pass.

The nominal frequency of the antennas used is 200 MHz and the precise positioning of the measurements along a measurement profile is ensured by an RTK GNSS, which delivers an NMEA position string during the data acquisition. The data processing was carried out with the GPR-SLICE software and the resulting data images were then repositioned in the overall plan of the site using the QGIS software.

The radar prospection was carried out in each room of the two houses selected along parallel profiles with spacings following the size of the rooms in order to cover the maximum available surface which is already relatively small.

Results

In the first case study, GPR mapping made it possible to detect the major structural elements of the *Maison au Vivier*: the rectangular basin in particular, as well as the dividing wall between the dwelling and the garden appear clearly. The internal divisions of the rooms also appear, but some walls observed during excavation do not show up on the radar amplitude map. Some rooms are filled with soils that respond particularly well and make it possible to have a precise measurement of the levels of functioning, that corroborate those observed during excavation. Finally, certain linear elements appear in the zone occupied by the garden: they could be constructions or developments linked to the latter.

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Fig. 2: GPR survey of the *Maison de Sucellus*: the main characteristics of the *Maison au Vivier* are visible.

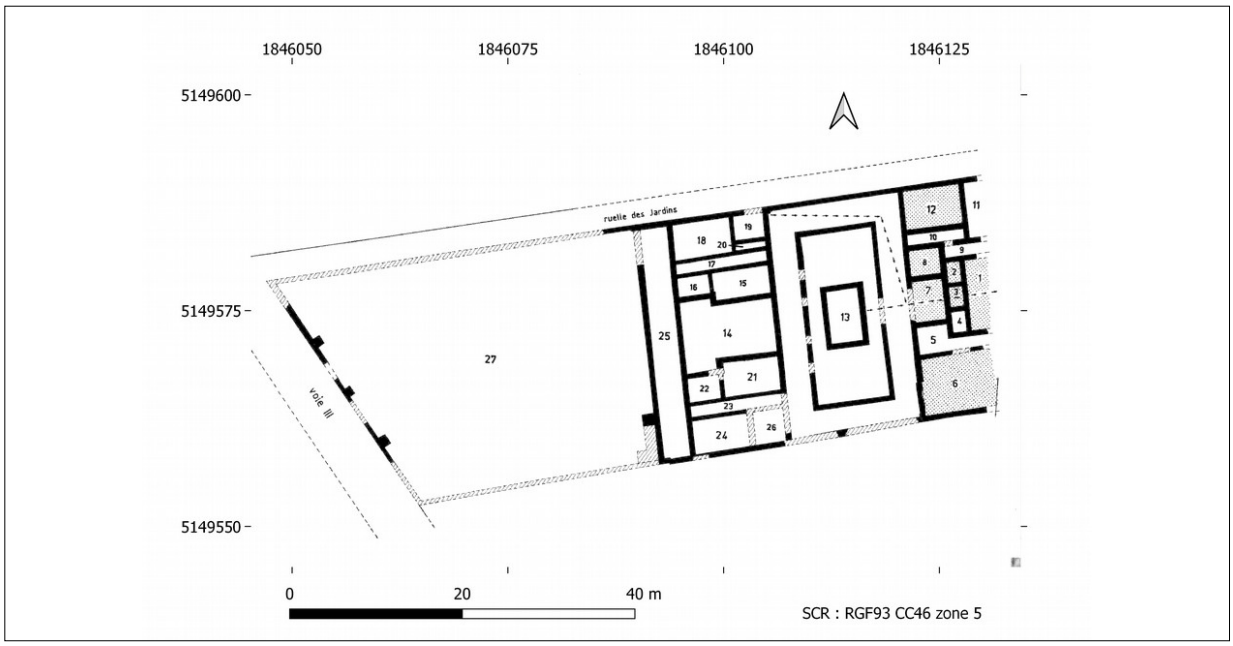

Fig. 3: Ground plan of the *Maison au Vivier*. DAO L. Brissaud.

In the second case, the results obtained are clearer for the southern and western parts of the house, where room divisions appear and complete those observed during the excavation. In the northern part, the division of rooms does not show up, perhaps because the walls were destroyed during the construction of the market. If these have disappeared, it is possible that certain highly reflective zones indicate the presence of floor levels of rooms, whose shape would nevertheless provide information on the internal organization in this part of the house.

Discussion and conclusion

These first two GPR tests on already excavated areas of Gallo-Roman buildings have shown the potential of this type of approach. In the two cases studied, the systematic exploration of all the open areas of the last state of occupation made it possible to identify the major divisions of the internal space of the buildings. However, some divisions are not visible, probably due to their destruction during reconstructions or after the abandonment of the site. The foundations of the last occupation also sometimes rest on the walls of the previous building state. Finally, the identification of ground levels provides valuable information on the operating levels of previous phases. Certain characteristic elements of the Roman house, such as a peristyle or a reception room, can make it quite easy to identify whether it is a public space or a private dwelling. If these latter elements are not clearly apparent, as in the case of the market, this discrimination may be more difficult to make.

The perception of the previous building phases of an urban space is often relatively restricted by the reluctance to destroy the most recent levels, and therefore the best preserved, in order to understand the evolution of this space. This type of research is therefore often the subject of very specific archaeological surveys when it comes to protected sites. The contribution of geophysics therefore makes it possible to obtain a broader and complementary vision, which allows the researcher to orient the excavation according to the study objectives. Our study shows once again all the potential of a joint and reasoned use of excavation and geophysical prospecting.

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Internal structure of the great tumulus of Apollonia as revealed by seismic tomography

Petros Bogiatzis [1,2*], George Vargemezis [1], Gregory Tsokas [1], Ilias Fikos [1], Eftychia Amanatidou [1], Nikolaos Kordatos [1], Prodromos Louvaris [1], Konstantinos Polydoropoulos [1], Alexandra Karamitrou [1,3]

1 Laboratory of Exploration Geophysics, Aristotle University of Thessaloniki, Greece
2 Ocean and Earth Sciences, University of Southampton, United Kingdom
3 Department of Archaeology, University of Southampton, United Kingdom
* Corresponding author: E-mail: petros.bogiatzis@geophysics.gr

Abstract
We investigate the tumulus of Apollonia using the NSTomo3D seismic tomography software. Results reveal P-wave velocities of >850 m/s at the perimeter and <650 m/s in the middle. High velocities are associated with travertine rocks that were used as building materials. Low velocities correspond to unconsolidated sediments used as filling material. Several structures revealed that are of potential archaeological interest.

Keywords
Apollonia; Macedonia; seismic tomography; tumulus

Introduction

The great tumulus of Apollonia in northern Greece is located ~50 km east of the city of Thessaloniki and ~3 km south of the lake Volvi. It is a part of the northern cemetery of the ancient city that was established ~1 km south of the tumulus. With a diameter of ~100 m and height of ~20 m, it is one the largest tumuli in the greater region of Macedonia. A series of previous geophysical surveys including electrical resistivity tomography and seismic soundings revealed complex internal structure (Tsokas et al. 2011). A recent limited excavation at the perimeter of the tumulus unearthed a looted rectangular Macedonian tomb of dimensions 7 × 4 m, founded on natural travertine rock (Acheilara et al. 2011). However, the possibility of additional burial monuments hidden within the tumulus necessitated further investigation by means of geophysical prospecting utilizing various methods, including a 3-D seismic tomography under the program EKATY.

Seismic methods are among the most popular in geophysical exploration over a wide range of applications including archaeology. Complex 3-D heterogeneity and strong topographic variations as in the case of imaging tumuli, may pose significant problems in 2-D surveys as the seismic wave propagation occurs in out of the plane directions. In such cases 3-D data acquisition and full 3-D inversion is crucial to obtain robust and meaningful images of the subsurface.

In this work we present the results of the 3-D P-wave travel time tomography of the great tumulus of Apollonia. For the tomographic inversion we have used the recently developed software NSTomo3D that allows to account for the topography and finite frequency effects by using finite frequency kernels instead of infinitely thin ray paths. Furthermore, it provides tools to efficiently calculate the full model resolution matrix that can be challenging in large inverse problems as such related to 3-D model inversions.

Data and methods

Data collection

The seismic tomography experiment was designed to provide a dense 3-D data coverage of the tumulus. A total of 24 geophones connected with a Geometrics StrataVisor seismograph were deployed in 13 locations that covered the

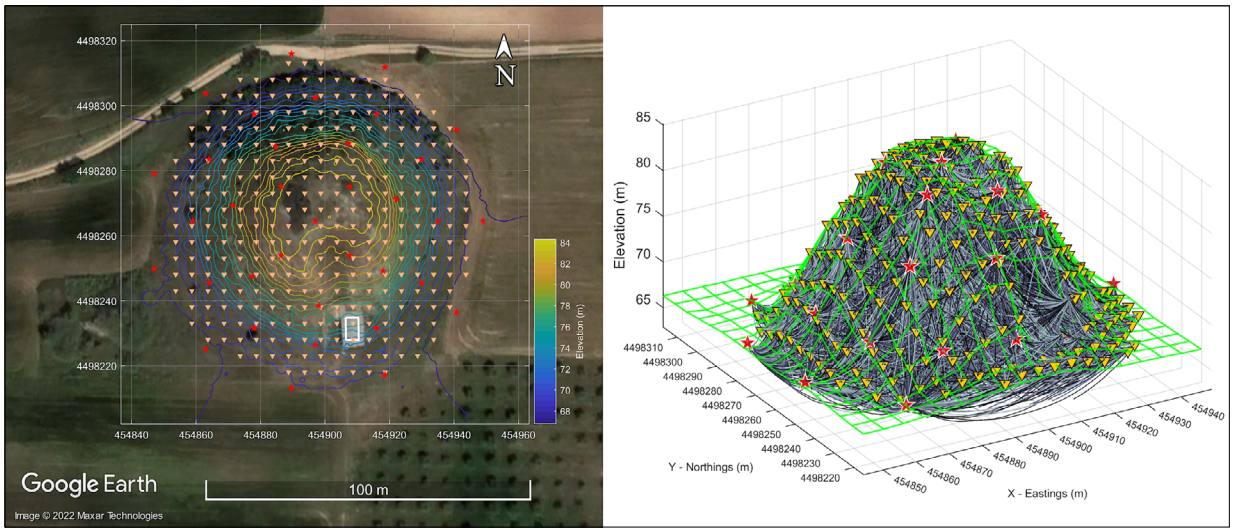

Fig. 1: The great tumulus of Apollonia. Left: satellite image obtained from Google Earth showing the tumulus and the surrounding region overlayed with the topography contours. The excavated area where the unearthed tomb can be seen as a white rectangle at the southern part of the tumulus. Locations of geophones and sources are shown with triangles and stars, respectively. Right: ray paths that correspond to the picked travel times. The map projection is the Hellenic Geodetic Reference System 1987, in m.

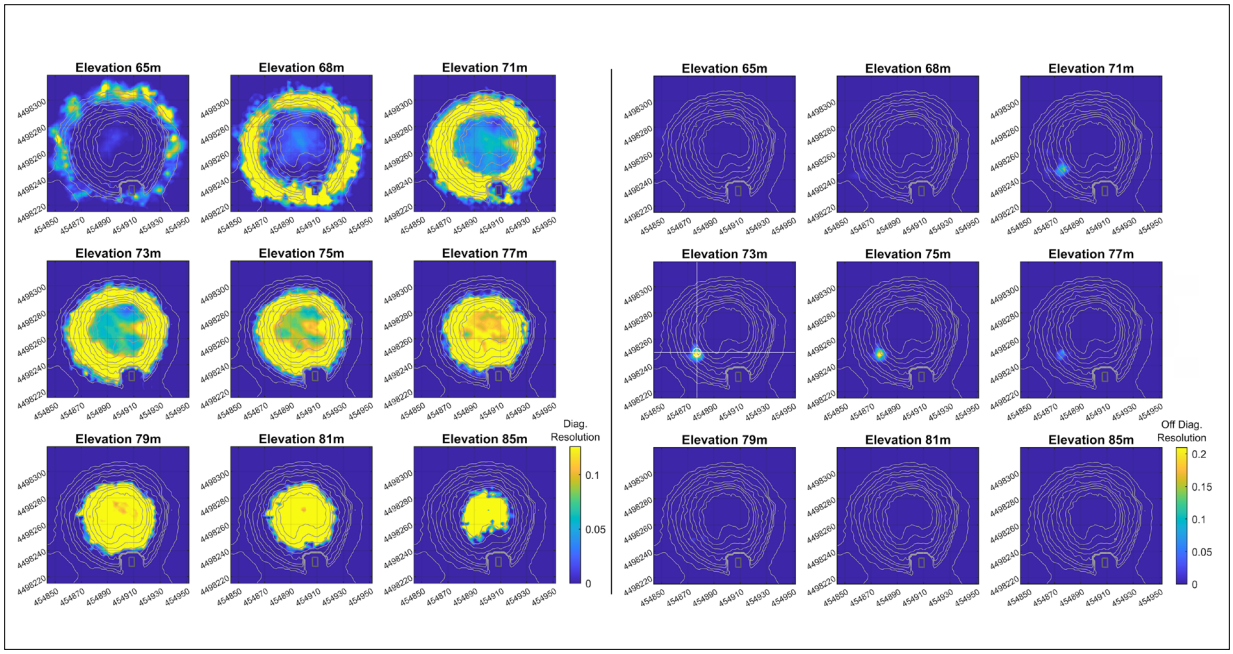

Fig. 2: Resolution analysis. Horizontal depth-slices showing (left) the diagonal elements of the resolution matrix and (right) the off-diagonal resolution corresponding to the point marked with the cross.

surface of the tumulus, forming a regular grid with spacing of 5 m. For each array/geophone a total of 33 P-wave sources uniformly distributed on the surface of the tumulus were established using a sledgehammer (Fig. 1). A total of 8,579 usable P-wave travel times were picked together with their error estimates, corresponding to 267 different geophone locations. Analysis of the frequency spectrum at a window around first P-wave arrival yielded a dominant frequency of ~40 Hz. This frequency was used in the calculation of the sensitivity kernels (Bogiatzis et al. 2022).

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Method

For the forward problem a high-quality irregular grid was constructed that included explicitly points delineating the topography. Grid points on the air were fixed during the inversion to the velocity of P-waves in the air (343 m/s). We inverted using damping and smoothing constraints. The optimal weighting of the constraints was derived through a 2-D L-curve analysis (Aster et al. 2013). The starting model was homogeneous medium with velocity of 600 m/s inferred by averaging the apparent velocities of the picked traveltimes ensuring that the errors follow a zero-centered Gaussian distribution. The inversion converged after ∼30 iterations achieving reduction of the RMS error of ∼43%. In addition to the velocity model, the full model resolution matrix was calculated efficiently using direct sparse methods and the Dulmage Mendelsohn decomposition (Bogiatzis et al. 2019) allowing to evaluate the robustness of the imaged features (Fig. 2 left). The off-diagonal elements of the resolution matrix show the extend of smearing/averaging of a hypothetical spike anomaly in the estimated tomographic model for each one of the model parameters. This allows the estimation of the 3-D resolution length, which in this case is less than ∼4 meters (Fig. 2 right).

Results

Large velocities >850 m/s are imaged in the perimeter of the tumulus and relatively low velocities <650 m/s in the central region (Fig. 3). This is consistent with presence of travertine rocks perimetrical, some of which are visible in the area and at the unearthed tomb. At the eastern and southern sides, the high-velocity anomalies are continuous and of high amplitudes. On the western side the high velocities have generally lower amplitudes and appear fragmented but wider as they extend closer to the center. The perimetrical ring of high velocities is interrupted at the northern side, where the velocities are similar to the interior of the mount, corresponding to unconsolidated soil. A general increase of the velocity with depth, can be attributed to pressurization of the sediments due to the overburden. A small high-velocity anomaly at the top of the mount is related with a modern concrete-made structure, used as topographic station.

Discussion and conclusion

Our results suggest that the Apollonia tumulus was founded using hard materials i.e., travertine rock, to form an open dome that subsequently was filled with soil. The western side of the dome which is segmented presents more complexity and interesting pockets of low velocities indicating possible targets of archaeological interest. The excavated tomb appears to lie in the region of high velocities. The interior of the tumulus appears less heterogeneous with no obvious targets. Our results are in good agreement with previous seismic soundings (Tsokas et al. 2011).

Acknowledgments

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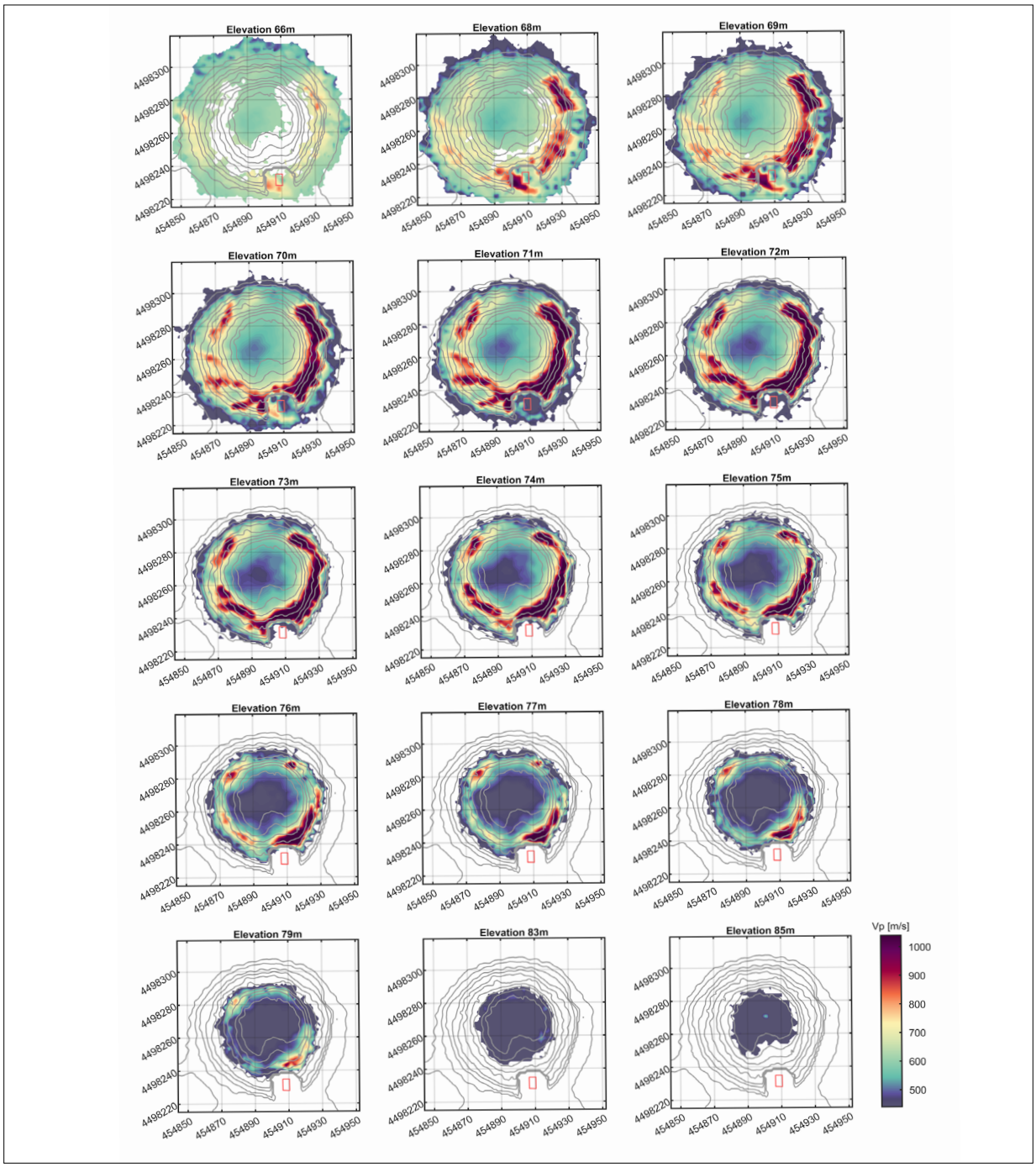

Fig. 3: P-wave velocity model. Horizontal slices at different elevations with the P-wave velocity.

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Combining remote sensing and geophysical data to determine Roman structures at Buzovytsia-1 settlement in Ukraine

Kseniia Bondar [1*], Oleg Petrauskas [2], Dmytro Mostovyi [3], Serhii Didenko [4], Roman Reida [2]

1 Taras Shevchenko National University of Kyiv, Kyiv, Ukraine
2 Institute of Archaeology of the NAS of Ukraine, Kyiv, Ukraine
3 Scientific Research Centre 'Rescue Archaeological Service' of the Institute of Archaeology of the National Academy of Science of Ukraine, Lviv, Ukraine
4 National Museum of the History of Ukraine, Kyiv, Ukraine
* Corresponding author: E-mail: ks_bondar@ukr.net

Abstract
An archaeological map of Buzovitsya-1 Roman time site was obtained based on a combination of geophysical and remote sensing results. The KH-9 Hexagon image reveals Roman structures.

Keywords
Buzovytsia-1 settlement; GPR; magnetometry; Roman building; satellite image

Introduction

Application of multiple methods increases the reliability of space reconstructions on archaeological sites. The paper represents an attempt to assemble relevant evidence from magnetometer and ground penetrating radar (GPR) surveys, remote sensing and geospatial investigations, results of limited archaeological excavations to recognize Roman structures on the Buzovytsia-1 settlement recently discovered in Chernivtsi region (Ukraine). It was demonstrated that neither a magnetometer survey nor a GPR survey is able to resolve all the archaeological issues on the sites of the region (Bondar et al. 2022a). Challenging conditions for magnetometry are represented by the use of limestone as a building material for Roman structures, and for GPR by high clay content in the soil causing adsorption of electromagnetic waves, and thus providing poor depth for GPR exploration. However, magnetometry can find baked clay structures and, in some cases, refilled pits, while GPR still can detect shallow stone structures. We involved remote sensing data to obtain additional archaeological information from the color of the topsoil varying with its composition.

Materials and methods

Buzovytsia-1 is the largest site of Chernyakhiv - Sântana de Mureş archaeological culture on the territory of Ukraine, which had been functioning during the late 2nd to the middle of the 5th centuries AD. It was discovered due to Roman imports found on the ground surface, as well as material pieces of evidence of Roman construction technologies - fragments of limestone, lime mortar, and bricks.

Geophysical data were collected with the use of total field cesium magnetometer PKM-1 on an area of 2 ha and ground penetrating radar VIY-3 with nominal center frequency 300 MHz antenna on a small plot of 25x25 m.

Declassified analogue panchromatic satellite image from the American reconnaissance program Hexagon (KH-9), taken on 21 May 1974 with the 0.6-1.2 m per pixel resolution has been used to analyse the localization of clusters of construction materials.

Limited archaeological trenching on an area of 48 m² has been performed to validate non-invasive results.

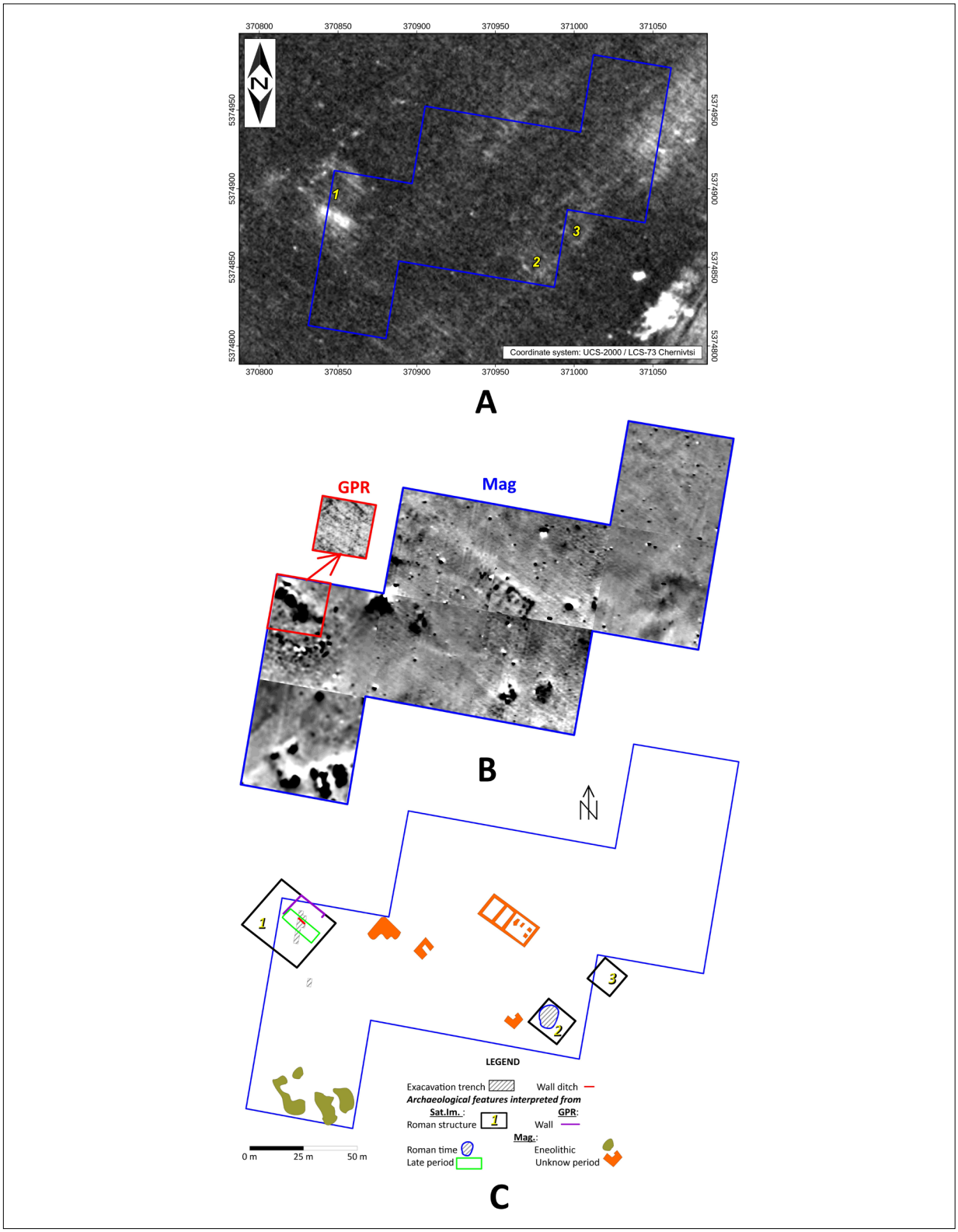

Fig. 1: Buzovytsia-1 settlement. a) Quasi-rectangular anomalies detected on a satellite image from the American reconnaissance program Hexagon (KH-9), taken at 21 May 1974. b) Geophysical results: magnetogram in greyscale and dynamics of the total magnetic field ± 5.0 nT, black is high, and GPR C-scan at a time of 12-15 ns, strong reflections are black. c) Interpretation scheme.

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Results

Remote sensing

The raster obtained as a result of the satellite image classification made it possible to trace three quasi-rectangular spots among the arable agricultural lands (Fig. 1a). The largest one (marked as 1) appeared to be at the place of a building remains cluster. Its approximate area is about 1400 m². The outer parts of the largest spot are whitish, while the inner rectangular-shaped area with dimensions 17x30 m is dark like the background of the field. Two other spots recognized from the image also have a quasi-square shape. We suggest them to be the places of an ancient building. Whitish areas at the edges of the spots correspond to the localization of ploughed building remains available at the moment the image was captured (1974).

Magnetometry

The area includes several types of magnetic anomalies (Bondar and Petrauskas 2021). Strong ones in the southwest are characteristic of and definitely sourced from Eneolithic buildings of Trypillian archaeological culture. A chain of positive magnetic anomalies with maximum intensities of 10-30 nT appeared at the upper slope within the area of spot 1 (Fig. 1b). However, most of the building's baked clay fragments were lying 10 m down the slope and creating an assembly of small and weak positive anomalies. The oval-shaped positive anomaly coincides with spot 2. A well-preserved building retaining the internal layout is suggested under the anomaly in the center. Quasi-right angles could be recognized in the shapes of some other anomalies.

Ground penetrating radar

On the C-scan there are two perpendicular linear anomalies in the time interval of 12-15 ns (Fig. 1b). The anomalies are formed by strong reflections, evidencing significant contrast of dielectric permittivity between the source structure and soil. The structure fits well with the northern whitish part of the characteristic spot 1 on the Hexagon image.

Archaeological excavations

The main excavation trench was laid to the north from the surface cluster of the building remains (Fig. 1c) in order to cut the strong magnetic anomaly. The wall ditch of the ancient building was discovered. A trench from the late period runs along the wall ditch of the building. To the south of it, rectangular blocks fastened with mortar, sections of concrete fill and four pillars were unearthed.

Discussion

Excavation data definitely testify to the remains of a building constructed using Roman technologies - building materials (plinth, mortar) and architecture (warm floor - *hypocaustum*). Findings from excavations and walkover surveys are identical. The cylindrical plinth was found in the excavation in situ at a depth of 1.4 m, and 20 m down the slope, the same plinth was found on the surface. Thus, these finds could belong to the same building.

In the 1950s, there was a small quarry on the territory of the settlement, from where limestone was mined by locals. This provides an explanation for the origin of the trench uncovered at the place of the ancient building`s wall. We assume a massive stone wall was clearly visible on the surface at that time, and the trench was dug to extract the stone. The chain of magnetic anomalies, obviously, was formed as a result of gradual refill of the abandoned trench with topsoil material, acquiring detrital remanent magnetization (Bondar et al. 2022b).

In the 1970s, intensive ploughing of the settlement territory began, as a result of which building materials of ancient structures appeared on the surface. This is the explanation for the origin of the whitish edgings of spots 1, 2 and 3 recorded in the Hexagon image. The southern edge of spot 1 looks brighter and is located on a terrain with a steeper slope. We assume remains of the southern wall of structure 1 to lie on a smaller depth and, thus, to have been ploughed more intensively. To date, construction remains are concentrated only in the southern part of spot 1. The northern part of structure 1 is supposedly better preserved, which is recognized from GPR data.

Thus, the wall uncovered in the excavation trench is the intrinsic wall of the building separating a room with *hypocaustum*.

Conclusion

The results of magnetometer and ground penetrating radar surveys, and remote sensing investigations proven by archaeological excavations testify to Roman

architectural structure (presumably, *villa rustica* - style) with an approximate size of 27x32 m.

Putting together all elements interpreted from different surveys allowed us to propose a preliminary archaeological map of the site (Fig. 1c) and define future targets for archaeological excavations.

Acknowledgments

Geophysical work was undertaken with support provided by the International Society for Archaeological Prospection, through the ISAP Fund grant scheme.

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Can magnetic susceptibility data separate archaeological palimpsests? A case study from the Hess Creek site in interior Alaska with archaeological prospection implications

Robert C. Bowman[1*], Kate S. Yeske[1], Holly McKinney[2]

1 Northern Land Use Research Alaska LLC, Fairbanks, Alaska, United States of America
2 Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska, United States of America
* Corresponding author: E-mail: rcb@northernlanduse.com

Abstract
Magnetic Susceptibility (MS) is applied at a high latitude Interior Alaskan site. MS is implemented in breaking apart cultural palimpsests. MS acts as a proxy for assigning archaeological traditions and complexes. MS functions as a prospection tool for site excavation expansion.

Keywords
archaeological prospection; interior Alaska; magnetic susceptibility; palimpsests; post-depositional disturbance

Introduction

Archaeological sites containing palimpsests are found the world over; however, they are increasingly common in locations subjected to advanced disturbances, such as areas containing increased bioturbation, cryoturbation, and solifluction (Rapp and Hill 2006). In Interior Alaska, cryoturbation and solifluction are common factors in site disturbance, and they have likely led to differing interpretations regarding site chronology, occupation, and prehistoric landscape use strategies.

In 2021, Northern Land Use Research Alaska, LLC (NLURA) archaeologists conducted partial excavation of the Hess Creek Site (LIV-00001), located 113.5 km north of Fairbanks and 36 km south of the Yukon River, along the Dalton Highway in Interior Alaska (Fig. 1). The partial excavation of the Hess Creek Site was completed as a mitigative measure defined under a Memorandum of Agreement between the Alaska State Historic Preservation Officer and the Alaska Department of Transportation and Public Facilities for a new gravel source in support of road mainte nance and construction projects. While some portions of the Hess Creek Site displayed minimal disturbance, stratigraphic data and artifact provenance throughout most of the location suggest post-depositional displacement from both cryoturbation and solifluction, leading to the formation of a site-wide palimpsest of cultural materials. Additionally, diagnostic artifacts and radiocarbon-dated materials indicate that this location was used repeatedly, beginning in the Terminal Pleistocene up until the Late Holocene, with artifacts typically assigned to three or four chronologically distinct archaeological traditions and complexes.

Materials and methods

During the field effort, both field-based environmental and laboratory-controlled Magnetic Susceptibility (MS) techniques were used to collect additional proxy data that could be used to further separate the collective assemblage into chronologically controlled cultural zones. In all excavation units (EUs) or blocks excavated, samples were taken in a column within locations displaying the lowest degree of visually observed stratigraphic distur-

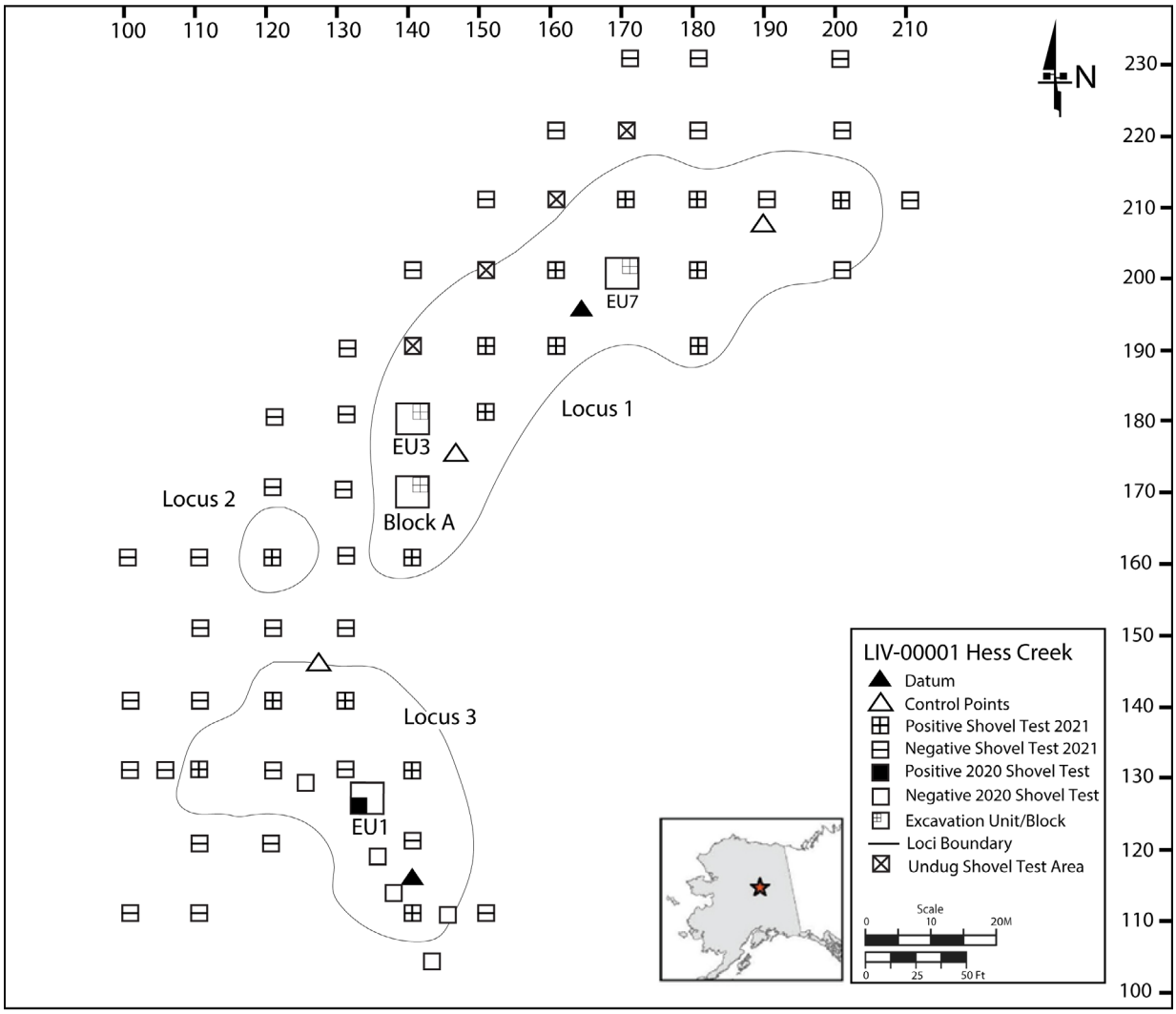

Fig. 1: Location of the Hess Creek Site (LIV-00001) detailing the excavation program across the site and observed loci.

bance. In the field, laboratory MS samples were acquired using five-centimeter-wide cubic boxes arranged vertically within the stratigraphic profile (Fig. 2). Prior to removing sample boxes from the walls of each EU or block, environmental MS was collected using a Bartington MS2E field unit with a MS3 meter and a Trimble Nomad field data logger equipped with Bartsoft software, which is designed to collect MS data directly in the field without additional sampling and processing. This data was taken approximately five centimeters away from, and parallel to, each column of cubic boxes. All samples were taken from the base of the root mat to the base of the excavation, which terminated on bedrock.

While results from the MS2E assembly were acquired directly in the field, laboratory samples needed to be transported and processed before data could be obtained. Data on laboratory MS samples was acquired using a Bartington MS3 meter with an MS2B laboratory-based unit. All samples were dried and placed in scalation vials prior to analysis. Low frequency and high frequency data was collected for each sample and frequency dependence percentages were calculated using Bartsoft software. Previous analyses conducted by Dalan (2006; 2008) show that both frequencies and calculations of percent dependence may provide information regarding cultural behavior at sites, with frequency dependence showing the highest degree of correlation with cultural alteration on the landscape.

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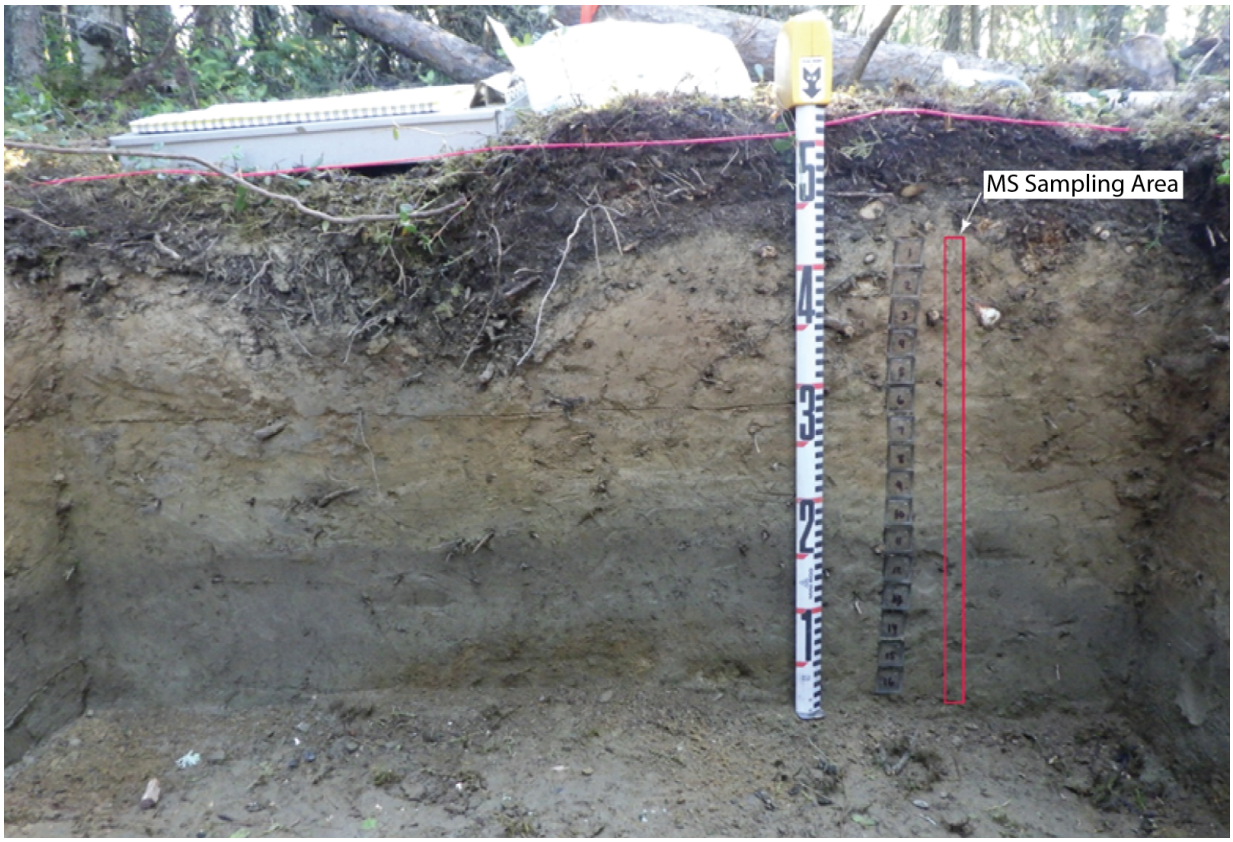

Fig. 2: Example of field and laboratory-based MS column sampling within EU3 and the Hess Creek Site (LIV-00001).

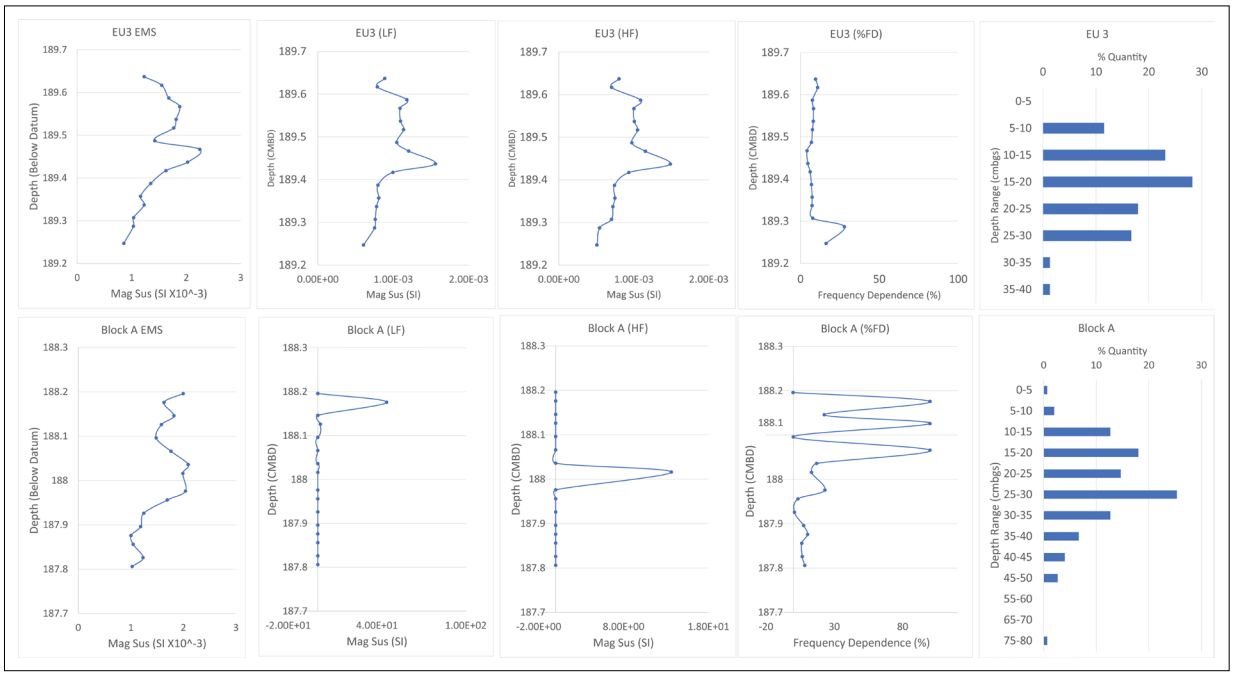

Fig. 3: MS results from EU3 and Block A from the Hess Creek Site (LIV-00001). EMS (Environmental Magnetic Susceptibility) indicates data collected with the MS2E field unit. All following data was collected from processed laboratory samples. Data on the far-right correlates to the percentage of artifacts recovered with five-centimeter excavation levels.

Results

MS data collected from several units at the site could not be properly parsed out due to advanced post-depositional alteration from colluvial forces, cryoturbation, and solifluction; however, results collected from the least visually perturbed sections of EU3 and Block A indicate that layers displaying increased quantities of artifacts with corresponding radiocarbon dates contained heightened MS values (Fig. 3).

Within EU3, an increase in MS values from 25 to 35 centimeters below ground surface (cmbgs) correlates with a larger excavated pit feature dating to 2515 to 2760 calendar years before present (cal BP). Frequency dependence also greatly increases in EU3 from 45 to 50 cmbgs, which is equivalent in depth with the base of the sampled pit feature.

Additionally, data obtained from Block A displays increased MS values throughout the stratigraphic column from 15 to 40 cmbgs alongside an increased quantity of artifacts and radiocarbon dates indicating occupation between 1405 and 1865 cal BP. A small increase in MS was also observed at the base of Block A from 50 to 55 cmbgs. This depth corresponds with the presence of a diagnostic Chindadn projectile point (associated with the Nenana Complex).

Discussion

Heightened MS values often displayed a strong correlation with archaeological layers at LIV-00001. Materials associated with high MS values in EU3 are associated with the Northern Archaic tradition, which spans from approximately 6,000 to 2,000 cal BP within this portion of Interior Alaska (Esdale 2008). Alternatively, higher MS values in Block A likely indicate repeated use of the site associated during the Athabascan tradition, which was present in the region between 2,000 cal BP and Anno Domini (AD) 1880 (Sheppard 2001). However, this pattern may also be the product of cryoturbation, which was visually present in these upper layers. The presence of high MS values at the base of Block A (associated Nenana Complex artifacts) indicates repeated use of the site beginning in the Terminal Pleistocene (between approximately 13,800 and 11,300 cal BP (Hoffecker 1983; Pearson 1997; Powers and Hoffecker 1989)).

Conclusion

Results from this study indicate that MS can be a powerful tool in parsing apart perturbed sites, especially when other proxy datasets are available for comparison. Since palimpsests are not uncommon in Alaska, the adoption of this technique is likely to yield additional informative results in the future and may be useful as a prospection technique for future excavation planning. This is demonstrated by the MS values obtained at the Hess Creek Site which indicate that expansion of both EU3 and Block A to the north and east directions would likely uncover more cultural material from the cultural zones described above.

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The structure of the burial mounds in the Eastern Hallstatt areas: a geophysical approach

Zoltán Czajlik [1*], Matija Črešnar [2*], Branko Mušič [2], Barbara Horn [2], Sándor Puszta [3], Eszter Fejér [1], Balázs Nagy [4], László Rupnik [1]

1 Department of Archeometry and Archaeological Heritage, Institute of Archaeological Sciences, Faculty of Humanities, Eötvös Loránd University, Budapest, Hungary
2 Centre for interdisciplinary research in archaeology, Department of Archaeology, Faculty of Arts, University of Ljubljana, Ljubljana, Slovenia
3 Independent researcher, Budapest, Hungary
4 Department of Physical Geography, Faculty of Sciences, Eötvös Loránd University, Budapest, Hungary
* Corresponding authors: E-mail: czajlik.zoltan@btk.elte.hu, matija.cresnar@ff.uni-lj.si

Abstract
Prospecting ploughed-out/erased burial mounds is an important part of the Early Iron Age sites research. A complex use of geophysical methods in forested areas is effective also in the case of tracing the construction of burial mounds. Burial mounds that appear similar on the DSM have relevant differences in their construction.

Keywords
burial mounds; Eastern Hallstatt culture; ERT; GPR; magnetometer prospection

Introduction

In the Early Iron Age (EIA), fortified hilltop settlements and (extensive) tumulus fields began to appear in the broader eastern Alpine region, also referred to as the eastern Hallstatt area. This is considered a fundamental and large-scale landscape transformation, creating site-complexes of more than 100 ha. As the main research focus was usually on the burial chambers and the riches they contained, only traditional fieldwork strategies (mainly excavations) were employed. In contrast, only little data was collected on the complete burial mound construction and especially on the areas between the individual barrows and the possible further sites in the area. Basic questions, like how many settlements and necropolises are in these site agglomerations, where are the borders of the site complexes, what are the limits of the single sites in it, what are the typical constructions of the burial mounds, often remain unanswered to this day.

Within the framework of a Hungarian-Slovenian project starting in 2020-2021, the two case study EIA site complexes of Süttő (HU) and Poštela (SLO) have been further investigated. Both have a long history of traditional research, but we tried to investigate them from a landscape archaeological perspective (Czajlik et al. 2019; Teržan and Črešnar 2021; for previous similar researches: von der Osten-Woldenburg 2011; Lindinger 2020). A more detailed prospection of the sites is important to analyse the similarities/differences in land use of the site complexes, which are situated in different geographical position within the Eastern Hallstatt Circle. As the fortified settlements on both site complexes are better examined, we now turn our focus on necropolises. At Süttő, out of the four known groups of burial mounds, three are mapped by magnetometer measurements. The fourth group is actually in a thicket bush, making it impossible to carry out geophysical investigation. At Poštela, the two distinct groups of burial mounds at the Habakuk-plateau are mapped geophysically, the measurements of the third group at Pivola is almost finished.

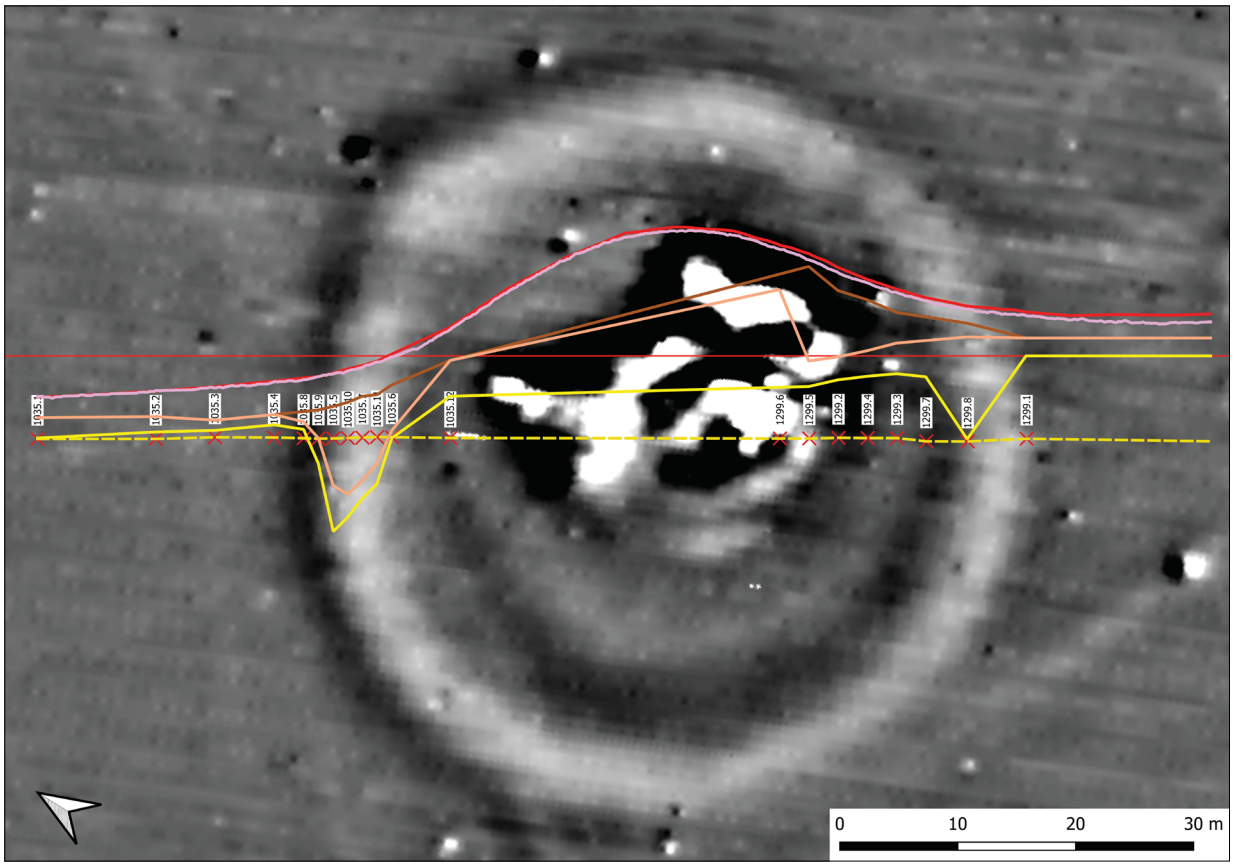

Fig. 1: Süttő – Sáncföldek (Komárom-Esztergom county, N Hungary): Magnetometer mapping and archaeological geomorphological coring results of tumulus 2 (in tumulus group "E"). Magnetic survey was carried out with GSM-19W Overhauser magnetometers in rover mode, positioning with Trimble Geo 7X GPS. The measured points are 0.5 m in-line, the distance between the lines is 0.75 m. The cross-profile is based on 20 shallow (1.1-2.75 m) boreholes in the original and anthropogenic disturbed loessy sediment of the Süttő-plateau. The dashed line shows the location of the profile across the tumulus.

Methods

The structure of the known burial mounds at Poštela has been largely preserved thanks to their location in forested areas, while most of the tumuli at Süttő are situated in a heavily cultivated area. On the loess plateau of Süttő - besides the natural erosion - they have been lowered and widened by agricultural planning (The limestone rock from the structures of burial chambers are often on the surface.). The current morphometrical parameters of the tumuli-surface are highly different from the original landforms. This difference is also the key factor in selecting the appropriate geophysical methods and/or a combination of them. At Süttő magnetometer (GSM-19W Overhauser magnetometers in rover mode, positioning with Trimble Geo 7X GPS) prospection was used. The measured points were 0.5 m in-line, the distance between the lines was 0.75 m. At Poštela a combination of magnetometry (Geometrics G-858, gradient mode), GPR (GSSI SIR 3000, 400 MHz) and ERT (ARES) was applied.

At both sites digital surface model (DSM) was developed using airborne laser scanning (ALS) data was developed, in case of Süttő based partly on unmanned aerial vehicle (UAV) photogrammetry. Further methods, such as aerial archaeology, coring and grid sampling were also used.

Results

There is a good correlation between the burial mounds, identified using ALS, and the burial mounds mapped by geophysical investigations (Fig. 1). Some further archaeological features, for example circular ditches were detected using geophysical methods. The circular ditches are typical in Süttő, although some burial mound do not have this structure.

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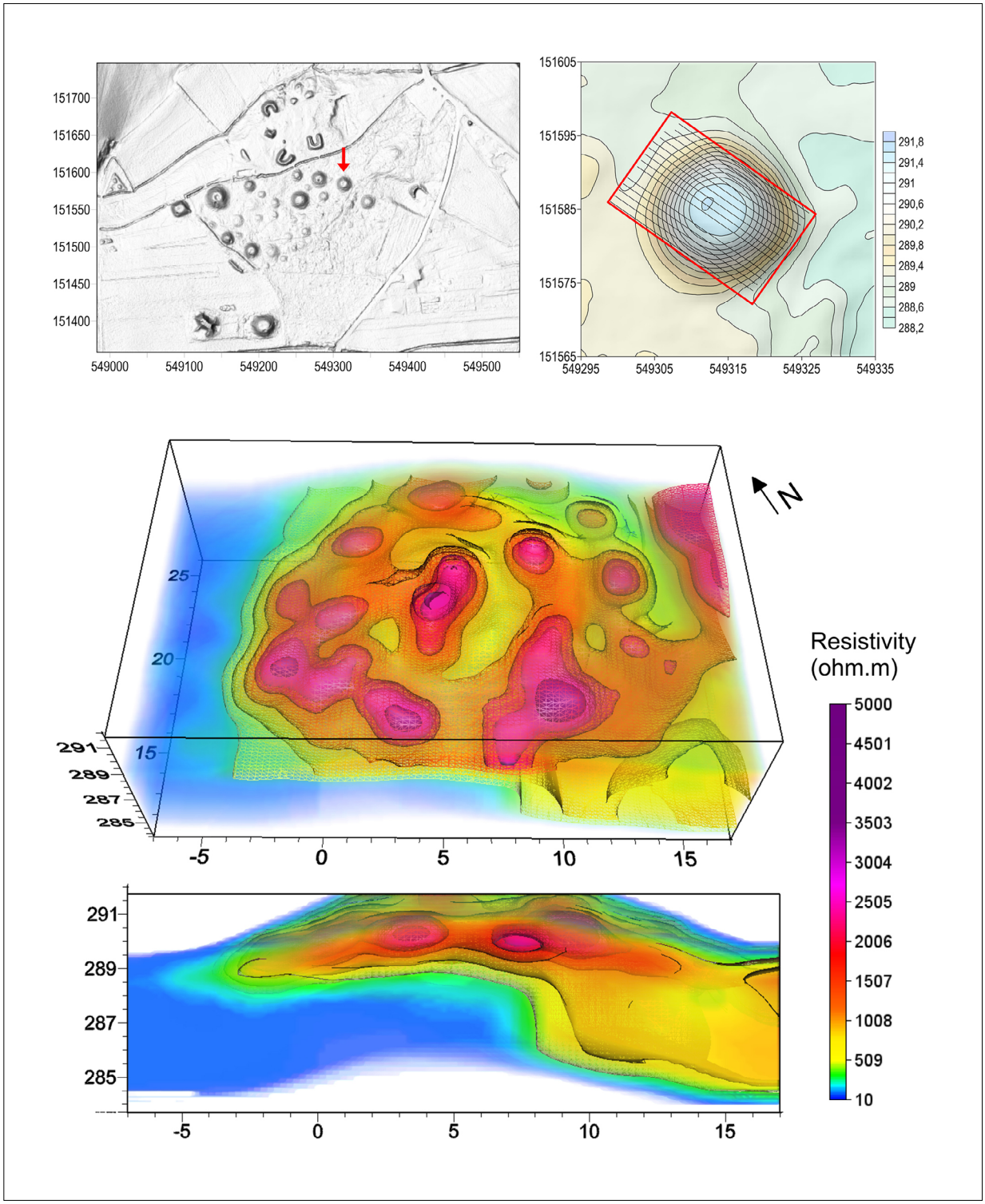

Fig. 2: Pivola (Podravska region, NE Slovenia): 3D electrical resistivity tomography (ERT) inversion model of a prehistoric burial mound at the largest necropolis of the Early Iron Age Poštela hillfort. The resistivity model was obtained from 14 parallel 2D ERT lines (measured with a dipole–dipole electrode configuration, an electrode spacing 0.6 m and a distance of 1 m between lines). The high resistivity anomalies most likely indicate the presence of stone material within the mound (i.e., burial chamber material), as well as partly lower moisture content of the mound. The low resistivity of the ground indicates predominantly clayey material, while the medium resistivity indicates coarse gravelly sediments.

Similarly, at Poštela the burial mounds were also surrounded by ditches, which have only recently been recognized with the help of ALS in geophysics. In both site complexes the bigger mounds have a burial chamber made of stone, which can be absent in the case of the smaller constructions. Lately, at Poštela, near Radvanje, evidence of a barely known group of tumuli emerged thanks to aerial photography.

Discussion

Due to the magnetometer geophysical survey, we can define the limits of the tumulus groups, the exact number of burial mounds, their dimensions, including that of the circular ditches, confirmed by coring. The stone burial chambers appear on the magnetometer maps, but their orientation and form must be defined using a combination of GPR- and ERT-measurements. The latter produced data in 3D, which could prove significant in architectural reconstructions in the future (Fig. 2).

Conclusion

We have the following evidence, collected in the course of the geophysical prospection of the Early Iron Age burial mounds at Poštela and Süttő:

- DSM (ALS/photogrammetry) is an important data set in the background of geophysical mapping.
- The workflow is depending on actual surface coverage and land use.
- In the case of intensive agricultural use, a combination of aerial photography, large surface magnetometer investigation and coring is effective. An important factor is the erosion of the burial mounds.
- In forested areas, a combination of different geophysical methods (GPR, magnetometry and ERT) seems successful.

An important goal of the project is to share our expertise at both site complexes, thus increasing our knowledge of both. We hope to complete the maps of the necropolises and possibly identify the distinct details about tumuli construction that would allow us to perform deeper topographical analyses.

Acknowledgments

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Geophysical prospections support the historical identification of the archaeological site at Lake Gala, Hebros/Maritsa/Meriç delta (Turkey)

Anca Dan [1*], Ercan Erkul [2*], Simon Fischer [2], Harald Stümpel [2], Sait Başaran [3,4], Elif Çokaman [4], Luc Lapierre [1], Helmut Brückner [5], Wolfgang Rabbel [2]

1 AOROC, CNRS, ENS, University Paris Sciences & Letters, France
2 Institute of Geosciences, Kiel University, Kiel, Germany
3 Archaeology, University of Istanbul, Turkey
4 Ministry of Culture, Turkey
5 Institute for Geography, University of Cologne, Germany
* Corresponding authors: E-mails: anca-cristina.dan@ens.psl.eu, ercan.erkul@ifg.uni-kiel.de

Abstract
Archaeological survey and combined geophysical measurements of magnetics were conducted. Geoelectrics and ground penetrating radar support the interpretation of a Roman station controlling a branch of the Via Egnatia leading to Ainos (modern Enez in Turkey). The site could be the first archaeological example of a road station in Thrace, constructed between the 1st and the 2nd century CE.

Keywords
geophysical survey (ERT, MAG, GPR); Hebros / Meriç River; historical and archaeological identification; Roman road; Thrace

Introduction

Between the 1st and the 2nd century CE, the Romans extended the sites and roads network of the Via Egnatia along the lower course of the Hebros. On the right bank of the river (now in Greece), the town of Doriskos was replaced by Traianopolis (Loukopoulou et al. 2005; Tsatsopoulou-Kaloudi 2015). On the left side (now in Turkey), besides the paved road leading to the city of Ainos (modern Enez), the Romans built at least one station overseeing the crossing over the Hebros and the Stentoris Lake (part of which still exists in the modern Gala Lake, cf. Gerhard 1929). We present here the first geophysical and archaeological attempt at studying the Eastern part of Via Egnatia and at identifying one of its stations in Thrace.

Materials and methods

Roman architectural marbles up to 1 m, including fragments of architraves-friezes, a soffit decorated with a simple panel with concave extremities, smooth shafts of columns and pilasters are visible on a promontory overhanging the SE shoreline of the Gala Lake, less than 10 km NE from Ainos (Fig. 1, Fig. 2 L1). Between the foot of the promontory and an ephemeral swamp filled with colluvial and alluvial deposits ca. 700 m to the SW (L2), parts of a Roman paved road, ca. 4 m large, emerge from the lake (Fig. 2 b, L3). The road's structure is similar with portions found before entering Ainos, but also with a segment continuing ca. 4 km further to the NNE on the shore of the Gala Lake, up the Byzantine village of Ntukenion (today Döken; Başaran 1999; Külzer 2008; Yeşil et al. 2017).

After registering the major archaeological pieces visible on the promontory (Fig. 2 c – h, L1), magnetic (MAG), electric resistivity (ERT) and georadar (GPR) measurements were conducted, in order to find out the plan and the depth of the Roman constructions (Fig. 3). For the MAG, a magnetometer array with 4 fluxgate probes (type



Fig. 1: Site location map of the investigation area on Lake Gala, Turkey (satellite image: Google Earth, Image Landsat/Copernicus).

Ferrex CON650, by Dr. Förster) was installed on a manual cart. The probes were mounted at intervals of 0.5 m, so that each parallel profile covered a 2 m width. In-line, measurements were taken every 5 cm. The ERT mapping was carried out with the RESECS-Multielectrode-System. A total of 23 electrical profiles, each of them 32 m long, were measured with the configurations Dipole-Dipole and Wenner. The distance between electrodes and parallel profiles was of 1 m. The pseudosections were inverted in 2D using the open-source software BERT (Günther and Rücker 2015). For the GPR, a single-channel instrument, SIR 4000 by GSSI, was used with a dual frequency antenna, including the main frequency bands of 300 MHz and 800 MHz. The profile spacing was 0.3 m and a scan was recorded in-line approximately every 2 cm.

Results

On the promontory L1, the marble pieces belong to a Roman public construction (Fig. 2 c - h). The absence of vegetal decoration suggests a date before the 3rd century CE (the soffit in the Fig. 2e has Micrasiatic parallels in the second half of the 1st or the beginning of the 2nd century CE, cf. Wegner 1978-1980; Cavalier 2005).

The geophysical measurements (Fig. 3) revealed rests of the foundations, parallel with the terrace overhanging the road: in the NW part of the magnetic survey, 9 m long linear anomalies in a rectangular pattern could correspond to load-bearing walls. To the S, anomalies are concentrated in two rectangular areas (rooms?) with an extension of ca. 9 m x 10 m and ca. 5 m x 6 m. Electrical resistivities up to 500 Ohmm are observed here at depths between 20 cm and 50 cm, while in the surrounding area they are below 50 Ohmm. Linear reflection patterns are observed in the GPR time slice that correlate with the MAG and ERT anomaly patterns.

Discussion

The monumental complex, to which belong the marbles and maybe the 9 m long linear anomalies, was built in the early Roman imperial period. The pattern and orientation

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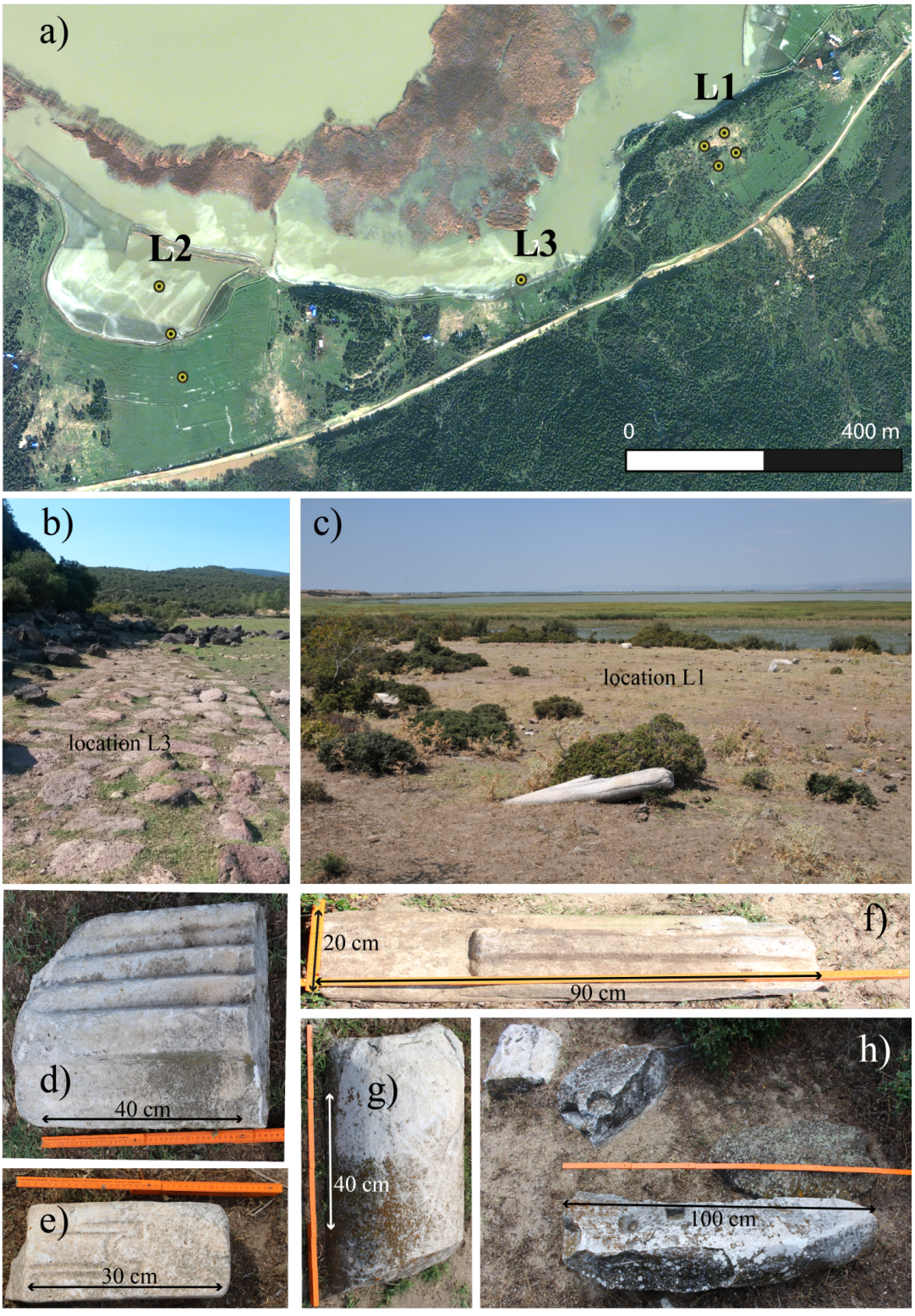

Fig. 2: a) The locations of the promontory of the identified station (L1), the ephemeral swamp (L2) and the Roman road (L3), on a satellite image of the sites (Pléiades © CNES (2022), Distribution AIRBUS DS). b) the Roman road L3 in front of the ephemeral swamp L2, view towards W. c) the archaeological site L1, view towards NW. d) Roman marble fragments of an architrave, e) soffit, f) door frame, c) and g) column, h) threshold and other blocs from L1.

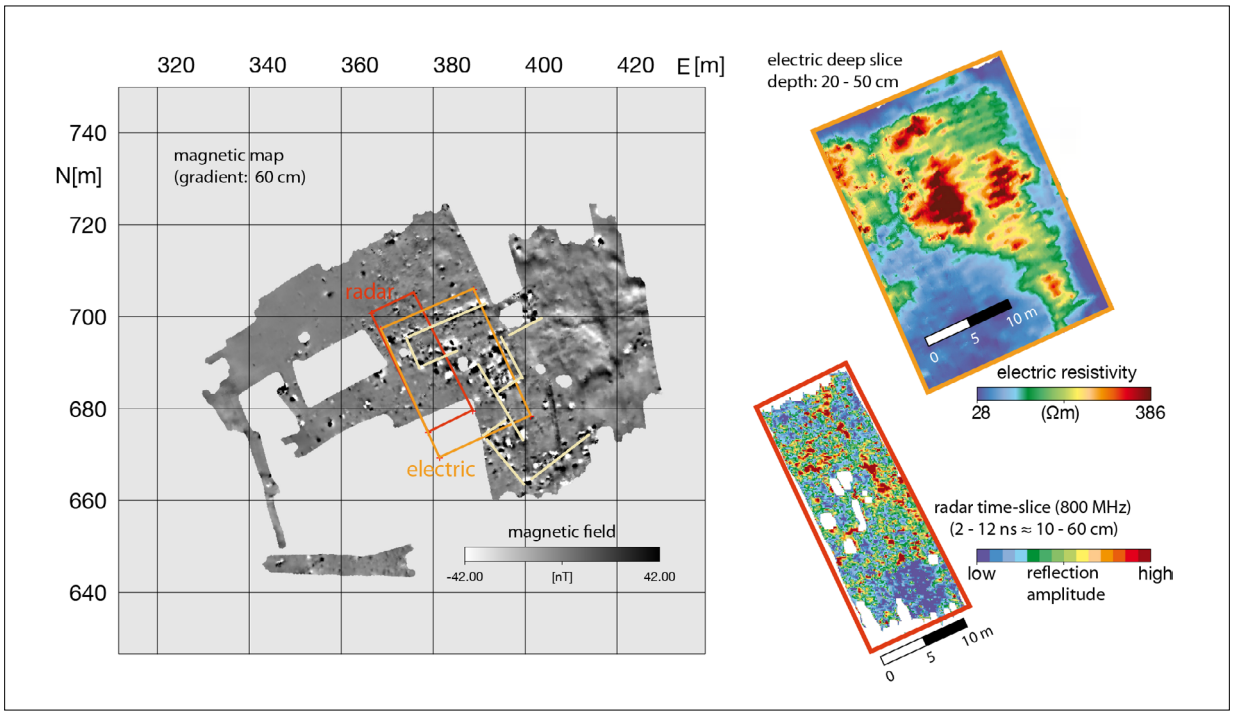

Fig. 3: Results of magnetics, electrics and georadar at the site location L1.

revealed by geophysics cannot correspond to a temple, but to buildings that overlooked the bay and the road – a branch of the Via Egnatia relating Ainos to Kypsela and, by ferry, to Doriskos/Traianopolis-Pheres. The road looks similar with the one on the right bank of the river, dated by a milestone from Pheres in the reign of Nero. Therefore, this station at Gala Lake could be one of the praetoria et tabernae constructed in 61-62 CE by Nero's governor of Thrace, Titus Iulius Vstus (Christol 1998; Leveau 2016). However, judging only by the shape of the blocks, without any pottery found on the promontory, one cannot exclude a date until the 2nd century CE, when Traianopolis was founded across the Hebros' mouths. Several blocks were later reused in a domestic context, to which could be associated also 2 empty tombs. The site was abandoned during Antiquity (no signs of Christianization have been found).

Conclusion

The MAG, GPR and ERT measures on the promontory, correlated with the interpretation of the architectural remains, recommends the identification of the archaeological site at Gala Lake with a monumental station on a *via militaris*, part of Via Egnatia's network. If so, this could be the first site that confirms the epigraphic information about the construction of monumental stations in Thrace, under the early Roman Empire. The place is promising for further geo-bio-archaeological research, and must be protected, due to its natural and cultural heritage.

Acknowledgments

We like to thank Şahan Kırçın, director of the Edirne Museum, for extensive support during the field measurements. The project was funded by the CNRS, through the project LEGECARTAS – LEctures GEoarchéologiques des CARTes AncienneS (2017-2019), and by the French Ministry of Foreign Affairs – Mission Archéologique d'Ainos (2020-present).

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An integrated geoarchaeological approach to the investigation of multi-period prehistoric settlements – the case of Neolithic Drenovac

Philippe De Smedt [1,2*], Charles French [3], Timothy Kinnaird [4], Tonko Rajkovača [3], Aleksandar Milekić [5], Petros Chatzimpaloglou [3], Jeroen Verhegge [1,2], Thomas Hermans [7], Gaston M. Veirana [1], Djurdja Obradović [6], Vesna Popović [8], Slaviša Perić [6]

1 Department of Environment, Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium
2 Department of Archaeology, Faculty of Arts and Philosophy, Ghent University, Ghent, Belgium
3 McBurney Laboratory, Department of Archaeology, University of Cambridge, Cambridge, United Kingdom
4 School of Earth and Environmental Sciences, University of St Andrews, St Andrews, United Kingdom
5 Department of History and Archaeology, Faculty of Philosophy Pale, University of East Sarajevo, East Sarajevo, Bosnia and Herzegovina
6 Institute of Archaeology, Belgrade, Serbia
7 Hydrology and Applied Geophysics Group, Department of Geology, Faculty of Sciences, Ghent, Belgium
* Corresponding author: E-mail: Philippe.DeSmedt@UGent.be

Abstract
A multi-method geoarchaeological investigation was performed to reconstruct multi-phase Neolithic settlement. Invasive and non-invasive surveys showed potential for providing archaeological and environmental landscape data in this complex setting. Large-area geophysical surveys showed potential for deriving stratigraphic information.

Keywords
archaeological prospection; frequency domain electromagnetics; geoarchaeology; Neolithic settlement

Introduction

The Neolithic site of Drenovac, located in the Middle Morava Valley of central Serbia, was occupied during two distinct settlement phases relating to the Early Neolithic Starčevo Culture (6100–5900 BC) and the Late Neolithic Vinča Culture (5300–4700/4500 BC), separated by a ca. 600-700-year hiatus. This has led to an extensive settlement with archaeological deposits up to 6.5 m thick (Perić 2017), in which Starčevo occupation layers are separated from the Late Neolithic ones by a sterile layer of uneven thickness. These are in turn covered by later colluvial deposits.

After excavations in the 1970's and 1980's, a research program was initiated in 2004, combining excavations with magnetic gradiometry surveys (Perić 2016, 2017) to fine-tune the chronological framework, inform on site formation and occupation dynamics, and provide insight into the spatial layout of the settlement. Based on these data and surface finds, the later Vinča settlement is now assumed to cover at least 40 hectares, comprising approximately 700 houses related to the late 6th to early 5th millennium BC occupation. Excavations show that these are among the best-preserved examples of Neolithic houses across Europe due to their burning, and subsequent covering with colluvium, offering strong potential for magnetic survey methods.

Despite these insights, understanding the evolving environment and land use from Starčevo through Vinča phases, as well as the evolution of the settlement's spatial layout, lingers behind. Addressing these research imbalances is complicated by nature of the settlement activity and the complex stratigraphic sequence of extensive natural and cultural deposits. Key aims were to investigate:

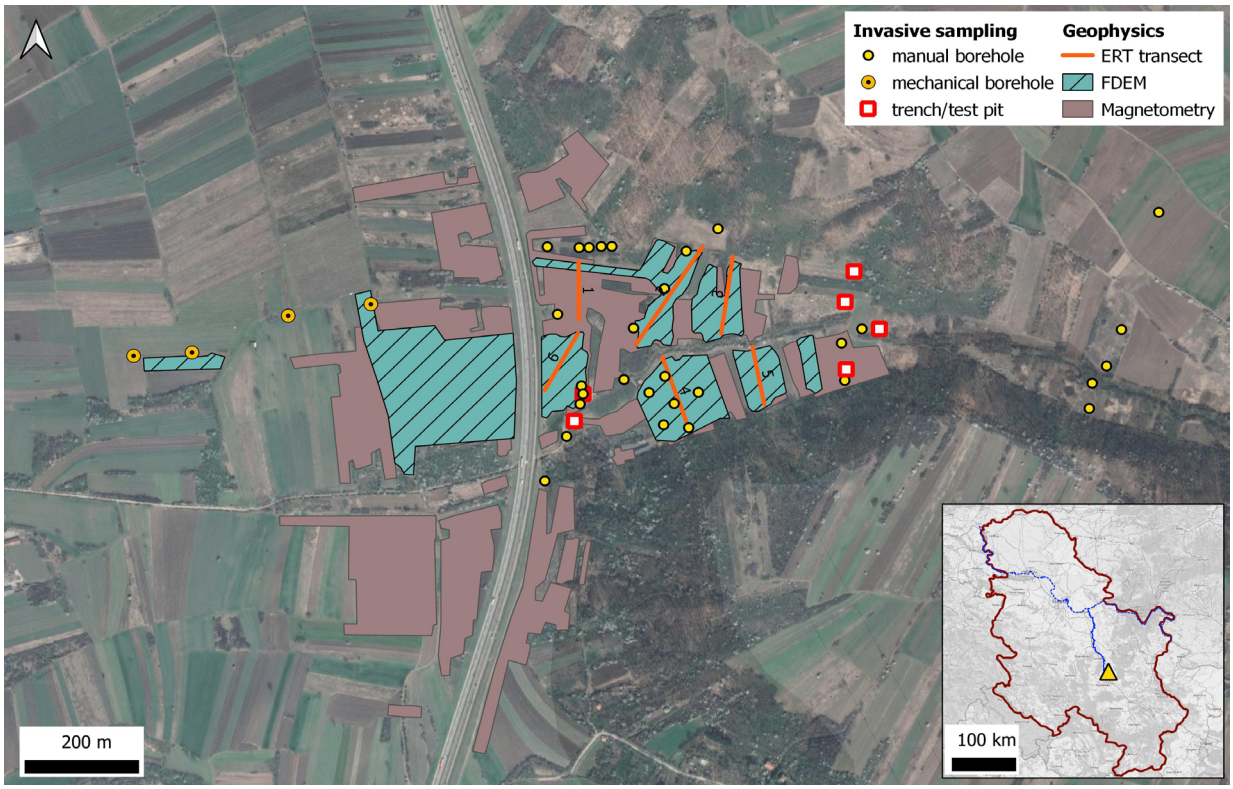

Fig. 1: Overview of the site with indication of the areas and locations covered by different survey methods (base map: ©2022 Google). The inset shows the site's location (yellow triangle) in Serbia.

- the extent and depths of Neolithic settlement remains;
- the presence and nature of buried soils contemporary with the Neolithic occupation;
- the occurrence and phasing of colluviated deposits;
- delineate any palaeochannels in the area.

These survey questions were combined with the goal to provide a chronological framework for reconstructing land use and environment from the 6th millennium BC onwards. Here, we focus on the contribution of different survey methods to resolving these research questions, with emphasis on the complementarity of electromagnetic and magnetic surveys at Drenovac.

Materials and methods

To tackle the key research challenges, a multi-method geoarchaeological approach has been adopted that combines targeted test pitting with borehole and geophysical prospection. During the 2019-20 field campaigns, excavations were performed to sample extensive profiles for micromorphological and chronological information (Kinnaird et al. 2017). In one trench, exhaustive sampling was performed to support interpretation of available geophysical data and optimize planning future surveys. These data were complemented with manual and mechanical borehole logs. A sampling overview is provided in Figure 1.

Complementing magnetic surveys conducted from 2010 onwards (Perić (2016) and Fig. 1), frequency domain electromagnetic induction (FDEM) survey was performed with a Dualem-421s and Dualem-21HS sensor. An 11-ha survey area (indicated on Fig. 1) was surveyed with the Dualem-421s in horizontal coplanar (HCP) mode, providing 3 perpendicular (PRP) and 3 HCP datasets with coil separations of 1 m, 2 m, 4 m (each +0.1 m for PRP). Targeting large anthropogenic structures (buildings) and palaeolandscape features, measurements were made in snake-line pattern using a 3 m between-line spacing and an inline sampling interval of ca. 0.3 m. In addition, a 0.5 ha area was surveyed with a 1 m sampling spacing with additional geometries in HCP and VCP mode. Complementing the FDEM surveys, electrical resistivity tomography (ERT) was conducted to help discern the stratigraphic position of present deposits.

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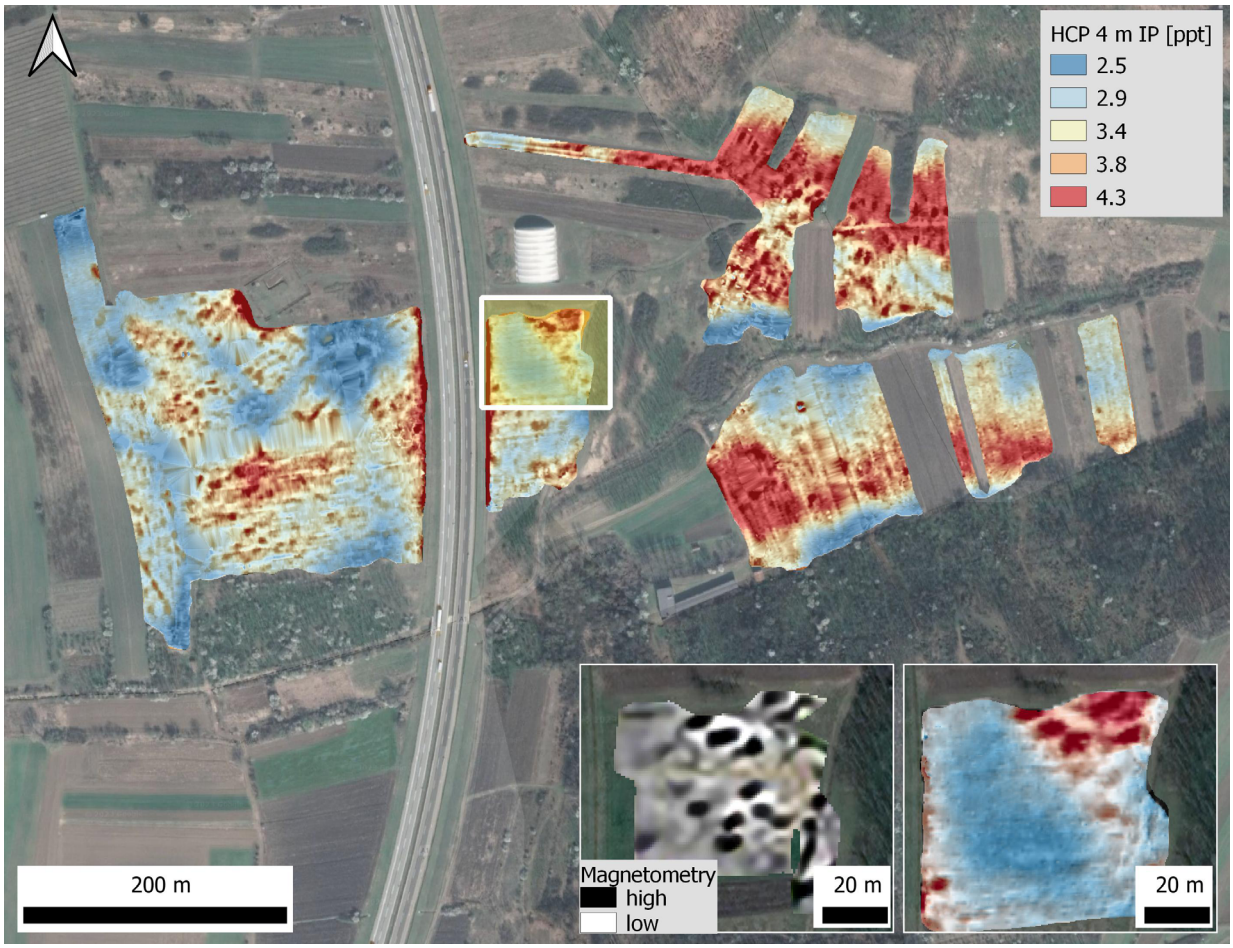

Fig. 2: Overview of the 4 m HCP in-phase data of the surveyed area (base map: ©2022 Google). The inset shows a comparison between the magnetometry data (Perić 2016) (left) and the FDEM in-phase data (right), showing a different expression of the magnetic anomalies, related to their stratigraphic positioning.

Results

On the environmental setting of the site, the combined invasive and geophysical data showed distinct variations in the occurrence, thickness, and type of colluvial deposits. Borehole surveys and test pitting show that deposits range from a few centimeters to over 3 m in thickness, and are generally composed of eroded topsoils, suggesting substantial Neolithic and post-Neolithic clearance and soil erosion occurring from the mid-6th millennium BC. While ERT data allow examining the vertical extent of these deposits, FDEM data not only enable tracing these deposits through the landscape, but equally allow discriminating which likely have an anthropogenic origin based on their magnetic enhancement. These observations are confirmed through comparison with magnetic susceptibility readings on excavation and borehole samples.

Most strikingly, the combination of magnetometry data with in-phase FDEM data shows clear potential for investigating the stratigraphy of the site, as the different discrimination potential of assumed houses in FDEM and magnetometry data was related to their respective stratigraphic position.

Discussion and conclusions

In this study, we demonstrate how in complex archaeological environments an integrated use of invasive and non-invasive survey methods enables a fuller insight on occurrence, type, and nature of archaeological remains as well as their environmental setting. Here, particular emphasis was put on the use of multiple magnetic survey datasets obtained through fluxgate gradiometry and multi-con-

figuration FDEM surveys. While magnetometry provides high sensitivity and clear discrimination of magnetically enhanced structures in-phase FDEM data from different configurations allows adding stratigraphic information, even when used qualitatively. Coupled with insights into the palaeotopography and configuration of archaeological features and deposits, this integrated framework provides a comprehensive basis for reconstructing the evolution of multi-period prehistoric settlements.

Acknowledgments

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Combined geophysical prospection of kurgans on the Uzun Rama plateau in the Caucasus, Azerbaijan: first results

Ercan Erkul [1*], Simon Levin Fischer [1], Andrea Ricci [2], Jutta Kneisel [2], Dennis Wilken [1], Bakhtiyar Jalilov [3], Wolfgang Rabbel [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
3 Institute of Archaeology, Ethnography and Anthropology, National Academy of Science of Azerbaijan
* Corresponding author: E-mail: ercan.erkul@ifg.uni-kiel.de

Abstract
In November 2021, a geophysical prospection using magnetics, electromagnetics, and ground penetrating radar, as well as a surface archaeological survey and aerial photography were conducted in the kurgan area on the Uzun-Rama plateau in central Azerbaijan. These non-destructive investigations aim to obtain information on the morphology, structure and spatial distribution of the kurgans in order to classify them according to various features. The preliminary results show that increased magnetic field intensity, increased electrical conductivity, and increased reflection energy in the GPR are observed in the top region of the kurgans, which contain information about the burial chamber.

Keywords
archaeological prospection; Caucasus; kurgan; electromagnetics; ground penetrating radar; magnetics

Introduction

The uniquely well-preserved and highly visible archaeological burial mounds in the Caucasus, known as kurgans, are a source that has been little explored to date and can provide crucial information on the spread of early metal cultures. In this region, kurgans were constructed and used from the mid-4th to 1st millennium BC. The resource wealth of the southern Caucasus, with its rich metal deposits (including copper, silver, and gold), is often reflected in the rich furnishings of the tombs, attesting to the use and accumulation of precious raw materials. Previous studies (Laneri et al. 2019) in this region have only focused on individual burial mounds and thus have not contextualized them with other kurgans or in relation to environmental and landscape conditions, including geology and topography. New analysis capabilities, including satellite imagery, Digital Terrain Models (DTM), and geophysical prospection allow for a large-scale survey of the barrow phenomenon for the first time in this region.

In November 2021, as part of the Cluster of Excellence ROOTS, work was carried out with geophysical prospection, as well as archaeological surface survey and aerial photography in the kurgan area on the Uzun Rama Plateau, approximately 15 km east of the city of Gence in central Azerbaijan (Fig. 1a & 1b).

These non-destructive investigations aim at obtaining information on the morphology, structure and spatial distribution of the kurgans in order to classify them according to different features. Prospecting work on monumental burial mounds has been challenging for geophysics depending on their size, height, slope steepness, and surface characteristics (Forte and Pipan 2008; Polymenakos and Tweeton 2017; Tsokas et al. 2018; Mecking et al. 2020). The kurgans in the Caucasus, due to the great geomorphological variability, offer us the opportunity to study these different structures in order to further develop our methods and contribute to the construction of the kurgans.





Fig. 1: a) Kurgans in the landscape. b) Site plan of the investigation area Uzun Rama Plateau in the Caucasus, Azerbaijan (Source: Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat / Copernicus).

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Fig. 2: a) Kurgan surface. b) Magnetic measurements with the cart on the Kurgan K9.

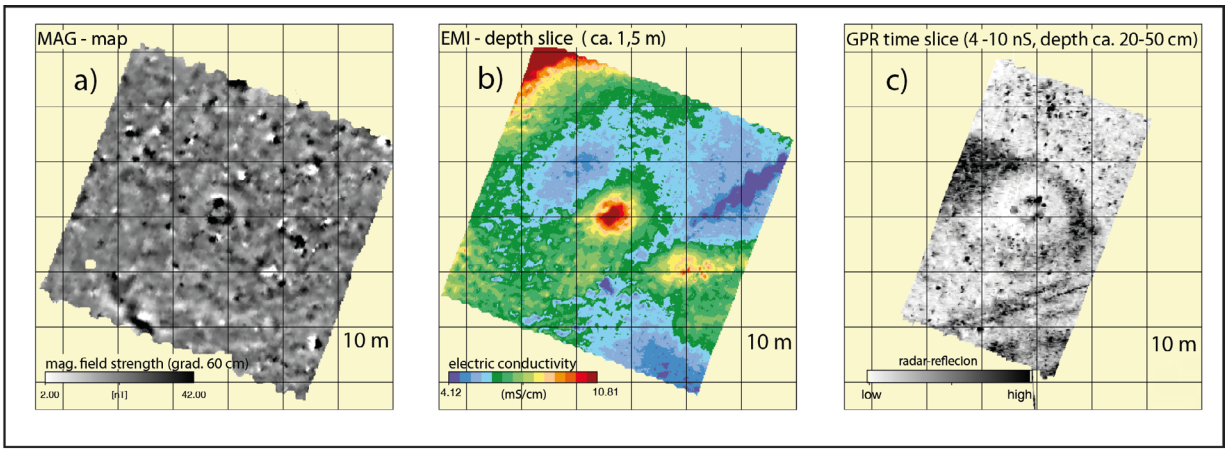

Fig. 3: Results of magnetics (a), electromagnetics (b) and georadar shown as time slice from 4 ns to 10 ns (c) on the Kurgan K9.

Methods

Geophysically, magnetics (MAG), electromagnetics (EMI) and georadar (GPR) methods were applied on 7 representative kurgans. In 4 cases, the layers of stones on the kurgan surface posed a challenge for conducting the measurements (Fig. 2a).

For the magnetic mapping a magnetometer array with 6 fluxgate probes of the company Dr. Förster (probe type Ferrex CON650) was installed on a hand cart. The individual probes are mounted on the trolley (Fig. 2b) at intervals of 0.5 m in such a way that a width of 2 m is covered during the field measurements with parallel profiles. Approximately a measured value was registered in-line every 5 cm. The electromagnetic mapping was carried out with the CMD-MiniExplorer from GF Instruments. The profile spacing was 1 m and a reading was recorded in-line approximately every 5 cm. For the GPR measurements a single-channel instrument, SIR 4000 from GSSI, was used with a dual frequency antenna including the center frequencies of 300 MHz and 800 MHz. The profile spacing was 0.3 m and a scan was recorded in-line approximately every 2 cm.

Results

Figure 3 illustrates the results of the measurements on Kurgan 9. This kurgan has a total diameter of about 20 m. The diameter of the top flat area is about 10 m. The height difference between the surrounding and the top of the kurgan is approximately 1 m.

Magnetics

In the central top area, higher magnetic anomalies form a signature, which delimits an area of about 5 m x 4 m. In the inner and outer area of this signature, moderate magnetic amplitudes are observed, forming a circular area of about 10 m in diameter (Fig. 3a).

Electromagnetics

In the central area, increased electrical conductivities up to 10 mS/m are observed. Between the central area and the edge of the kurgan the electrical conductivity decreases to 5.5 mS/m up to a diameter of 20 m (Fig. 3b).

Georadar

Increased reflection energy is observed in the central region and at the edge of the kurgan (Fig. 3c).

Discussion

These preliminary results show that increased magnetic field intensity, increased electrical conductivities, and increased reflection energies in GPR are observed in the top area of the kurgans. Thereby, the magnetic minimum in the central area correlates with increased electrical conductivities and low reflection energy. Additionally, observed magnetic maxima, which correlates with lower electrical conductivities and high reflection energy in GPR (Fig. 3) are visible. These anomalies are probably due to the walls of the burial chamber, which are made of dried mud bricks and were burned at the end of the use of the kurgan.

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Conclusion

These results suggest that the combination of magnetics, electromagnetics and georadar makes it possible to prospect the burial chamber as differentiated as possible. Additionally, results from measurements on a topographically flat area with destroyed burial kurgans indicate that geophysical prospection can also be used to map them. In this way, kurgans can be explored in a non-destructive and as differentiated manner as possible to obtain information about their dimensions and internal structure, and to support archaeological interpretation for kurgan classification.

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GPR on city roadways: two case studies with feedback from trial trenching

Benjamin Fores [1*], Guillaume Hulin [2], François-Xavier Simon [3], Laurent Paez-Rezende [1], Fréderic Devevey [1]

1 Inrap, Paris, France
2 Inrap, Paris, France and Metis UMR 7619, Paris, France
3 Inrap, Paris, France and Chrono-Environnement UMR 6249, Besançon, France
* Corresponding author: E-mail: benjamin.fores@inrap.fr

Abstract
GPR surveys were performed in dense urban areas in France. Underground utilities and the narrow width of the streets can make GPR really challenging for archaeological features detection. The relevance of GPR compared to trial trenching is discussed.

Keywords
archaeological prospection; multi-channel GPR; urban areas; utilities

Introduction

Ground penetrating radar (GPR) has been widely used for decades for utilities detection (Gabryś et al. 2019) and is being increasingly used in urban areas to evaluate presence of archaeological remains, especially in a led-development archaeological context (Paez-Rezende and Hulin 2021). This non-destructive method - whose relevance is no longer to prove for the detection of buried remains (Goodman 2008) - seems appropriate in this context where trial trenching can be burdensome as it requires a stripping step of the asphalt and subsequently the modification of the road traffic. This is especially true with the new multi-antenna GPR devices that can be towed with no impact on the local road traffic. However, the urban context has some limitations that counterbalance these aspects (Trinks et al. 2009; Masini et al. 2020). Firstly, utilities can be extremely numerous (water, gas, electricity, optic fiber, some of which are unknown and/or disused). All of them could obviously be very inconvenient in detecting something else, not to mention that trenches installation may have partly destroyed the archeological remains. Moreover, roadway maintenance may also create heterogeneities of the upper layer of the road. Lastly, the narrowness of the streets is a drawback for identifying archaeological structures as we may only cross a small section of them. Here we present a collection of GPR data we obtained in two French cities and we discuss the pros and cons and when it is appropriate or not to implement GPR in urban areas, especially for surveying the roadway.

Materials and methods

For these studies an *Impulse Radar Raptor* multi-channel GPR with 450 MHz antennas spaced by 8 cm – either in its manual (8 channels) or towed system (18 channels, Fig. 1) was used. A GNSS Trimble R4S device has been associated, occasionally replaced by a Trimble S5 total station for crowded environments. We used the *Condor* Software to process the data and create the depth-slices and *GPRSlice* to visualize B-scans. We acquired the GPR datasets during the spring of 2022 in Limoges and Cherbourg. The geophysical survey was carried out prior to the trial trenching in Limoges; whereas in Cherbourg the trenching was already in progress during the GPR acquisition. We covered more than 6.5 km of streets in Limoges (the roadway, roundabouts and intersections) and about 1 km in Cherbourg (roadway, sidewalks and some lawns). In both cases, we did not stop the traffic during the acquisition.



Fig. 1: Towed 18-channels Raptor GPR with GNSS positioning in Cherbourg.

Results

Over the kilometer of road mapped in Cherbourg, three areas with potential archaeological anomalies are identified with high confidence level. On the most convincing, a medieval tower, its rampart and counterforts are clearly detected at a depth of 60 cm. Multiple reflections which could be linked to a cemetery are also seen 100 cm below the ground surface. A trial trench carried out a week after the GPR acquisition confirms the presence of the rampart and the cemetery (Fig. 2).

In Limoges, GPR results reveal a set of Gallo-roman remains in a street close to the city center (Fig. 3). Most of them appear deeper than a meter despite the presence of several pipes. Remains were expected in this area based on the results of an excavation performed in the 1970s. On the other 6 km, no archeological features can be clearly identified and no remains are known from previous excavation or ancient maps. Feedback from the on-going trial trenching will certainly be of great interest.

Discussion

The results presented here have to be balanced with the totality of the surveyed area. The utilities density increases considerably as one approaches the city center and consequently masks many of the archaeological anomalies. The archaeological remains observed below tens of pipes in a street of Limoges (Fig. 3) is an exception. In most of the cases, the density of utilities is such that it is not possible to state the presence of remains underneath. In Cherbourg, the three interesting areas from an archaeological point of view are all located on a road surrounding the city center and less affected by underground utilities. Moreover, some sections of walls observed in the trial trenches are not visible on the GPR dataset. At most, some areas can be flagged as potentially interesting areas populated with reflections of unknown origin.

Surveying a street is especially challenging as it is a convenient path for utilities and it offers a very narrow, incomplete view of the subsurface. The *a priori* information is also of prime importance. In both cities studied, most of the anomalies are found in areas already identified as high archaeological potential areas. Even a simple presumed indi-

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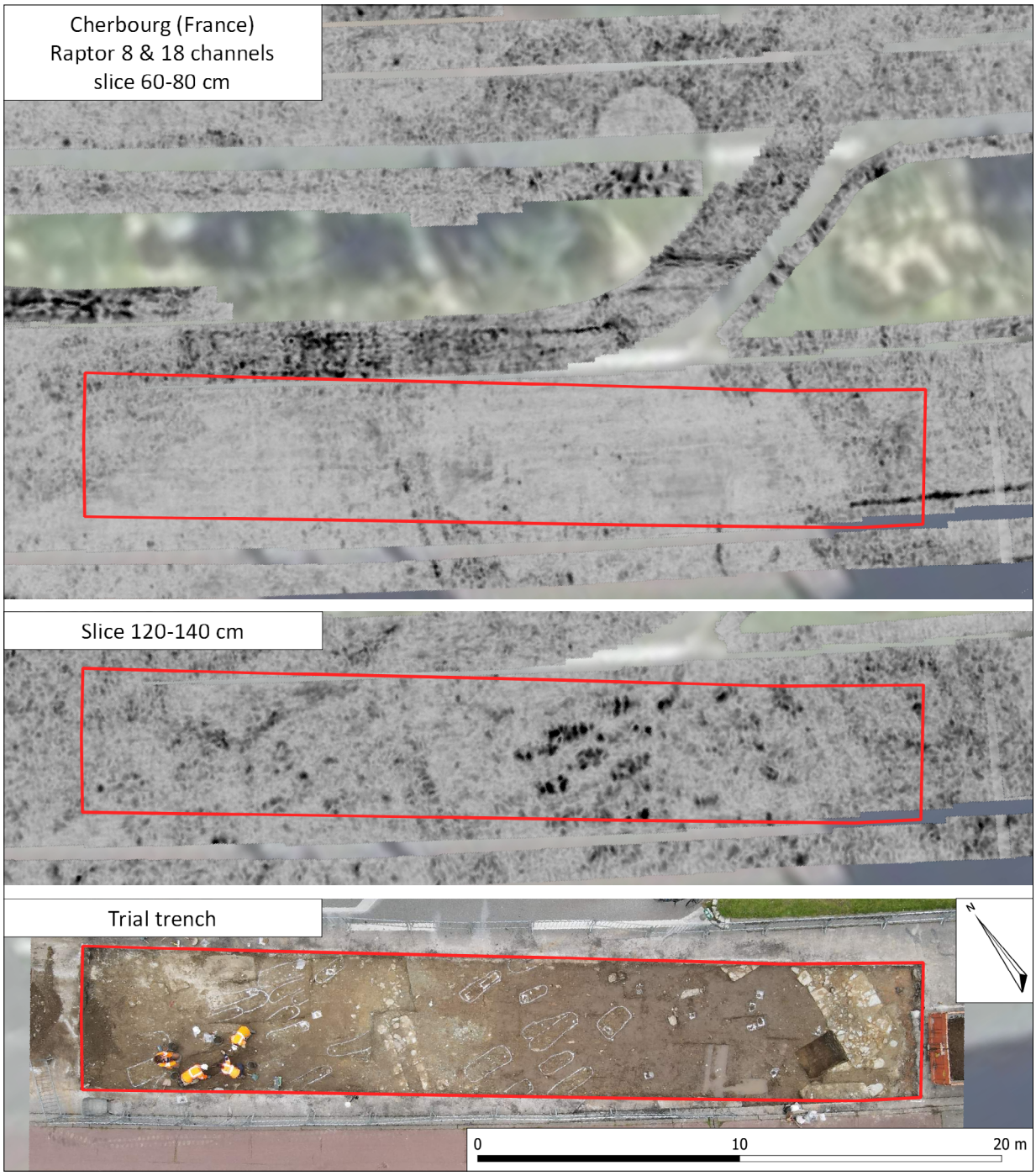

Fig. 2: Part of the results of the GPR survey in Cherbourg: depth-slice at about 60-80 cm, 120-140 cm, and the trial trench (drone photography, J.-L. Lamache). IGN orthophoto background.

cation of the remains can be of great importance to discriminate a wall from a pipe, especially considering the number of unknown and/or disused utilities. Given the frequently weak and noisy data under the numerous utilities network, the distinction may not be possible on the B-scan basis.

Conclusion

The multi-channel GPR has a strong potential for urban archaeology. It allows a fast acquisition of high definition images of the subsurface even on roadways. This approach

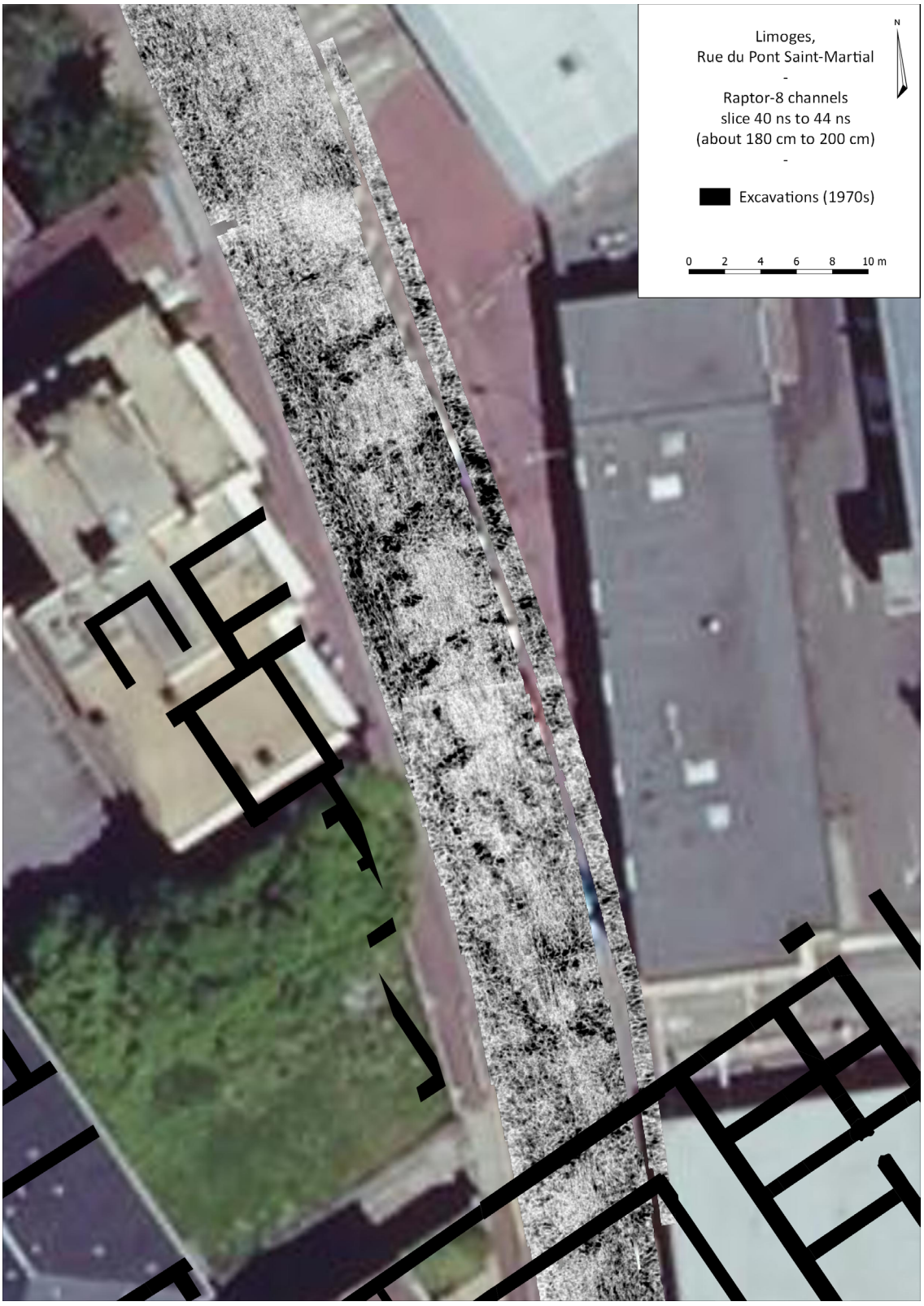

Fig. 3: Part of the results of the GPR survey in Limoges: slice from 180-200 cm overlapping the results of 1970's excavations. IGN orthophoto background.

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is particularly suitable for preventive/rescue archaeology. Surveying large urban areas, such as squares, may be often relevant. However, for road surveys, the use of GPR should be considered more carefully. It is likely to get only a map of the utility network, even if this knowledge remains of primary interest for choosing the location of the trenches in the case of preventive/rescue archaeology. GPR should be preferred on wide streets, where the number of known utilities is moderate. Reflections that are initially difficult to interpret based only on GPR data can be identified by the trial trenching and still provide useful information afterward to have an extended view of the features.

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Experiences from motorized GPR surveys in Iceland

Manuel Gabler [1]*, Knut Paasche [1], Ragnheiður Traustadóttir [2]

1 Norwegian Institute for Cultural Heritage Research (NIKU), Oslo, Norway
2 Antikva ehf., Reykjavik, Iceland
* Corresponding author: E-mail: manuel.gabler@niku.no

Abstract
Motorized multi-channel GPR investigations in Iceland in July 2022 showed great potential for large-scale archaeological geophysical surveys. Investigations on selected sites demonstrated effective fieldwork opportunities with excellent signal penetration through thick layers of ash and sand and very good contrast of turf houses towards the surrounding soil. Although Iceland has very challenging landscapes, many places are perfect suitable for motorized surveys making them very efficient for landscape archaeological investigations.

Keywords
archaeological prospection; heritage management; Iceland; landscape archaeology; motorized ground penetrating radar; turf houses

Introduction

Iceland is known for its diverse geology, harsh weather conditions, and fascinating history dating back to the 10th century AD. The appearance of archaeological sites is very different. On the one hand many remains of old houses or settlements can still be seen in the topography only covered with a thin layer of grass. On the other hand, many sites have been covered by thick layers of ash or sand due to volcanic activities or erosion, allowing perfect preservation conditions for archaeological remains in the ground. Earlier geophysical investigations around Iceland showed good results for magnetic, resistivity and ground penetrating radar (GPR) surveys for archaeological purposes (Stamnes et al. in print; Wilken et al. 2016; Wunderlich et al. 2015). So far, these surveys were all conducted with handheld systems on a rather small-scale. The introduction of large-scale motorized geophysical prospection methods in the latest decade has demonstrated huge benefits for landscape archaeological research and heritage management (Trinks et al. 2018). High-resolution GPR prospection has so far shown the greatest potential to successfully detect, and map buried archaeological remains in Scandinavian conditions (Nau et al. 2017, Stamnes 2016). It was therefore an obvious choice to test and demonstrate the potential of motorized GPR at known sites in Iceland.

In July 2022, the Norwegian Institute for Cultural Heritage Research (NIKU) in cooperation with Skálanessetur ehf., Antikva ehf., University of Iceland, Gunnarsstofnun, National Museum of Iceland and Byggðasafn Skagfirðinga conducted motorized GPR investigations at eleven sites across Iceland (Fig. 1). The main goals were to get a broader understanding of the methods potential in Iceland, its practicability, the signal penetration abilities through thick ash and sand layers and the contrast of turf buildings. The archaeological focus for the case studies was connected to monasteries, farms, and early farm-churches. Following some results from these investigations will be presented and discussed.

Materials and methods

The applied system is already well established and used since several years. It was developed by the LBI ArchPro and is based on Guideline Geo`s 16 channel Malå Imaging

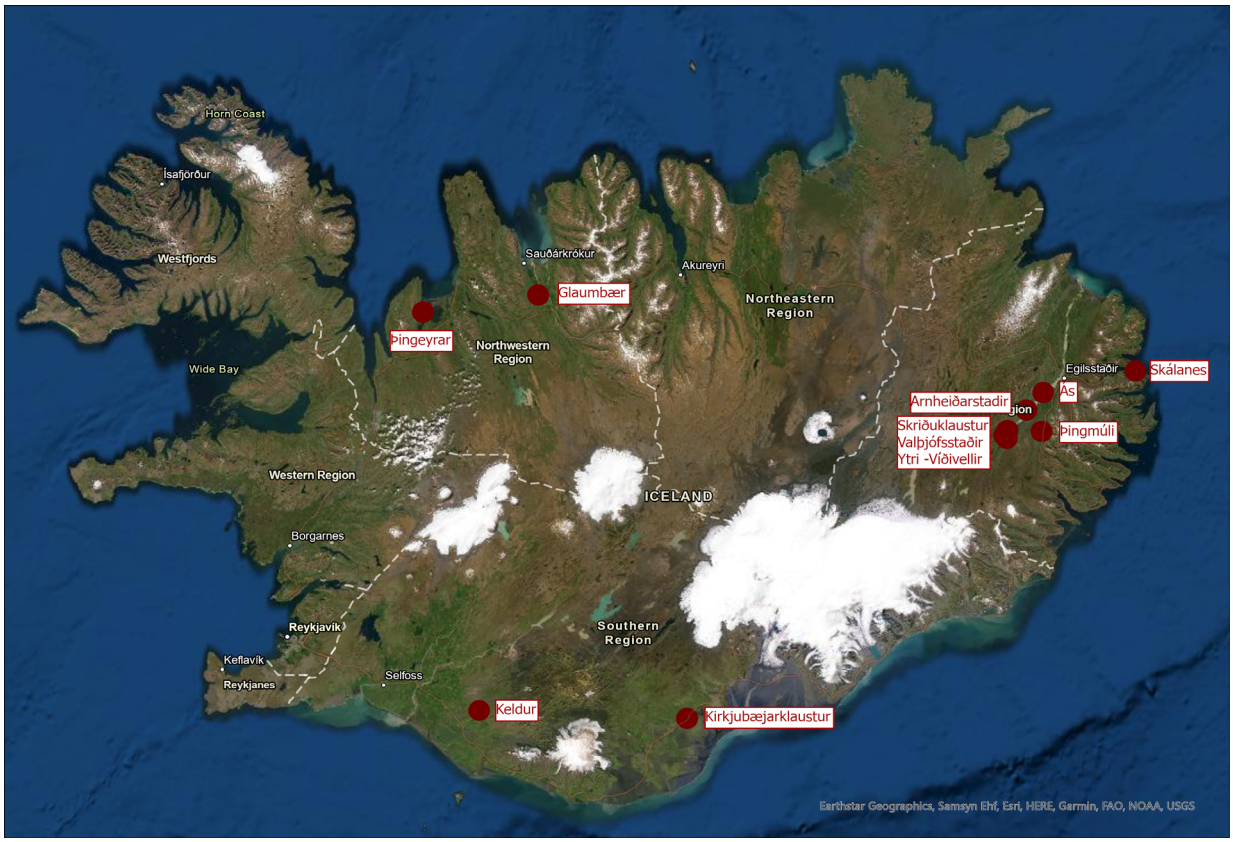

Fig. 1: Locations of the survey sites from July 2022. Background image: Esri ArcMap "World imagery" base map.



Fig. 2: Motorized GPR system (MIRA) during the survey at Keldur with traditional turf houses in the background. Image: Knut Paasche (NIKU).

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Fig. 3: Left image: GPR depth-slice from Keldur (120-160 cm depth). Turf walls (Area 1, 2) of old farm buildings are clearly visible as absorbing features. Right image: GPR depth-slice from Valþjófsstaðir (40-80 cm depth). The data show a variety of different geological patterns within one field. The graveyard with its enclosure and individual graves is clearly visible in the marked area. Background image: Esri ArcMap "World imagery" base map.

Radar Array (MIRA) equipped with 400 MHz antennas, mounted in front of a Kubota RTV900 (Fig. 2). Positioning was achieved with a RTK-GNSS system, mounted on top of the radarbox. Data processing and visualization was carried out using the software ApRadar, developed by the Central Institute for Meteorology and Geodynamics in Vienna and the LBI ArchPro.

Results

From a mechanical and logistic perspective, the used equipment was well suited for the investigations of the selected sites. Large areas in Iceland are used for hay production and offer very good driving conditions after harvesting. At many places the soil is very silt and sandy which offers a good natural drainage, enabling good driving conditions even after heavy rainfall. At all sites GPR worked well, with good signal penetration and good contrast of archaeological features towards the surrounding soils (see Fig. 3 as example). The detailed archaeological data interpretation is still work in progress, but two places will be presented in more detail to demonstrate the methods potential. At both below presented sites, earlier small-scale geophysical investigations showed promising results (Kristjánsdóttir et al. 2016, Jónasson 2019) and were there-fore chosen as case-studies for large-scale investigations.

Keldur

Keldur farm is a well-known historical place going back to the 10th century and is mentioned in many of the medieval sources. At Keldur one of Iceland oldest turf houses is still preserved. The GPR results clearly show an earlier known turf structure (1 in Fig. 3) but due to the large-scale application it was possible to detect an additional earlier unknown building complex just 80 m south of the known building under an approximately 1 m thick sand layer (2 in Fig. 3). The turf walls appear as absorbing features in the GPR data,

clearly limited towards the surrounding soil, making it possible to identify several buildings/rooms that are part of an approximately 100 x 90 m large farm.

Valþjófsstaðir

Valþjófsstaðir is an early chieftain's manor and churchsite at least since the thirteenth century. Historical sources date the farm to the Viking period. Within the investigated field (Fig. 3), different geological patterns can be observed, demonstrating the variety of Icelandic geology. The enclosure of the previous known graveyard and the graves have a very distinct contrast towards the surrounding and can clearly be identified in the GPR data (marked area in Fig. 3).

Observations and conclusion

The results of these investigations confirm the earlier promising results of archaeological geophysics in Iceland. The project also clearly demonstrated that large-scale motorized surveys can be applied successfully, effective, and with a high detection rate of archaeological features in Iceland. Turf structures showed an excellent contrast to the surrounding soil and could clearly be identified. That is of mayor importance as turf was one of the main building materials in Iceland's history. There are without doubt many challenges and clear limitations regarding logistic, accessibility and drivability at some sites but many of them can be solved with careful planning and local knowledge of the sites and its access is mandatory. The detection rate of many archaeological features with GPR is high and large areas in Iceland are perfectly suited for the method. In combination with other methods such as high-resolution LIDAR (many building remains are still visible in the topography) whole landscapes could be effective surveyed with non-invasive methods and should therefore be an integral part of the national heritage management in Iceland.

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Integrated archaeological and engineering geophysical investigation of the castle ruin Mödling (Austria)

Jakob Gallistl [1]*, Hannes Schiel [1], Ralf Totschnig [1], Alois Hinterleitner [1], Mario Wallner [1], Ingrid Schlögel [1], Klaus Löcker [1], Helmut Scharsching [2]

1 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
2 Verein der Freunde und Förderer der Burg Mödling, Mödling, Austria
* Corresponding author: E-mail: jakob.gallistl@geosphere.at

Abstract
An extensive multi-method investigation of a castle ruin has been conducted that extends the spectrum of geophysical methods used in archaeological prospection. For complex sites like a castle ruin, the incorporation of seismic and geoelectrical methods can facilitate the interpretation of ground penetrating radargrams, particularly in the existence of bedrock.

Keywords
electrical resistivity tomography; ground penetrating radar; multi-method; refraction seismic tomography

Introduction

After its prime in the 12th century, with being the residency of a collateral line of the Babenbergers, the castle Mödling has ever since been in decline. It was stripped of its ashlar stones at the end of the 18th century, and rebuilt as a romantic castle ruin by Johann I. of Liechtenstein. In an effort to restore the initial foundation walls in the 1970s, the area was subjected to significant disruptions leaving the present-day castle ruin in shambles.

We present results from an integrated investigation applying archaeological and engineering geophysical prospecting methods to uncover what is left behind of the old foundations of the original Babenberger castle. The geophysical measurements had two main objectives: (1) delineate unknown foundations or other remnants of the past history of the castle ruin and (2) detect the depth to the bedrock and provide a basis to differentiate between loosened bedrock and toppled building materials/rubble.

Materials and methods

The geophysical measurements included (i) refractions seismic tomography, (ii) electrical resistivity tomography (ERT) and (iii) ground penetrating radar (GPR) profiles. Measurement at a total of 6 RST profiles were conducted with between 40 to 120 30 Hz vertical geophones with 1 m spacing in each profile. The seismic wave field was recorded with Geode seismographs (by Geometrics) for 512 ms with a sampling rate of 0.25 ms. A 5 kg sledgehammer was used as the seismic source and shots were made at each geophone to ensure adequate coverage along the profile.

To support the interpretation of the seismic results two ERT profiles were measured with 80 and 120 electrodes in each profile and applying an electrode spacing of 0.5 m. The data were collected with an ABEM Terrameter LS2 using a pulse length of 0.5 s and a dipole-dipole electrode configuration. Furthermore, GPR profiles were collected with a Mala GroundExplorer GX 160 MHz antenna.

The areal GPR measurements were performed with a Sensors&Software PulseEkkoPro 500 MHz antenna with 3 antenna pairs mounted in parallel to permit a faster coverage of the area. Where applicable, we also computed depth slices for the 160 MHz data. Figure 1 presents

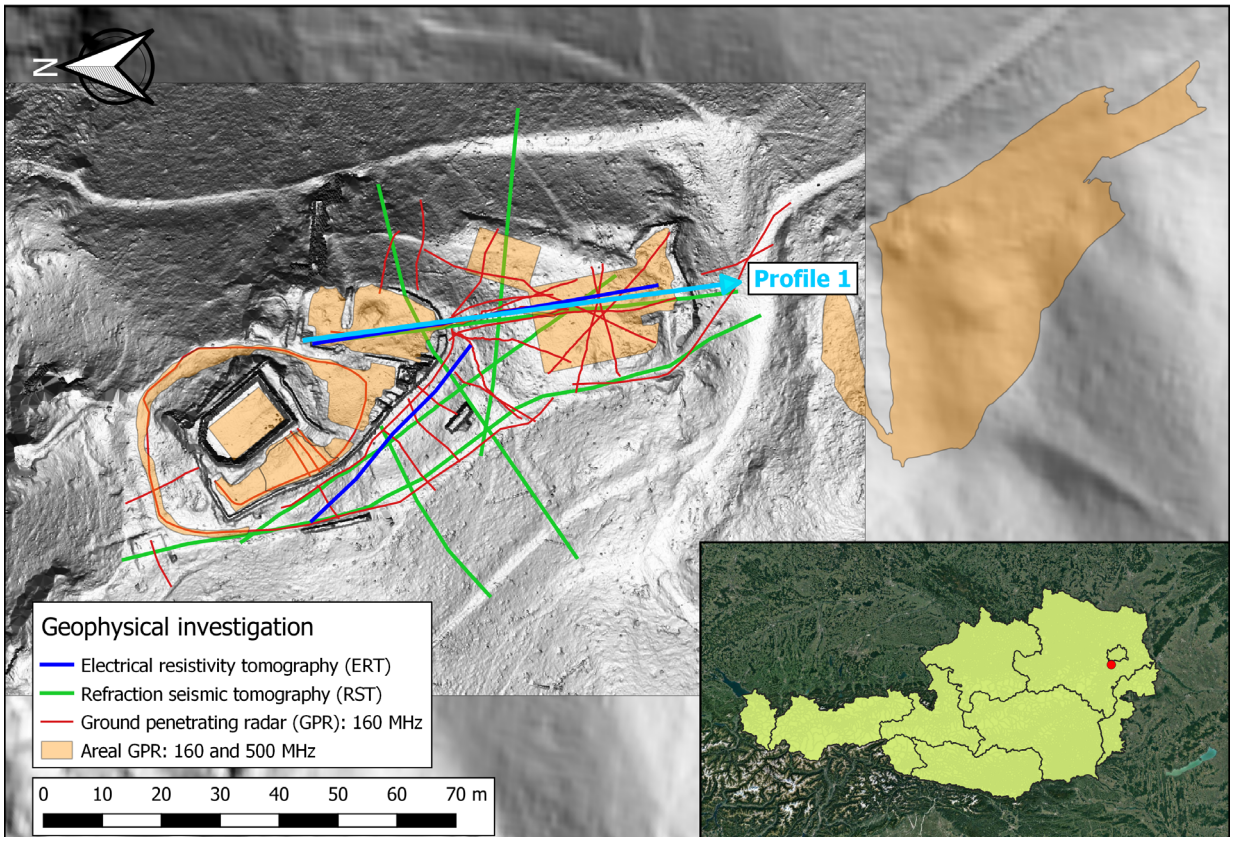

Fig. 1: Overview of the applied geophysical methods and their location as well as areas where the density GPR data permitted to obtain areal information. LIDAR data provided by Land Niederösterreich – data.noe.gv.at and LIKWID (likwid.at).

an overview of the study area and the location of the individual geophysical profiles as well as the zones of areal GPR information.

Results

Figure 2 presents the geophysical imaging results for the profile 1, which covers large parts of the investigated area (c.f. Fig 1). The RST imaging results in general show an increase in P-wave velocity (V_p) with depth ranging from 200 to 3400 m/s. Low velocity zones (V_p < 600 m/s) can be observed in shallow depths down to 3-5 m, particularly between 10 and 40 m along the profile. Such areas can be considered weakly compacted and are probably comprised of loose building material or fine-grained topsoil. Below, the velocity increases to values between 1200 and 2200 m/s and are indicative of fractured bedrock.

In comparison, the ERT imaging results show more heterogeneity in shallow depths (1-3 m), i.e., a sequence of low and high resistivity anomalies, particularly in the first 15 m of the profile. Given the abnormally high resistivity of the anomalies (> 5000 Ωm) we interpret the features as buried walls surrounded by fine-grained deposits. The discrepancy between the ERT and RST imaging results in the first 15 m of the profile can be explained by both the lower spacing used for the ERT measurements and the ability of the ERT method to resolve near-surface small scale anomalies – whereas the RST tends to provide smoother images, due to the larger smoothing factor applied in the inversion. Nevertheless, both methods show a depression between 20 to 35 m along the profile, which can also be observed in the radargram (Fig. 2C) as a reflective layer. Moreover, the high resistivity anomaly at approx. 10 m along the profile also corresponds to an area with increased P-wave velocity (> 1000 m/s) as well as a highly reflective feature in the radargram. A comparison with the LIDAR scan in Figure 1 shows an east-west oriented wall at approx. 10 m along the profile 1, therefore sustaining our interpretation. The linear patterns in the radargram between 0 to 10 m along the profile are air reflections from larger walls.

The comprehensive archaeological-geophysical inter-

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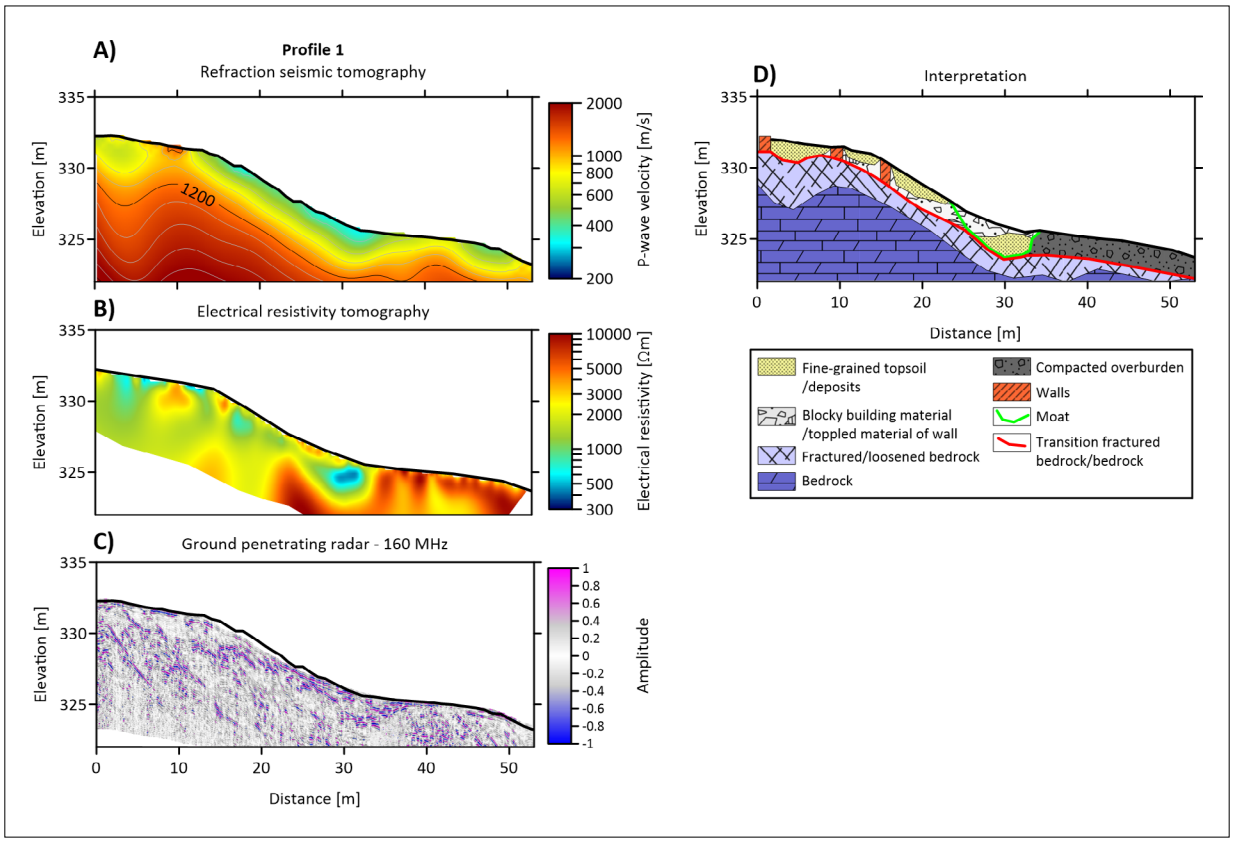

Fig. 2: Geophysical imaging results for the profile 1 (cf. Fig. 1): A) refractions seismic tomography, B) electrical resistivity, C) ground penetrating radar and D) archaeological-geophysical interpretation.

pretation presented in Figure 2D can be summarized in the following: (buried) walls in shallow depths at 0, 10, 16 m along the profile sit on top of non-fractured and fractured bedrock. Above the bedrock sits a layer of fine-grained deposits intermixed with blocky building material or larger stones of toppled walls. Of particular interest is the depression between 25 and 34 m along the profile. We interpret this as a moat, which was first backfilled with fine-grained sediments and then, with the ongoing deterioration of the castle ruin, toppled material of the castle walls. For complex sites such as a castle ruin, that consist of a sequence of various intermingled temporal layers, an integrated investigation in which ERT and RST are used as complementing methods to GPR could be a step forward for an improved interpretation.

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Geophysical surveying in Egypt: periodical report for 2021–2022

Tomasz Herbich [1]

1 Institute of Archaeology and Ethnology, Polish Academy of Sciences, Warsaw, Poland
E-mail: tomasz.herbich@gmail.com

Abstract
A magnetic survey of an Old Kingdom necropolis at Abusir near Saqqara yielded data for a reliable reconstruction of its layout. Water management in the hinterland of the Late Antique and Byzantine city at the site of Marea in northern Egypt could be reconstructed based on the results of a magnetic survey. The resistivity method was applied to record stone structures situated below the ground water table at the site of Heliopolis in Cairo.

Keywords
ancient Egypt; Byzantine period; magnetic prospecting; resistivity prospecting; water management research

Introduction

The author resumed geophysical research in Egypt in the spring of 2021, following a two-year break caused by the Covid-19 pandemic. The work that was carried out was part of the research program of the following expeditions: at Abusir, dir. Miroslav Bárta, (Czech Institute of Egyptology, Charles University); at Marea, dir. Tomasz Derda (Faculty of Archaeology, University of Warsaw); at Matariya/Heliopolis, dir. by Dietrich Raue (Leipzig University) and Aiman Ashmawy (Ministry of Tourism and Antiquities of Egypt); and at South Abydos, dir. Josef Wegner (University of Pennsylvania). The surveys continued the author's earlier work at these sites. The sole exception is Abusir, where the work was a follow up to what Roman Křivánek has done and was aimed at verifying the results of Ian Mathieson's survey. Assisting the author in this work were Robert Ryndziewicz and Konrad Jurkowski.

Methods

Site characteristics and survey objectives determined the choice of geophysical methods: magnetic survey in Abusir, Abydos and Marea, and electrical resistivity in Matariya. A Geoscan Research FM256 fluxgate gradiometer was used for the magnetic prospection, the sampling in this case being 8 measurements per 1 m^2, the traverses 0.5 m apart. Electrical resistance of the ground was measured with an ADA-05 resistivity meter (Elmes, Poland) using a twin-probe array, the traversing probes set 2 m apart. Here, the sampling grid was 1 measurement per 1 m^2.

Results

Abusir

The survey covered an area in the southern part of the site, bordering on Saqqara, in a burial complex from the Third to Sixth Dynasties (Old Kingdom, 2687–2190 BC) explored by the Czechs from the late 20th century. The area had been prospected with geophysical methods by both Ian Mathieson and Roman Křivánek (Herbich 2022). The objective was to investigate the area of the necropolis north of the burial complex. 17 ha were prospected, tracing the extent of the cemetery located at the base of the desert plateau running along the Nile Valley. The plans of most of the tombs could also be reconstructed based on the geophysical results. The tomb layout is typical of Old Kingdom burials. The building material is presumed to be mud brick based on the nature of the anomalies and the amplitude of magnetic values.

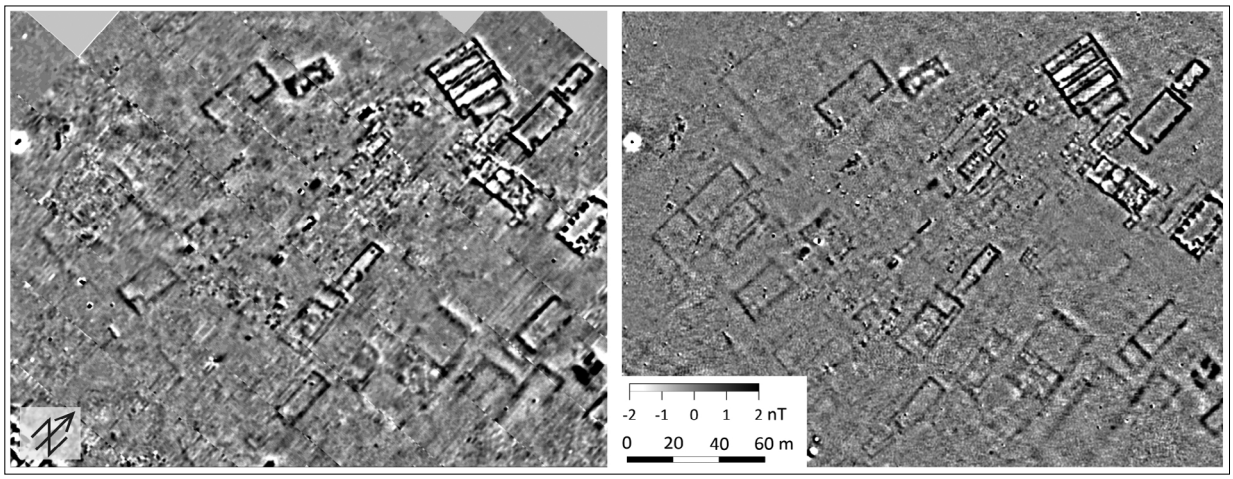

Fig. 1: Abusir. Magnetic maps. Left, results of Ian Mathieson's team; right, results obtained in 2021.

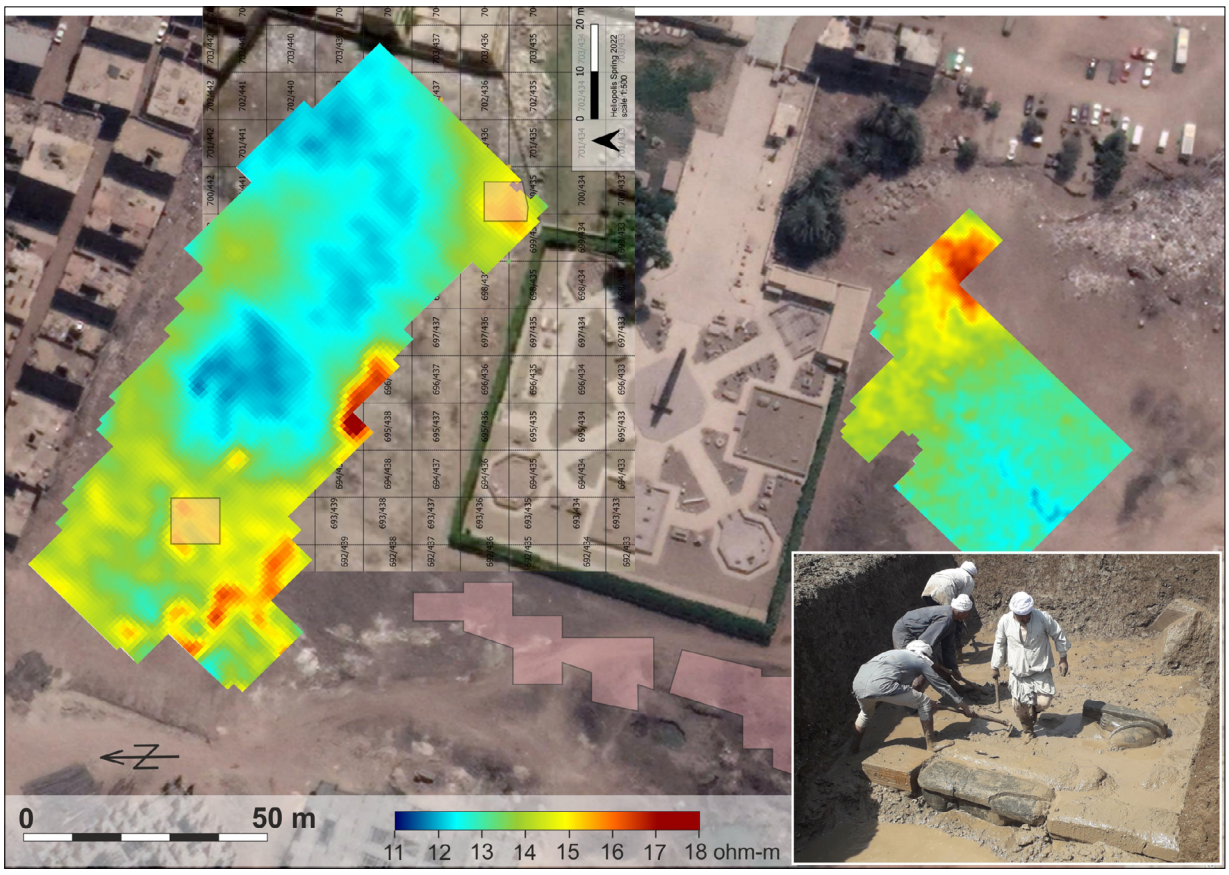

Fig. 2: Matariya. Electrical resistivity map. The excavation area of 2022 and sites where the geophysical results were archaeologically tested marked in transparent pink. Photo shows sphinxes from the New Kingdom during exploration (satellite image: Google Earth, ©2023 Maxar Technologies).

The prospection south of the burial complex aimed to verify the results obtained by Mathieson's team. These are not very clear in many places because of a loose sampling grid (traverses 1 m apart) which was additionally oriented N–S, the traverses doubling the orientation of most of the tombs. Using the same type of instrument (FM), but applying a denser sampling grid and orienting the traverses at an oblique angle in relation to the tomb orientation

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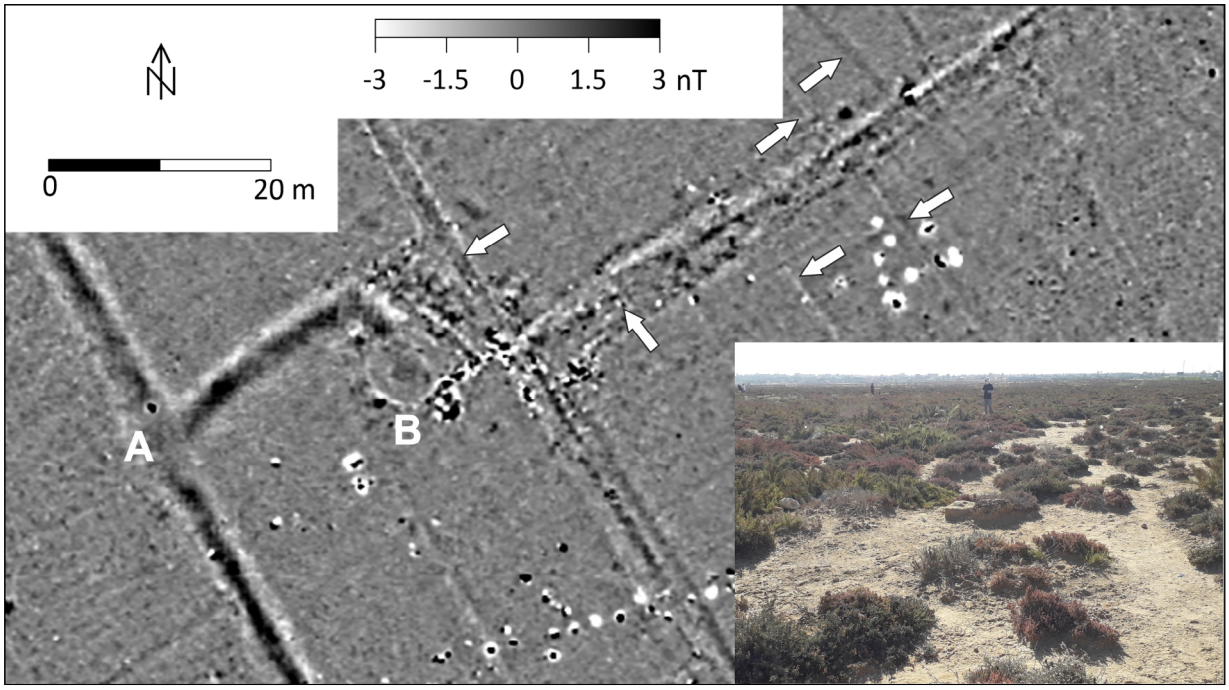

Fig. 3: Marea. Fragment of the magnetic map. A – main channel, B – saqia. Arrows indicate channels distributing water to the fields.

allowed for a much more precise reconstruction of individual tomb plans and revealed the presence of previously unrecognized burials (Fig.1).

Abydos

Work northeast of the burial complex of Senwosret III (1878–1843 BC) was aimed at tracing the remains of burials in this part of the site. A necropolis of unknown rulers of the Second Intermediate Period (c. 1650–1600 BC) had already been mapped by magnetic prospection (Herbich and Wegner 2003; Wegner and Cahail 2015). A series of low amplitude anomalies recorded now could correspond to a Predynastic necropolis mentioned by excavators from the early 20th century; this hypothesis will be tested archaeologically. The survey in another part of the necropolis, discovered south of the mortuary temple and settlement of Senwosret III in 2004, did not uncover any new tombs.

Matariya / Heliopolis

The work at Matariya is a salvage project investigating the area of one of the most important ancient Egyptian temples, the sun temple in Heliopolis, which is now the location of a new urban housing district with full road and commercial infrastructure. The temple, which was destroyed in late antiquity and again in medieval times, was buried first in alluvia during regular Nile inundations in the past and then under several meters of urban trash. Today, the ruins are found for the most part below the groundwater table. Knowing that limestone, which does not have magnetic properties, was the main building material, the electrical resistivity method of prospection was an obvious choice (Herbich and Ryndziewicz 2019). The eastern part of the temple was surveyed, supplying data for immediate archaeological testing. A few areas of distinctly higher resistivity values were recorded (Fig. 2). Testing of one of these areas revealed remains of a structure, which turned out to be of modern date.

Marea

Marea was an important urban center in late antiquity and the early Byzantine period (4th–7th centuries AD). Local limestone was the principal building material, with only occasional use of fired brick. Magnetic prospection and a topographic survey carried out over the past ten years have yielded an approximate town plan, point-checked only to a small degree by archaeological excavations ongoing since the mid-20th century (Derda et al. 2021). The general street network and various urban quarters were mapped using a cesium magnetometer and measuring the total magnetic field intensity. The current geophysical pro-

ject tested the efficacy of a fluxgate gradiometer compared to the cesium instrument and extended the prospection to the agricultural hinterland of the city. The FM survey of a test area yielded a somewhat more detailed picture of the architecture compared to the results obtained with a cesium instrument, but not good enough to reconstruct individual house plans as was the case earlier in the industrial part of Marea (Herbich 2005; Pichot 2010). Investigations south of the city have traced the channels distributing water from the lake throughout the town, including the main canal and a saqia waterwheel transferring water to a higher level from where it was channeled directly into the fields (Fig. 3). The results of the project have created the opportunity for a full reconstruction of the water economy in the agricultural hinterland of the town.

Concluding remarks

Magnetometry is still the main method applied in geophysical prospecting in Egypt. GPR has been found recently to be highly effective in prospecting mud-brick architecture in Sudan, especially in areas where the magnetic method is compromised by an extensive presence of pottery and fired brick (Obłuski, Herbich and Ryndziewicz 2022). However, in Egypt, administrative restrictions have limited the application of this method by foreign missions.

A positive outcome noted in some Egyptian academic centers is a close collaboration between geophysicists and archaeologists, taking advantage of current geophysical prospection results (obtained with the magnetic, electrical resistivity and GPR methods) to plan archaeological excavations.

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Archaeological field evaluations in Vieux-Aregenua: the benefits of combining geophysical surveys and trial trenches

Karine Jardel [1*], Paul Chesnais [1], John Nicholls [2]

1 Service Archéologie, Conseil Départemental du Calvados, Caen, France
2 Target Archaeological Geophysics, Kessel-Lo, Belgium
* Corresponding author: E-mail: karine.jardel@calvados.fr

Abstract
The Roman city Vieux-Aregenua was already the subject of a pilot test. Magnetometer and electromagnetic induction (EMI) surveys were carried out. The trial trenches of the archaeological field evaluation were strategically placed as to take into account the results of the survey. The surveys allowed definition of the general layout, to characterise the areas and surfaces, and the identification of the buildings. The combined analysis of geophysics and trial trenches permitted the re-examination of the interpretation of geophysical anomalies.

Keywords
archaeological investigation; EMI; magnetometer survey; Roman city; trial trenches

Introduction

The unique setting of the village of Vieux (Normandy – France) proved to be favourable for the implementation of a geophysical survey in addition to trial trenches that were excavated in the context of an archaeological field evaluation (the first stage of developer-led archaeology in the French legislation) (Jardel et al. 2021). Indeed, the analysis benefitted from the results of a pilot project conducted between 2015 and 2018, where different methods had been tested, providing a reference for the study.

Materials and methods

The surveys extended over 4 areas investigating a total of 1.45 ha of land. Some of these areas were very small in size due to their locations in gardens attached to private houses with many obstacles present.

Two geophysical techniques were used, magnetometer and electromagnetic induction (EMI) surveys, with data recorded at 75 Hz and 10 Hz along lines spaced 0.27 m and 0.5 m, respectively. The magnetometer survey, using a multi-sensor cart, was completed in Zone 1 towing the instrumentation behind a quad bike and in Zones 2-4 pushed by hand to fully investigate areas with restricted access (Nicholls 2021).

The DUALEM EMI surveys were confined to Zones 1 and 3 and the apparatus was towed behind the quad bike due to its size and weight.

A survey grade GPS was used with both sets of geophysical instrumentation permitting precise navigation during data collection and accurate positioning (< 0.05 m) of the final geophysical measurements.

After the fieldwork, the raw geophysical data were merged with the GPS measurements also recorded in the field. All measurements were subsequently transformed from WGS84 geodetic coordinates to RGF93. The magnetometer and EMI measurements were then processed separately using in-house software developed according to the requirements of each set of instrumentation.

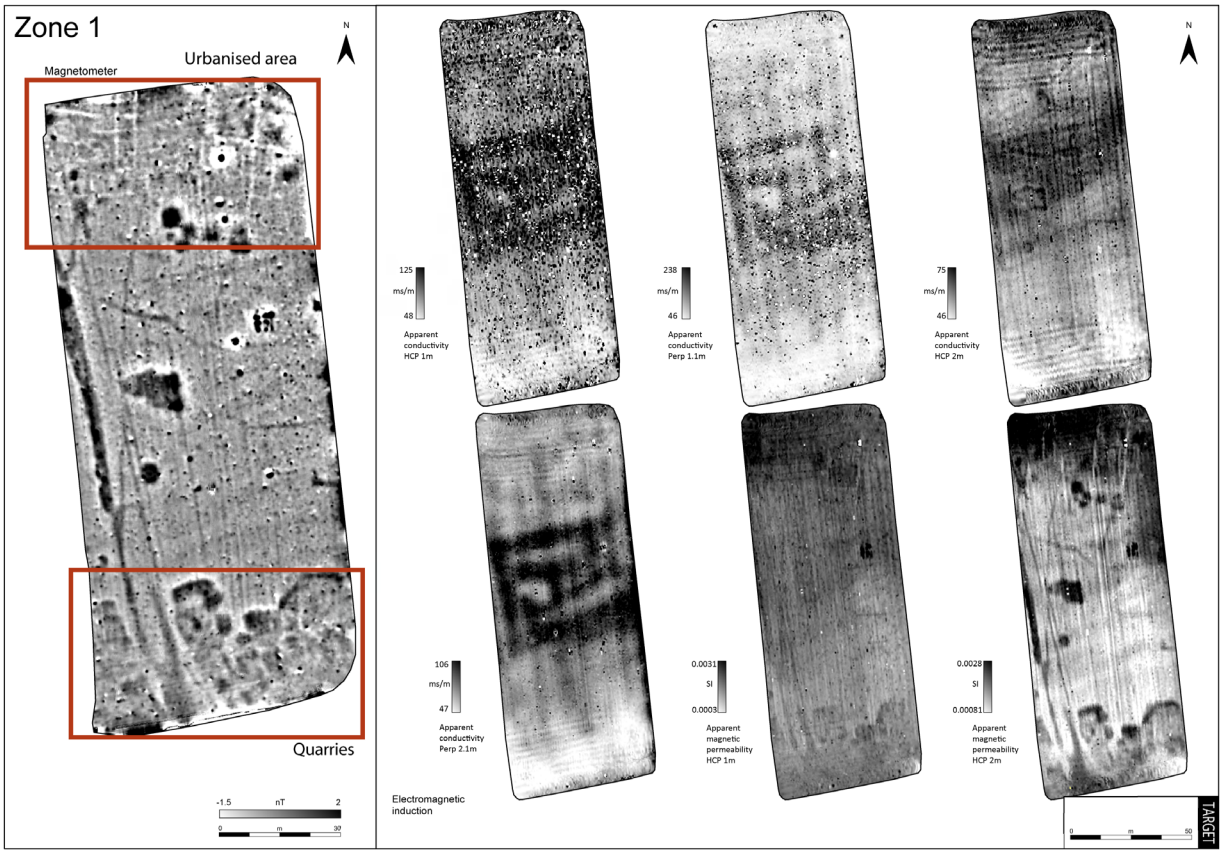

Fig. 1: Magnetometer (left) and EMI (right) results from Zone 1.

Results

The condition of the terrain in Zones 2, 3 and 4 was exceptionally poor for a geophysical survey severely affecting the results. By contrast, the results for Zone 1 are very clear (Fig. 1). They reveal the continuation of the roman city over parts of the area with the probable presence of staging posts or warehouses. The south-western limit of the ancient capital gives way to a suburban area where ditches, a road, limekilns and a vast quarry area were uncovered.

Discussion

The geophysical survey in Zone 1 showed the general layout of the structures, revealing different types of sectors. We propose to review two of these. Firstly, we will present the results of the geophysical prospection; secondly, those of the trial trenches and the revision of the geophysical interpretation, and thirdly we will conclude on the input of the cross-analysis of the geophysical survey and trial trenches. This is still rarely implemented in developer-led surveys in France.

An urbanised sector in the north

The complex network of weak negatively contrasting linear and rectilinear responses marks out buildings (Fig. 2 a and b). Two orientations are apparent: northwest/southeast (2) and west/east (1). However, no clear layout is discernible, but it is possible to eliminate some hypotheses: no domus-type plan, no characteristic public building plan.

After excavation, the geophysical anomalies can be reinterpreted (Fig. 2 c). A greater quantity of built features was found than expected. Knowing this, the images collected outside the trenches benefit from a second level of reading.

The excavation helps to clarify the role and function of certain remains and buildings. There is a distinction between two adjoining buildings and the presence of a hypocaust nearby (indicated by collapsed *pilae* stacks) and provides further details concerning construction

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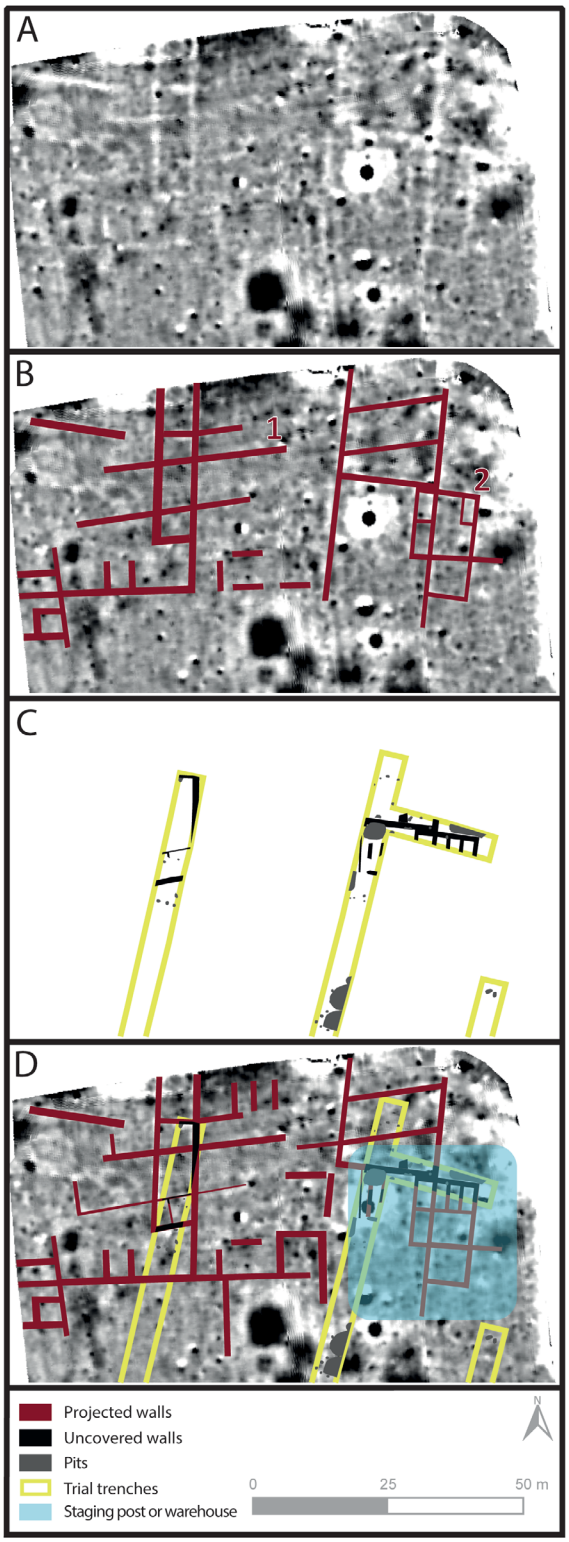

Fig. 2: Detail of the urbanised area A: Magnetogram B: interpretation of the magnetic anomalies, C: archaeological features revealed in the trenches, D: cumulative geophysical interpretation/trial trenches.

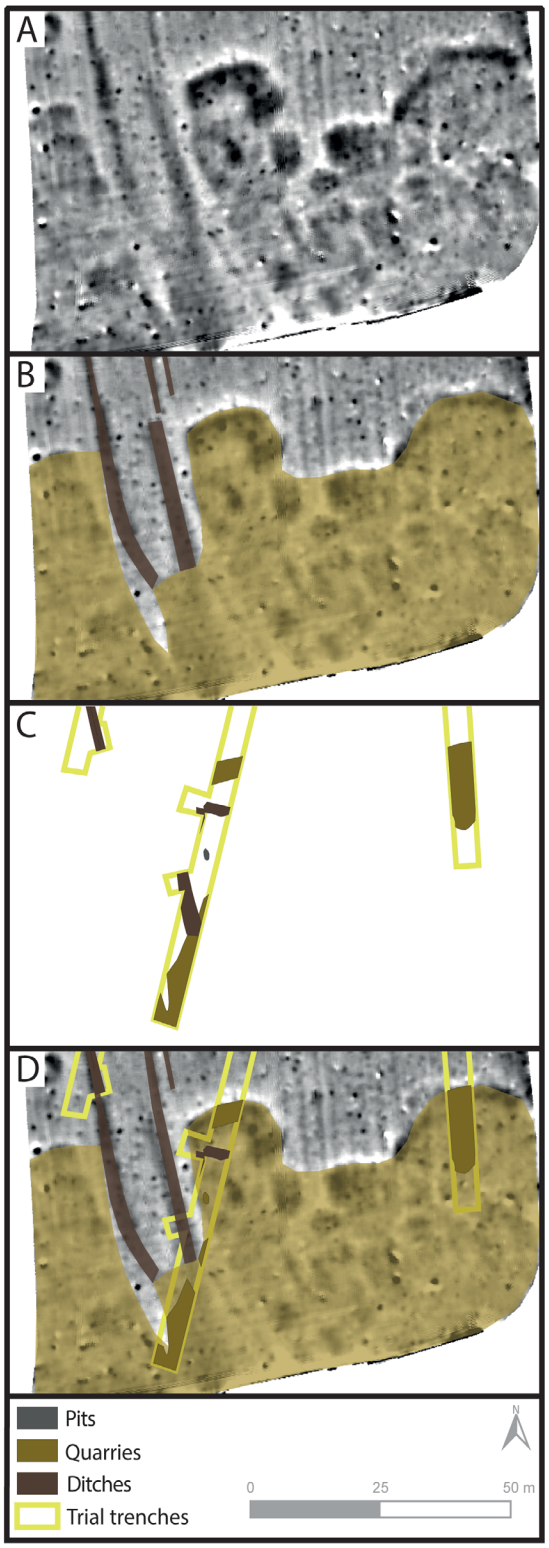

Fig. 3: Detail of the quarry area, A: Magnetogram, B: interpretation of the magnetic anomalies, C: structures revealed in the trenches, D: cumulative geophysical interpretation / trial trenches.

methods (*opus vittatum*, built with limestone known as Caen stone). The discovery of artefacts, in particular small finds, contributes to the hypothesis of a staging post or a roadside inn.

The chronological data (relative and absolute from standing building studies and archaeological artefacts) dates the construction of the building to between the end of the first and the beginning of the 2nd century AD.

The cross-analysis approach of geophysical surveys on the one hand and trial trenching on the other generates interesting methodological implications. Indeed, the results of the survey guided the placement of the trial trenches targeting the questions raised by the survey notably the presence or absence of features, conservation, stratigraphy, identification and, dating. It also provided the general layout of the remains, showing the precise delineation of spaces: urbanised sectors (roads, buildings, facilities), suburban areas and the south-western limit of the Roman city. Finally, the method allows an extended interpretation of the architecture. The identification of the general characteristics of the buildings and their layout either promotes their interpretation or allows us to exclude certain hypotheses, namely to rule out the possible presence of a domus and public building, suggesting instead the existence of a staging post or warehouse.

Quarries

In the southern part of Zone 1, positive/negative responses reveal a large anomaly with irregular boundaries, interpreted as a large quarry area over 5000 m^2. In the centre of Zone 1 a similar response marks out a smaller second anomaly also with an irregular shape and was hence interpreted as a hypothetical quarry of 350 m^2 (Fig. 3).

The excavation confirmed the presence of quarries and allowed to identify the nature of the rock mined, in this case limestone (rubble and lime). The artefacts collected date the extraction from between the first and the middle of the 2nd century (by dating of pottery sherds). The depth of the operation was also noted at 1.65 m (43.35 NGF). The quarries were probably not reused as a dump but this observation is restricted to the trial trenches' limits.

As mentioned above, the results of the survey guided the placement of the trial trenches in order to answer the questions raised by the survey regarding the presence or absence of features, conservation, stratigraphy, identification and dating. It also provided the extent, surface and depth of the remains.

Conclusion

Within the framework of this archaeological field evaluation, the combined use of the geophysical survey and trial trenches made it possible to improve the methodological approach. The excavation trenches were indeed able to be strategically placed as a result of the archaeological questions raised by the geophysical prospecting. Moreover, as an initial interpretation of the geophysical anomalies reveals multiple data, a second analysis after trial trenching makes it possible to complete and improve on the interpretation of the architecture and town planning of this district of the ancient capital. It also helps to address the chronological questions, taking into account the stratigraphic pattern identified in the trenches (relative and absolute dating).

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Is this settlement intersected by a ditch? A comparison between magnetic prospection data, ALS data, and archaeological and geological excavation results from the Early Bronze Age fortified hilltop settlement of Ratzersdorf, Lower Austria

Doris Jetzinger [1*], Alexandra Krenn-Leeb [1], Volker Lindinger [2], Ronny Weßling [3], Mandana Peresson [4], Robert Supper [5], Reinhard Roetzel [6], Robert Peticzka [7]

1 Department of Prehistoric and Historical Archaeology, University of Vienna, Vienna, Austria
Human Evolution and Archaeological Sciences, University of Vienna, Vienna, Austria
2 ARDIG Archäologischer Dienst GesmbH, St. Pölten, Austria
3 Crazy Eye 3D-Studio, Vienna, Austria
4 Department of Raw Materials, Geosphere Austria, Vienna, Austria
5 Department of Geophysics, Geosphere Austria, Vienna, Austria
6 Department of Sedimentary Geology, Geosphere Austria, Vienna, Austria
7 Department of Geography and Regional Research, University of Vienna, Vienna, Austria
* Corresponding author: E-mail: doris.jetzinger@univie.ac.at

Abstract
In this case study we present preliminary results from a joint analysis of magnetometry data, remote sensing data, and excavation results generated in the course of research on the Early Bronze Age fortified hilltop settlement of Ratzersdorf/Am Dachsgraben in Lower Austria. In an effort to evaluate the interpretive potential of each data set we conclude that a combined analysis of all available data is essential for a comprehensive understanding of anthropogenic and natural features and formation processes. At the Ratzersdorf site specifically, the visibility of both anthropogenic and geological structures in the magnetometry data demonstrates the importance of the combination of complementary data for the verification or falsification of preliminary interpretive ideas.

Keywords
ALS data; Early Bronze Age; excavation; fortified hilltop settlement; magnetic prospection

Introduction

When studying archaeological sites, having various sets of data available for analysis and interpretation is paramount. Different kinds of anthropogenic, geological, and other natural features will manifest differently in different data, or may not show up in some data at all. Accordingly, the use of several complementing data sets such as remote sensing data, prospection data, and excavation data has become a standard in archaeological research.

In this paper, we present preliminary results gained from the joint analysis of data sets generated within the Ratzersdorf project, an archaeological research project focusing on the Early Bronze Age fortified hilltop settlement of Ratzersdorf/Am Dachsgraben near Wölbling in Lower

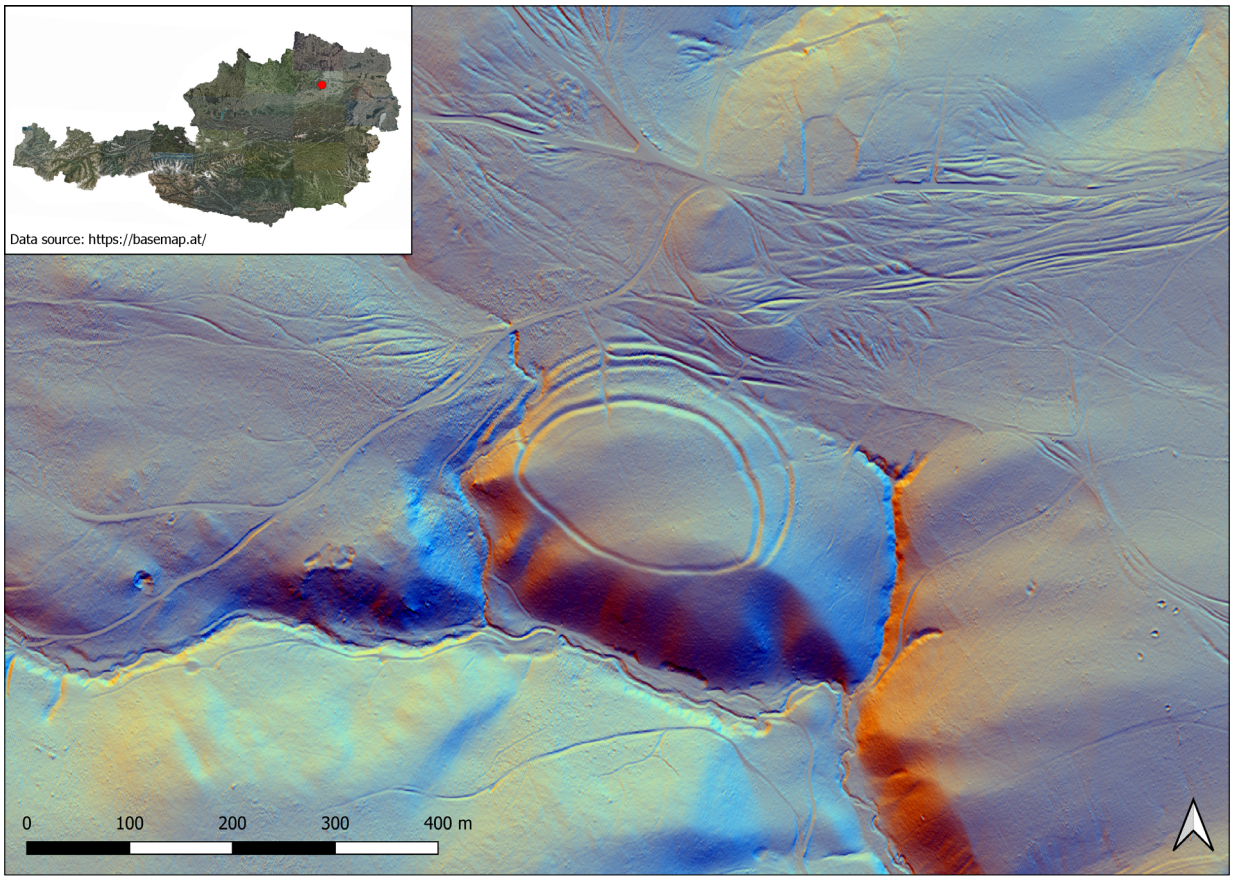

Fig. 1: Location and topography of the Ratzersdorf site as seen in a 1 m resolution DTM derived from ALS data. Ramparts and ditches are clearly visible (Ratzersdorf project, IUHA Vienna; LiDAR NÖGIS, BEV; data source: https://basemap.at/).

Austria. The data consist of magnetometry data, Airborne Laser Scanning (ALS) data, and archaeological and geological excavation results. The aim of the presented study was to compare these data to assess which features show up in which data sets and how the combination of different data during analysis influences the interpretation of identified features. Results from the study help to evaluate the merits and limits of each individual data set as well as those of the combined analysis.

Materials and methods

The Ratzersdorf site

The Early Bronze Age fortified hilltop settlement of Ratzersdorf/Am Dachsgraben was first discovered in 1928 and is under monument protection since 2006 (Blesl 2002; Krenn-Leeb 2021). The site is situated on an east-west oriented hilly outcrop on the western edge of the Wölbling Basin in Lower Austria (Fig. 1). The hilltop plateau comprises an area of approximately 25.000 m² and is surrounded by a rampart-ditch-rampart system. To the north and east, a second rampart-ditch-rampart construction reinforces the fortification while the flat, easily accessible northern slope is protected by at least two additional rampart-ditch systems. The steep western, eastern, and southern slopes act as natural fortifications (Krenn-Leeb and Weßling 2020). Since 2018, an annual research excavation and fieldschool led by Alexandra Krenn-Leeb of the Department of Prehistoric and Historical Archaeology of the University of Vienna takes place at Ratzersdorf (Krenn-Leeb 2021).

Data sets and methodology

At the start of the 2018 and 2019 fieldwork, magnetic prospection was carried out by Volker Lindinger of the ARDIG Archäologischer Dienst GesmbH. The majority of the settlement area on the hilltop plateau as well as parts of the open space between the second and third rampart were measured, covering a total of 30.347 m² (Fig. 2). Magnetic measurements were conducted with a Bartington GRAD

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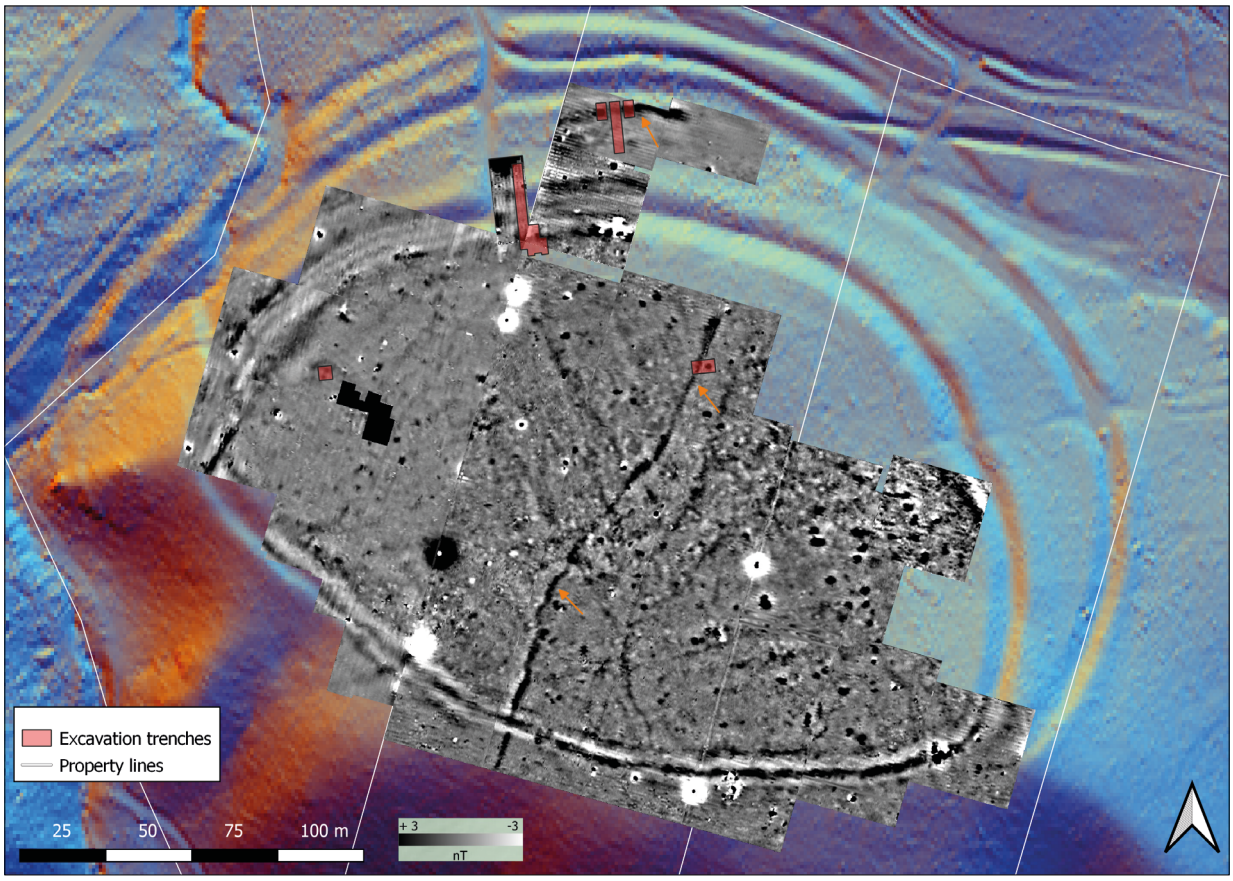

Fig. 2: Magnetometry data obtained in 2018–2019 and locations of the 2018–2022 excavation trenches (Ratzersdorf project, IUHA Vienna; Lindinger V./ARDIG; LiDAR NÖGIS, BEV).

601 dual fluxgate gradiometer with a resolution of 0.1 nT, a cross-line spacing of 0.5 m, and an inline spacing of 0.125 m (Lindinger 2019).

The excavation areas were selected according to possible anthropogenic features visible in the magnetometry data to confirm the existence of these features in the subsurface and gather information on their composition. Preliminary interpretations based on the magnetometry data were complemented by results of the archaeological excavations and of geological test trenching. ALS data provided by the Department of Geoinformation of the Government of Lower Austria (LiDAR NÖGIS, BEV) further supplemented the data base, helping to determine which features were still visible in the modern topography.

Results

The geophysical prospection revealed several potentially archaeologically relevant structures, among them the innermost and part of the second rampart-ditch-rampart systems as well as a large number of positive magnetic anomalies on the hilltop plateau interpreted as pits and ditches. In this study, we concentrate on two specific anomalies: Firstly, a north-south oriented positive, slightly bent linear anomaly on the plateau that was initially interpreted as a ditch that appears to intersect large parts of the settlement. Secondly, a positive linear anomaly following the course of the third rampart and its southern slope (Fig. 2, anomalies indicated by orange arrows). In the ALS data, the strong, north-south oriented anomaly is not visible, while the anomaly at rampart 3 appears to be partly identical with the rampart itself. Due to this inconclusive evidence, both anomalies were cut during excavations to gather additional information.

The linear anomaly on the plateau was clearly distinguishable during excavations and was discovered to be not a ditch, but a geological feature that was likely formed in the course of periglacial processes. It was visible as a fissure filled with eolian, clay-rich sediment which may cause the



Fig. 3: Likely periglacial fissure filled with clay-rich sediment (a). Post hole and daub on rampart 3 (b) (Ratzersdorf project, IUHA Vienna).

magnetic signal (Fig. 3a). The geological feature was also confirmed during Electrical Resistivity Tomography (ERT) measurements (Krenn-Leeb et al. 2023). Conversely, the anomaly on rampart 3 did not show up as one distinct structure during excavations. Geological test trenching revealed west-east oriented fluvial processes in the location of the anomaly beneath and to the south of the rampart which appear to be following the natural slope and may show up in the magnetic data. A linear array of daub and postholes running roughly along the top of the rampart could intensify the positive magnetic anomaly (Fig. 3: b). Preliminary interpretations as to the cause of this anomaly are thus still inconclusive. The current state of research indicates that both anthropogenic and geological processes and structures are visible in the magnetic data and can be verified through excavations. Additional results are expected as excavations in this part of the site are still ongoing.

Discussion

The study results have revealed several important insights. The targeted excavations have proven crucial for the interpretation of features in cases where the prospection and remote sensing data were conflicting or inconclusive. Additional information generated through the excavations and the geological test trenching was able to expand and complement the first interpretive approaches based on the prospection data. Thus, the combination of all data sets is paramount for a comprehensive, informed analysis and interpretation of features at the Ratzersdorf site.

In addition, in the course of this study we were able to identify anthropogenic as well as geological structures and formation processes at the site. Both anthropogenic and geological features are therefore proven to show up in the magnetic data, but they are not distinguishable as one or the other. This circumstance again speaks to the necessity of combining several different data sets for feature analysis and interpretation and especially emphasizes the importance of targeted excavations.

Conclusion

Comparison between and joint analysis of magnetic prospection data, ALS data, and excavation results in the course of the Ratzersdorf project have been successful to date, enabling researchers to identify and comprehensively interpret anthropogenic as well as geological features and processes at the Ratzersdorf site. Aside from feature identification and interpretation itself, these results further our understanding of the Ratzersdorf site as a whole by providing insights into the construction of its anthropogenic structures and the local geology and formation processes.

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"and sent for expert men from Rammelsberg...": the siege tunnel of Henry the Lion at Desenberg from 1168

Fritz Jürgens[1*], Dennis Wilken[2], Ulrich Müller[1], Nils Wolpert[3], Manuel Zeiler[3]

1 Institute of Pre- and Protohistoric Archaeology, Christian-Albrechts-University, Kiel, Germany
2 Institute of Geosciences, Kiel University, Kiel, Germany
3 LWL-Archäologie für Westfalen, Münster, Germany
* Corresponding author: E-mail: f.juergens@ufg.uni-kiel.de

Abstract
In this paper, we show first results of seismic and EMI data comprising evidence of a siege tunnel mentioned in medieval written sources. The tunnel would be the oldest archaeological evidence of a man-made tunnel in Westphalia (Germany).

Keywords
archaeological prospection; EMI; medieval mining; reflection seismics

Introduction

The Desenberg mountain cone with its castle ruins is the landmark of the Warburger Börde (Fig. 1 top). In addition to its appearance, however, the history of the castle is also extremely remarkable. The castle was first mentioned in 1070. In that year, King Henry IV laid siege to the castle, which was a stronghold of Otto of Northeim. Through the latter's heirs, the castle came into the possession of Henry the Lion, who in turn gave it as a fief to Widukind von Schwalenberg (Kneppe and Peine 1991). However, after Widukind had murdered Theoderich, the city count of Höxter, at a public court day in 1156, he was stripped of all his fiefs and banished, but evaded these measures and joined a princely revolt against Henry the Lion in 1166. When he also did not accept the conciliation at the Imperial Diet in July 1168 by Emperor Frederick I, Henry the Lion laid siege to Widukind of Schwalenberg on the Desenberg. But since the castle withstood the besieger and their machines, Henry brought in miners from the Harz mountains near Goslar. They drove a tunnel into the Desenberg and blocked the castle well, after which the castle garrison surrendered (Meyer 1826). The castle was besieged and destroyed several times in the following centuries until it was finally abandoned in the 16th century (Peine and Kneppe 2014).

Smaller archaeological excavations in the 1960s and 90s revealed mainly modern and a few medieval structures, but nothing remains of the 12th century castle. A hollow in the terrain on the north-eastern slope of the mountain (labeled "A" in Fig. 1) was interpreted during prospections as a possible tunnel entrance from the year 1168, which was to be verified with the geophysical measurements. As the area is a nature reserve, invasive investigation methods are not feasible.

Methods

The possible tunnel entrance lies at the foot of the mountain. From here the topography rises by 25 m to the first rampart-protected level of the castle. If the tunnel or tunnel filling was visible at the possible entrance area in the first few meters of subsoil, the distance to the surface would increase significantly when coming to the castle area. Thus, we decided to use large offset FDEMI (frequency domain electromagnetic induction) to be able to trace possible tunnel remains as far as possible up the mountain, and then to switch to reflection seismics to bridge the large distance between surface and tunnel.

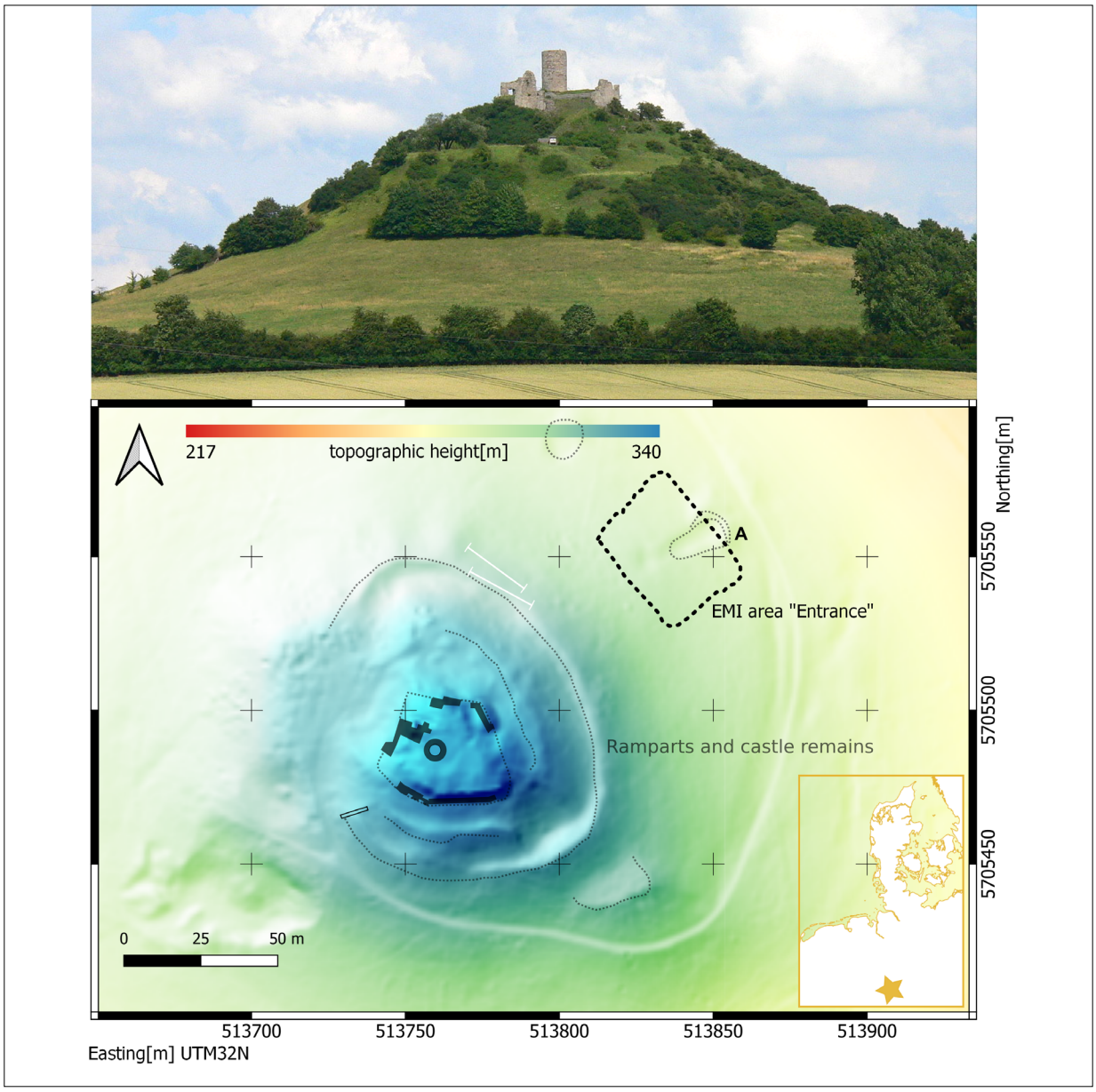

Fig. 1: Top: image of the Desenberg castle and the mountain today (File:Ruine Desenberg Westansicht.jpg by Presse03 (talk) is licensed under CC BY-SA 3.0). Bottom: Topographic map of the mountain with ramparts and plan of the castle remains on top of DEM. The investigation area A is indicated by a dashed line, seismic lines are shown as solid white lines.

For the entrance area, we used the CMD Explorer by GF Instruments. The device consists of one transmitter and three receiver coils. The planes of the coils were oriented horizontally (horizontal coplanar, HCP). The distances between the transmitter and receivers were 1.48, 2.82, and 4.49 m. EMI measurements were done where possible in the surroundings of the so-called entrance. Accurate positioning was achieved by RTK (Real Time Kinematic) DGNSS (Stonex S9i).

Processing of the EMI data included: coordinate offset correction, inline spatial bandpass filtering to remove walking noise, removal of the turns between profiles. Correcting offset of profile direction due to the different distance to the slope of the mountain. A drift correction was not necessary for the conductivity/quadrature data. Finally, the data was interpolated using 2D linear interpolation. Beyond EMI mapping of apparent conductivity, we performed 1D conductivity inversions on example profiles.

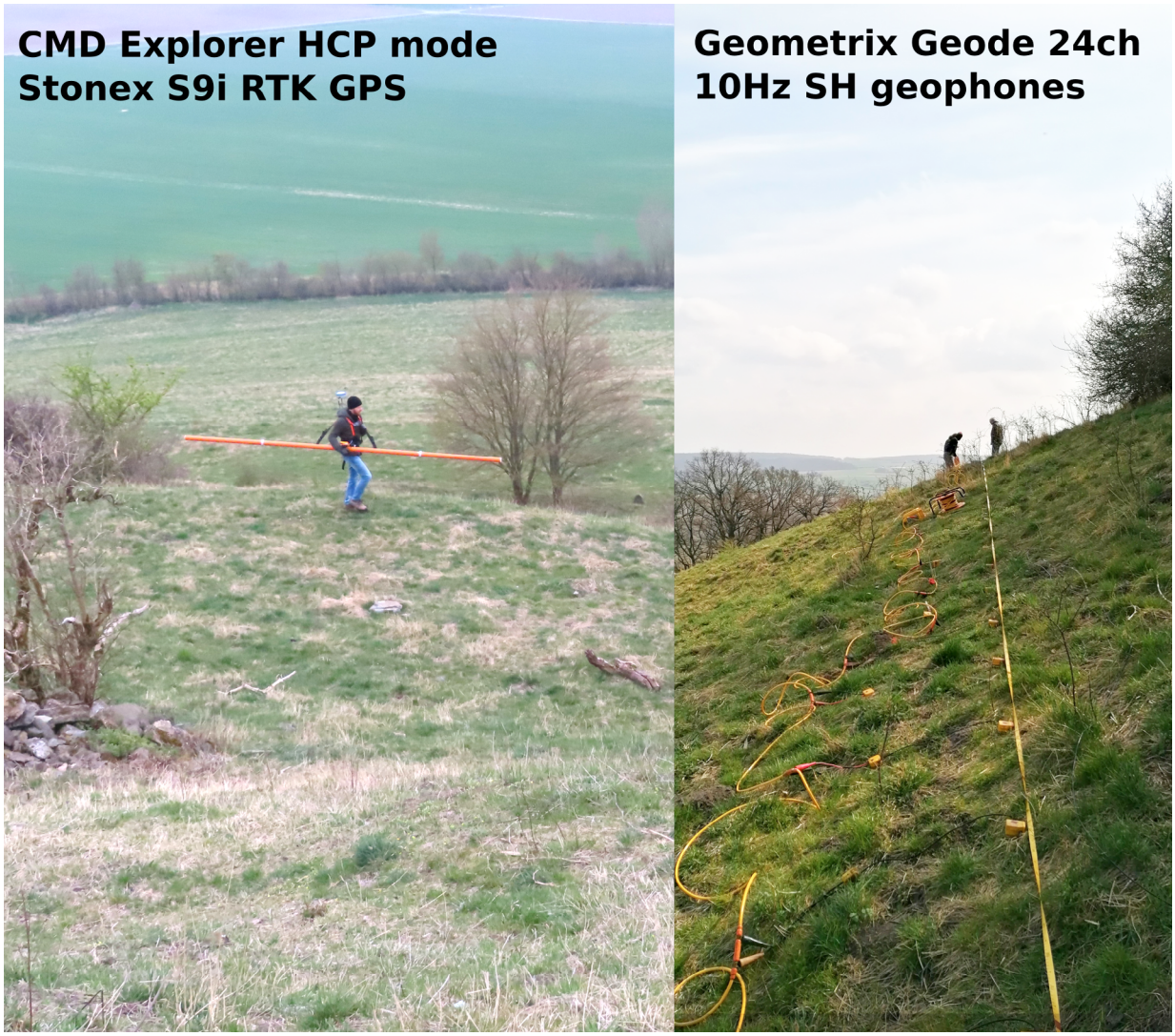

Fig. 2: Left: the CMD-Explorer setup in use at the Desenberg. Right: Seismic line at the Desenberg.

Leaving the entrance area and considering the slope and thus the possible depth of the tunnel, only seismic methods are feasible. We therefore performed two 24 m seismic horizontal (SH) shear-wave reflection profiles with a geophone distance of 1m. Shots were done using a 2 Kg hammer blow on a steel bar perpendicular to profile direction (SH polarization). Acquisition was performed using a Geometrix geode seismograph.

Processing of the seismic data included: sorting of traces, using only the two traces next to the shot point to create a 0.5 m constant offset section. This section was bandpass filtered, trace normalized using the first quantile of each trace, fk-filtered, multiplied by a linear time gain function, and converted to depth using an average velocity of 100 m/s.

Results

Figure 3 a) shows the apparent conductivity maps of the three different EMI coil separations. The first two coils appear quite turbulent, probably due to shallow debris and small scale topographic changes. Nevertheless, lower conductive areas correspond to the two ridges framing the possible entrance area. The largest coil separation clearly shows these two ridges as low conductive linear features, having one small connection in the center. The higher conductive feature framed by the ridges seems to bend westwards at the south-western end of the investigation area.

Figure 3 b) shows the inversion results of the two example profiles, one crossing the two ridges and the ge-

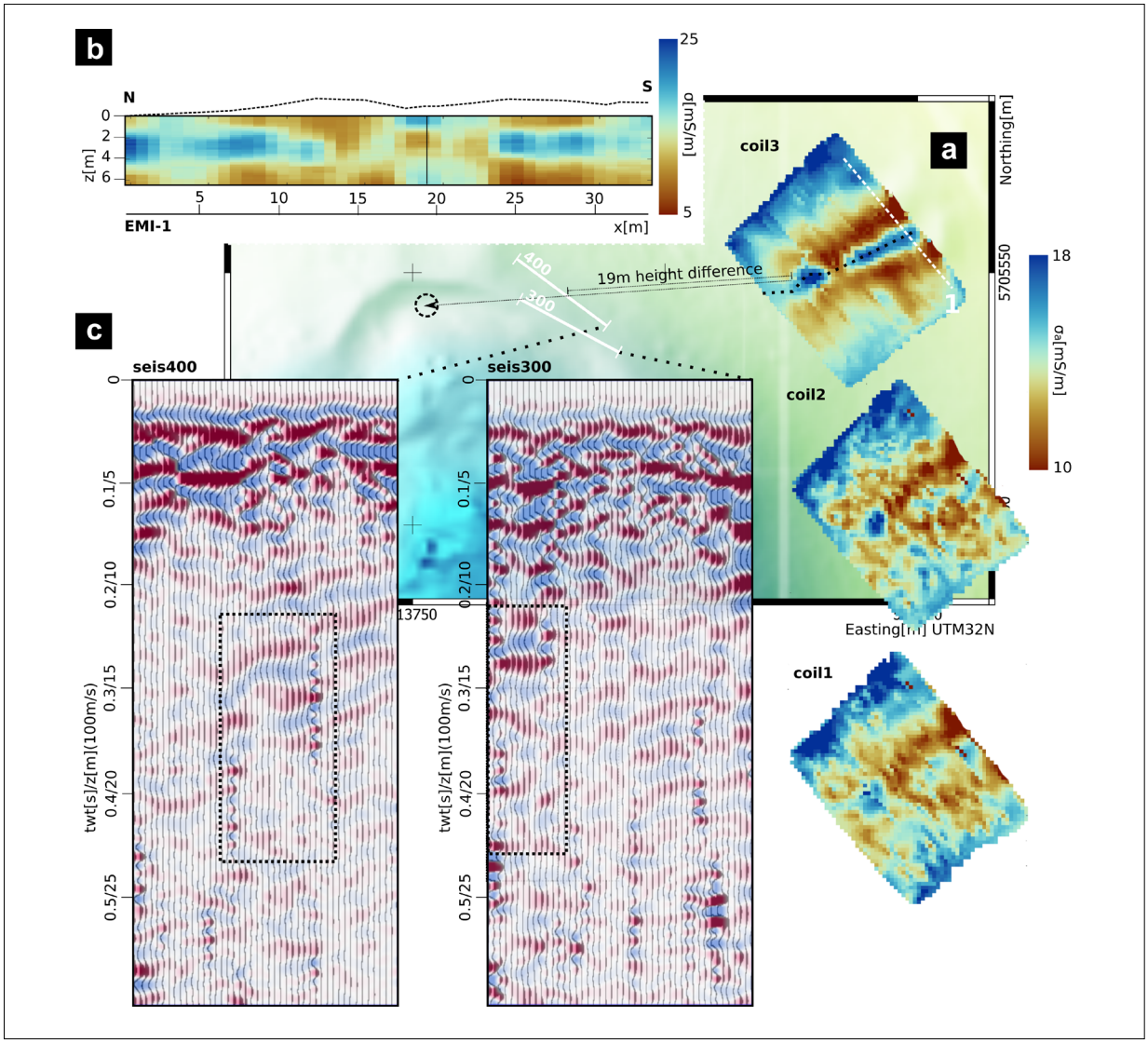

Fig. 3: a) Apparent conductivity maps of the three different coil separations. b) Inversion results showing the conductivity depth distribution on an example profile (see map in the center of the figure). c) Sweismic zero offset sections.

neral background and one crossing the small connection. Figure 3 c) shows the resulting seismic sections. Considering the topographic change and the resulting depth in the seismic lines, we highlighted peculiar reflection/diffraction events interrupting the reflectors of geological origin.

Discussion

Interpreting the measurements taken at Desenberg is not straightforward. The seismic reflection/diffraction events at a depth of about 15 m, that disturb the original geology, might give indications of the tunnel. Their position, in the middle of profile seis400 and at the edge of profile seis300, would support the hypothesis that the tunnel runs towards the first rampart-protected level of the castle. This would be the most suitable location for a well from a construction point of view, as this point of the castle is the lowest and would therefore mean the least effort for well construction. The EMI data from the presumed entrance to the tunnel probably represents a history of backfilling. The lower conductive areas that would correlate with the side walls of the tunnel are striking. Possibly this phenomenon is due to the collapse of the tunnel after its abandonment, when the higher conductive upper earth layers slid centrally into the tunnel area, exposing the underlying lower

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conductive material. The same applies to a round anomaly further up, visible in all three depth ranges of the EMI, which could represent a backfilled funnel, that is typical for those kinds of tunnel constructions.

Based on the EMI, it can be assumed that the tunnel course is imaged by the backfilled low resistive linear structure. Together with the seismic measurements and the archaeological interpretation of the visible castle structures, these probably represent the relics of Henry the Lion's siege tunnel of 1168, which has been handed down historically.

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Reassessing Italian Renaissance church interiors through non-invasive survey

Donal Cooper [1], **Stephen Kay** [2*], **Elena Pomar** [2]

1 Faculty of Architecture & History of Art, University of Cambridge, Cambridge, United Kingdom
2 British School at Rome, Italy
* Corresponding author: E-mail: s.kay@bsrome.it

Abstract
The study shows the investigation of an Italian Renaissance church with combined laser scanning and ground penetrating radar. The survey discovered through GPR multiple unknown tombs and remains of a lost chapel. The full dataset was merged as a point-cloud in Leica Cyclone for a holistic view of the standing architecture and sub-surface remains.

Keywords
churches; ground penetrating radar; laser scanning; Renaissance

Introduction

Church interiors in Renaissance Italy were the most significant settings for viewing art. Recent research has emphasized how closely integrated artworks, like altarpieces, were with their architectural and liturgical settings. However, these interiors have invariably been radically transformed over later centuries. Conventional scholarship in art history focuses on building analysis and documentation to reconstruct historical viewing conditions. This project took a fresh approach, drawing upon ground penetrating radar (GPR) to investigate elements now hidden beneath church pavements, and laser scanning to combine the building architecture with the sub-surface features.

The project took as an initial case-study the Church of Sant'Agostino (San Gimignano) to assess the possible existence of a rood screen - a monumental structure removed in the Counter Reformation that once dominated church interiors and determined the visibility of artworks inside (Cooper 2017). GPR was also used to investigate the exterior of the church with the aim of locating a side chapel, destroyed in later centuries.

The Church of Sant'Agostino was built just before 1300 and by the end of the 14th century it was a prestigious ecclesiastical centre (Razzi 2014). The church has numerous burials in the floor of the nave and cloister, as well as an apparent cemetery alongside the building. The interior walls of the church are decorated with magnificent frescoes of the 14th and 15th centuries. Of importance to the research project is an altarpiece by the Sienese artist Simone Martini, three sections of which are preserved at the Fitzwilliam Museum, Cambridge University. One of Martini's earliest works (c. 1317) the polyptych has been little studied and its precise original position within the church is unknown, its format suggesting that the panels were for a side altar.

Materials and methods

The methodology developed to record the Church of Sant'Agostino was to combine different non-invasive techniques which would permit the integration of sub-surface features and standing architecture. A number of different techniques were used including GPR (GSSI 400 MHz), laser scanning (Leica RTC360) and targeted photogrammetry.

In order to merge the results into a shared environment, the data collection was underpinned by a topographical survey. Following processing in GPR-Slice, time-slices were added into a Geographic Information System (ESRI Arc-

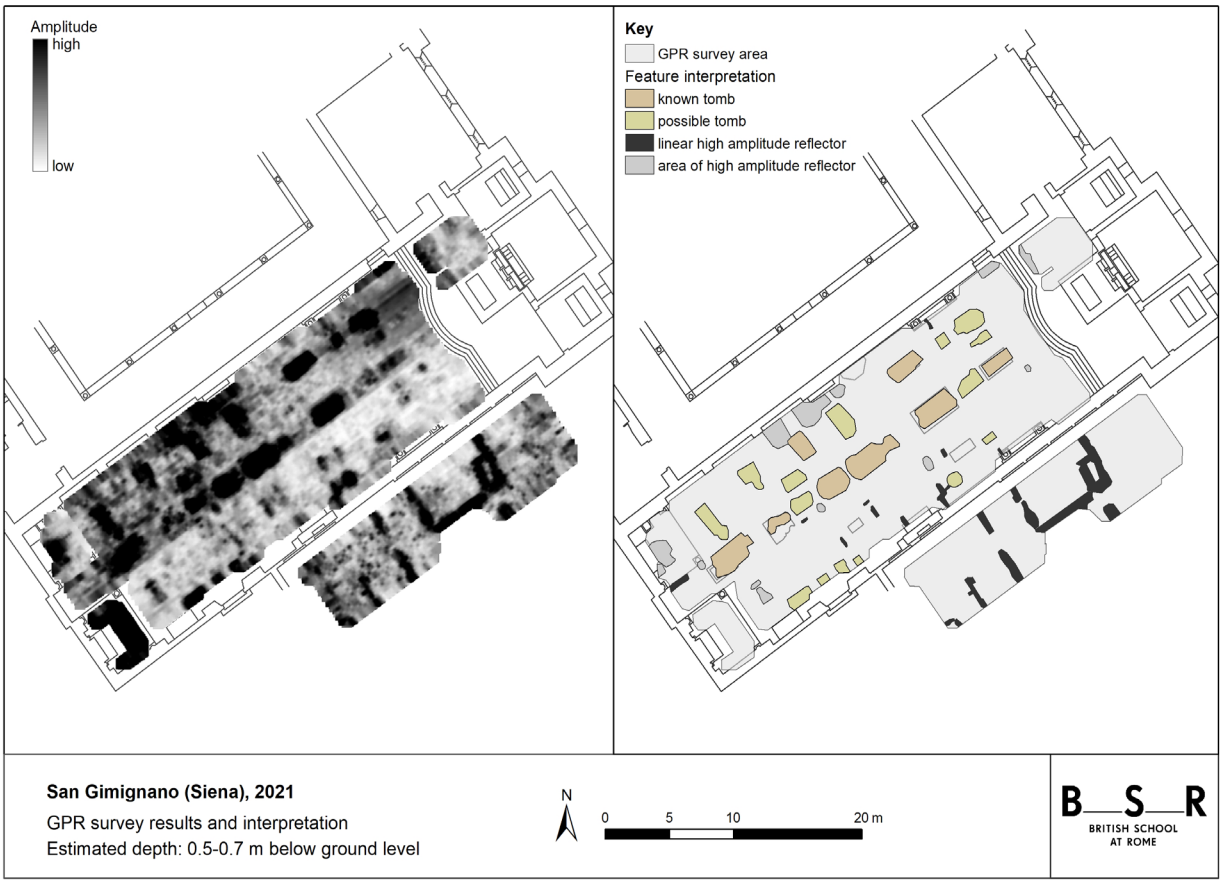

Fig. 1: Church of Sant'Agostino. GPR survey results and interpretation.

Map) for 2D visualization and analysis, and high iso-amplitude features were extracted from GPR-Slice as point clouds to be analyzed in a 3D environment (Cyclone 3DR).

Results

The GPR survey in the nave of the church revealed a distribution of tombs greater than is visible in the pavement (Fig. 1). The survey identified 15 previously unknown tombs, whilst several known tombs were shown to no longer be in their original position (with no cavities or disturbance beneath the marble tombstones). The form of burial also varied as some tombstones had cavities recorded below that are too small for an inhumation. It is therefore feasible that small ossuarys were inserted into the pavement.

The presence of a rood screen in the early phase of the church could not be determined by the GPR survey, as few traces of a linear feature, as expected for traces of a foundation, were recorded across the church. However, the survey alongside the southern exterior wall of the church revealed several regular high amplitude anomalies that appear to confirm the presence of a small chapel, recorded in historical documentation as the brotherhood chapel of San Martino (Fig. 2).

Discussion

The case-study of the Church of Sant'Agostino illustrates the suitability of the methodological approach for the investigation and documentation of churches of Renaissance Italy. The GPR survey provided valuable information regarding previously unknown features, such as numerous unmarked tombs in the nave of the church, as well as relocating the San Martino chapel against the exterior southern wall (Fig. 2).

The integration of the GPR data with the 3D point cloud recorded by the laser scanning of the standing building, as

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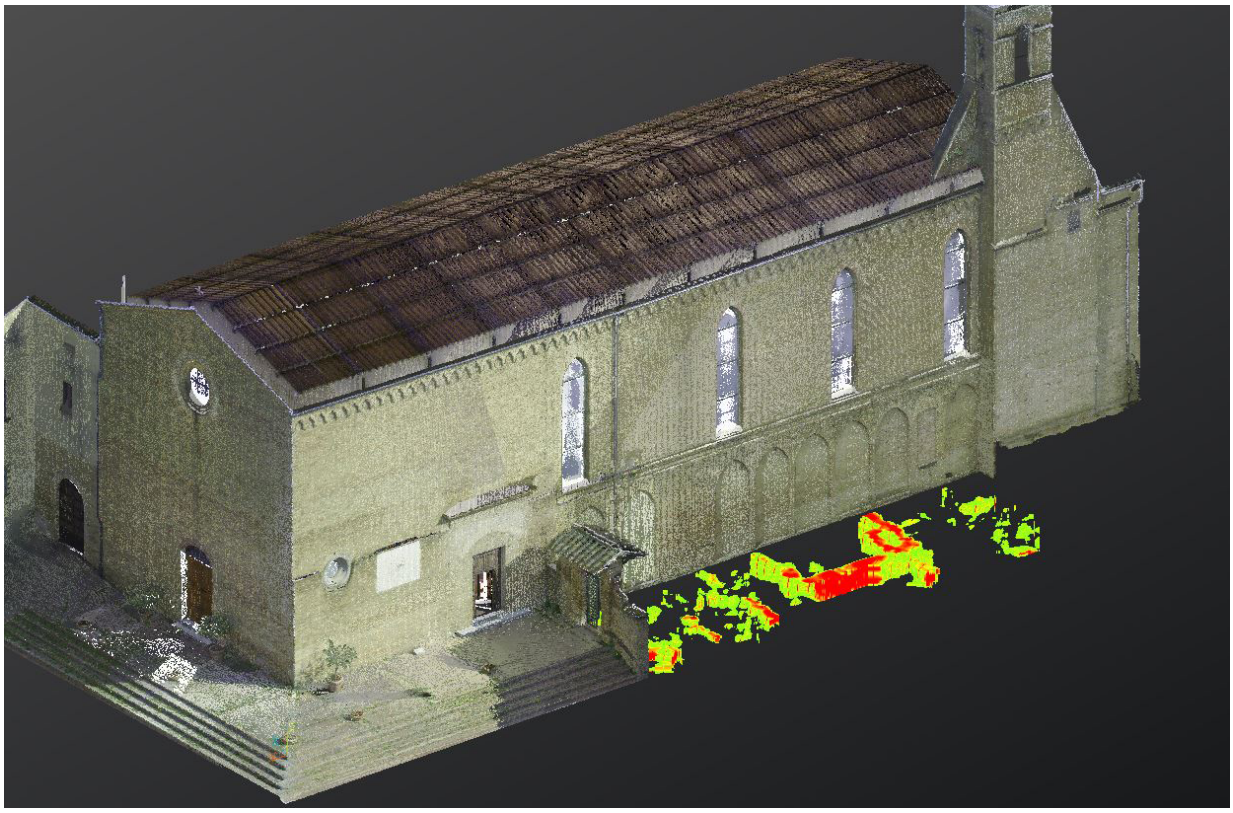

Fig. 2: Church of Sant'Agostino. Point cloud data of the laser scan of the church and GPR survey of the exterior area.

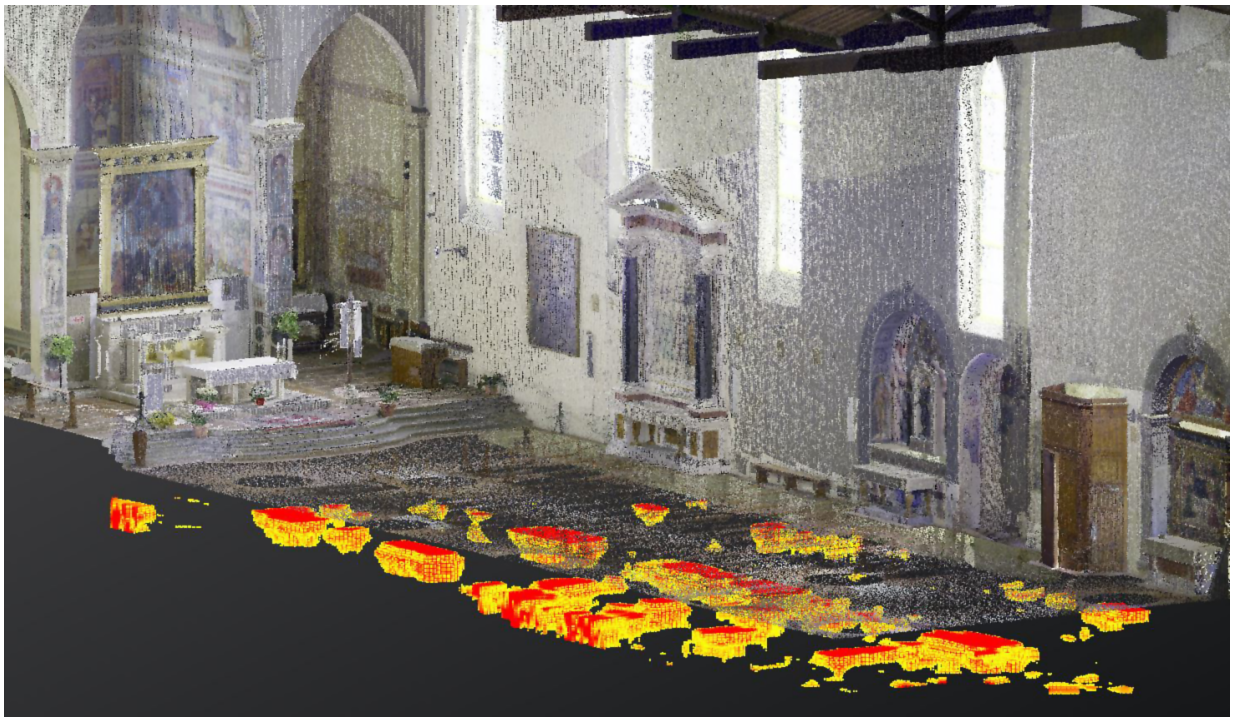

Fig. 3: Church of Sant'Agostino. Point cloud data of the laser scan of the church interior and the location of tombs recorded by the GPR survey.

well as detailed photogrammetry of the tombstones, provided a unified representation of the visible and hidden reality, as well as a direct comparison between different chronological phases of the building. Through the integration of the high amplitude features as a point cloud into Cyclone 3DR, an examination can be made of sub-surface features with the position of architectural elements in 3D (Fig. 3). Furthermore, the accurate recording of all tombs within the nave will also assist in a better understanding of the internal layout and potential viewing positions of artworks, as tombs were placed in correspondence to altars and entrances into the church. The 3D model generated of the church now allows the testing of the repositioning of the Martini polyptych at different locations in the church, also in consideration of the newly discovered tombs and altar bases.

Conclusion

The combination of laser scanning and GPR point clouds offers a holistic perspective for the consideration of the original layout of buildings and how artworks may have been viewed. Through the combination of building analysis and the study of historical documentation with the non-invasive techniques, a much greater understanding has been achieved of the church of Sant'Agostino.

The methodology implemented at the Church of Sant'Agostino in San Gimignano will be further tested at other Renaissance churches in central Italy. The combination of structural building survey and geophysical prospection has shown how church interiors, where architectural structures that have been removed, may have affected the interaction with artworks.

Acknowledgments

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A swamp as an obstacle to approach – archaeological and geoelectrical investigations on the Early Bronze Age fortification of Ratzersdorf, Lower Austria

Alexandra Krenn-Leeb[1*], Robert Supper[2], David Ottowitz[2], Birgit Jochum[2], Armin Preiner[2], Ronny Weßling[3], Doris Jetzinger[1]

1 Department of Prehistoric and Historical Archaeology, University of Vienna, Vienna, Austria
Human Evolution and Archaeological Sciences, University of Vienna, Vienna, Austria
2 Division of Geophysical and Applied Geological Services, GeoSphere Austria, Vienna, Austria
3 Crazy Eye 3D-Studio, Vienna, Austria
* Corresponding author: E-mail: alexandra.krenn-leeb@univie.ac.at

Abstract
Interdisciplinary cooperation between geoelectrics and archaeology made it possible to identify a swamp as an integral part of a defense concept for the first time in Austria at the Early Bronze Age hilltop settlement of Ratzersdorf, Lower Austria. The marsh and a spring were included as natural topographic structures in the defense conception of the fortification.

Keywords
defense conception; Early Bronze Age; fortified hilltop settlement; geoelectric prospection; swamp

Introduction

In the late Early Bronze Age, numerous fortified hilltop settlements with a central site character became established in Central Europe. They often have complex defense structures and required intensive protection for some time. But the majority of these sites were destroyed at the beginning of the Middle Bronze Age. In most cases, the fortification structures were not rebuilt and the sites were abandoned. Obviously a social, economic, and political-ideological change made these fortifications obsolete (Jaeger 2016; Krenn-Leeb 2013).

Within the framework of a long-term research focus on the settlement region "Wölbling Basin" in Lower Austria under the direction of Alexandra Krenn-Leeb, landscape archaeological questions concerning the use of fortified hilltop settlements, space, activity zones, architecture, fortification structures, settlement site selection from the Neolithic Period to the Bronze Age are in the foreground of the interdisciplinary investigations (Krenn-Leeb 2019). The Wölbling Basin is located in the Dunkelsteinerwald and belongs geologically to the Bohemian Massif.

Therefore, since 2018 archaeological excavations have been taking place at the Early Bronze Age fortified hilltop settlement with a central site character of Ratzersdorf near Wölbling (1800–1600 BC; Krenn-Leeb 2021). The fortification is situated on a west-east oriented, oval spur-like hilltop on the western edge of the Wölbling Basin and is naturally bordered on three sides by deeply incised streams and steeply sloping hillsides. The site is ca. 440 m above the sea level and has an approx. 440 x 340 m extension (approx. 120 000 m^2).

Materials and methods

The oval plateau area of approx. 25 000 m^2 is surrounded by a circumferential, excellently preserved rampart/wall-ditch-rampart system. In the northern and eastern part of the plateau, a second rampart-ditch-rampart system reinforces the fortification. The northern flank is subsequently protected by at least two more rampart-ditch constructi-

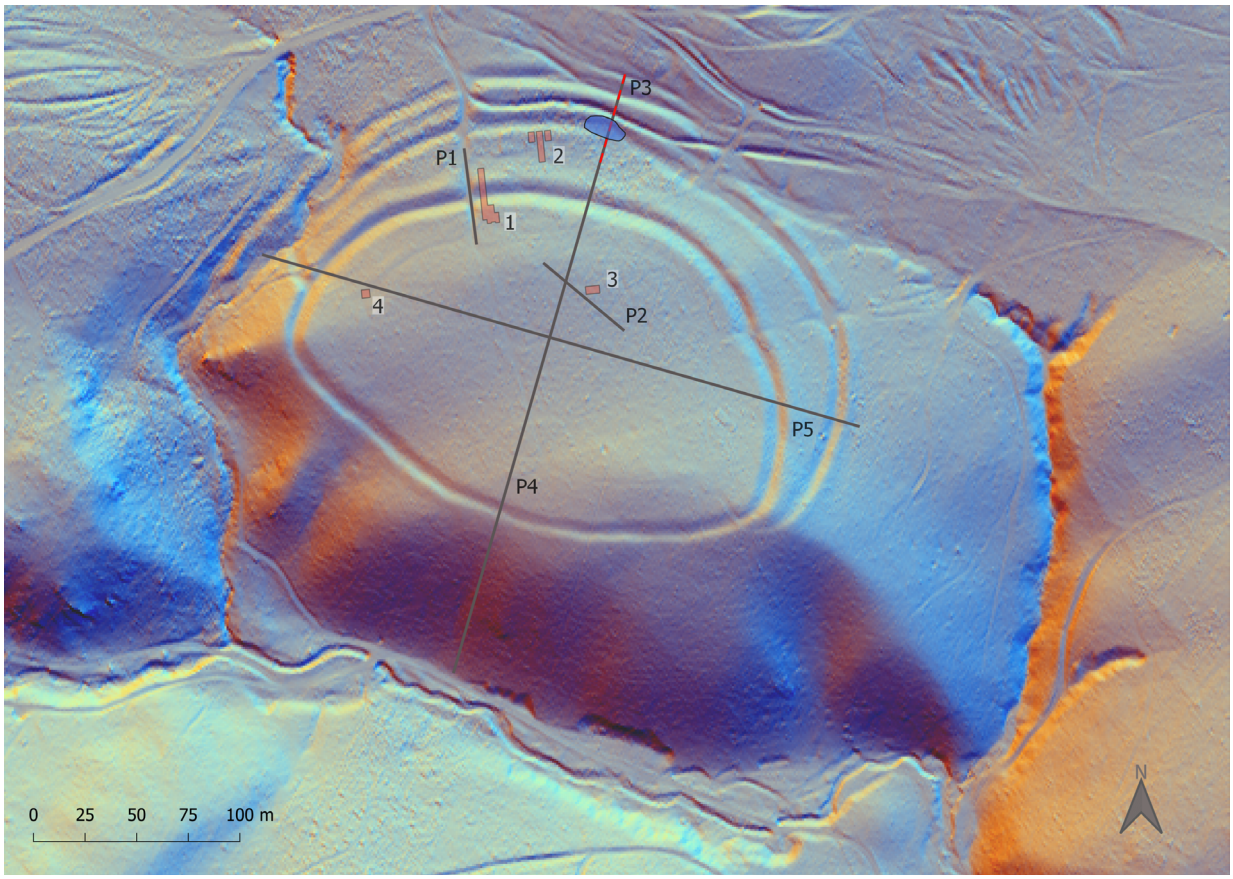

Fig. 1: The Early Bronze Age fortification with ramparts and ditches of Ratzersdorf, Lower Austria. Red: excavation areas 1–4. Gray: Profiles P1–P5 of the geoelectrical measurements. Blue: the integrated water spring (Ratzersdorf project, IUHA Vienna; LiDAR NÖGIS, BEV; https://basemap.at/).

ons. These fortifications represented obstacles to approach that were difficult to overcome. They mainly protected the easily accessible northern area of this Early Bronze Age central site (Fig. 1).

Terrain structures visible in the airborne laserscan to the northeast of the site led Robert Supper to suspect wetlands at the same location. The geoelectrical measurements initiated as a result were carried out over wide areas of the fortification between 2020 and 2022 (Supper et al. 2021).

The most common geoelectric field measurements usually make use of a linear, symmetrical electrode configuration in the 4-point arrangement, with the outer electrodes injecting the current and the inner electrodes measuring the potential difference.

For quality control purposes, the measurement results are presented in the form of a so-called „pseudosection", where the measured apparent resistances are plotted against the respective electrode spacing („pseudodepth"). A model of the resistivity-depth distribution is calculated from the pseudo resistivities using an inversion procedure to obtain the resistivity structure of the subsurface. Data inversion was performed using the commercial software Res2Dinv. The results are profile sections, where the topography along the profiles has been taken into account (Milsom 2003).

Results

The geoelectric measurement results provided good data quality. The topography of the profiles was integrated into the inversion (default setting), which means that the final result is already provided with topographic height information. Five profiles were measured (Fig. 2).

Profile P1 ran parallel to trench 1 on the modern forest road. The aim of this first test measurement was to verify the visibility of the archaeologically documented rampart and ditch structures in the geoelectrical measurements,

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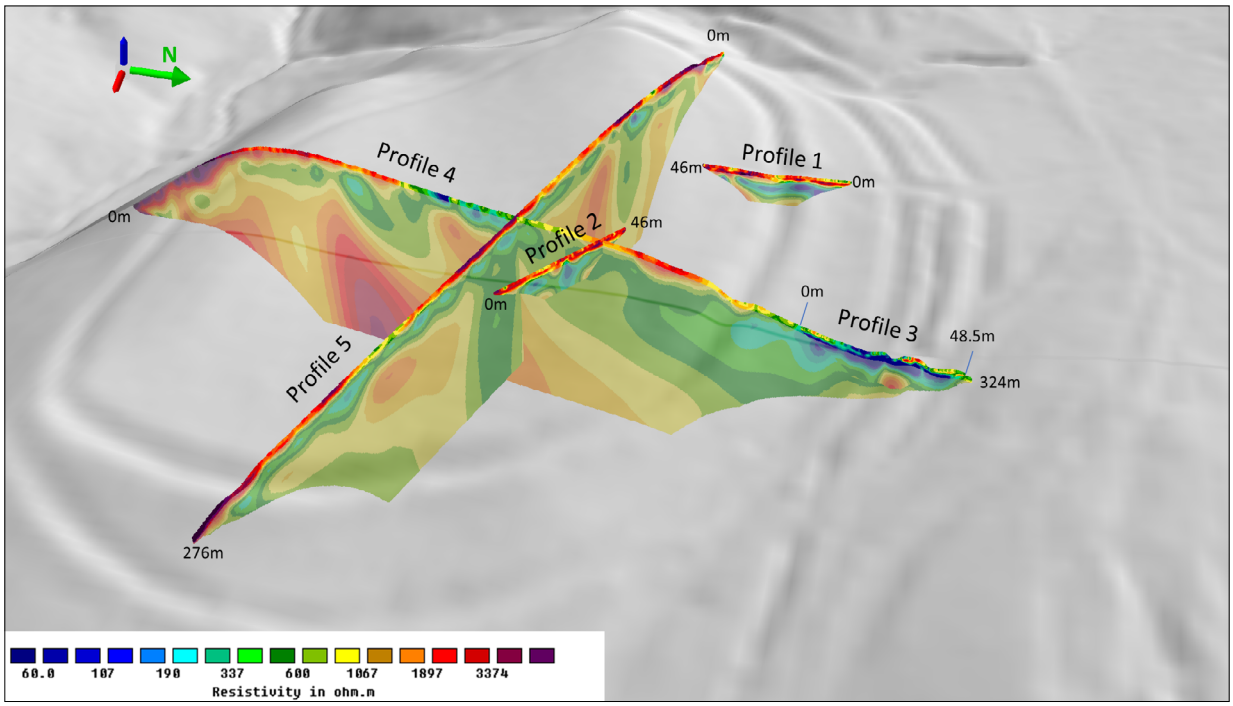

Fig. 2: The profiles P1 (length 46 m), P2 (length 46 m) and P3 (length 48.5 m) have an electrode spacing of 0.5 m, the profiles P4 (length 324 m) and P5 (length 276 m) an electrode spacing of 3 m (Ratzersdorf project, IUHA Vienna; GeoSphere Austria).

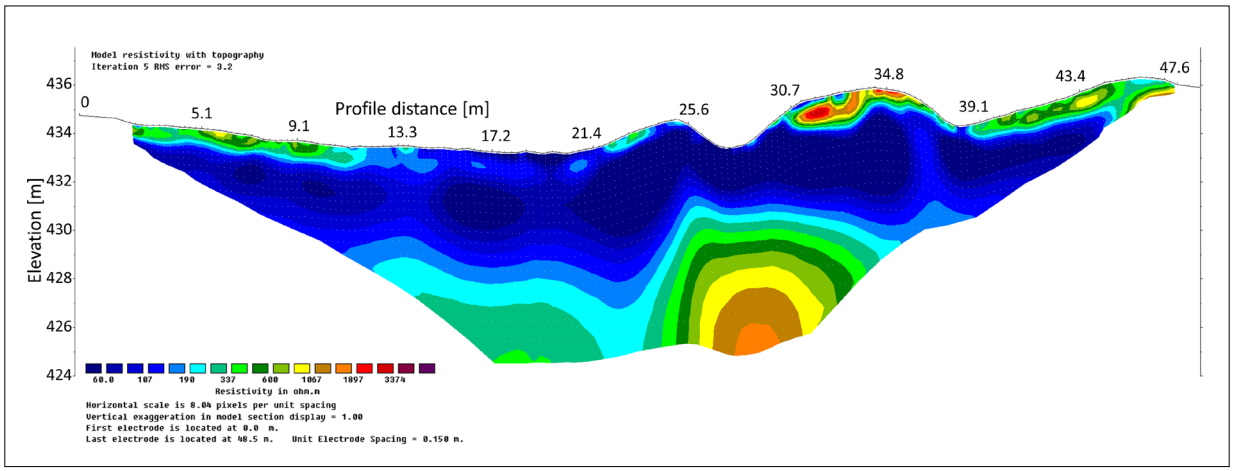

Fig. 3: Profile P3 shows a horizon with a low resistivity, which indicates a wetted area (Ratzersdorf project, IUHA Vienna; GeoSphere Austria).

which could be confirmed positively. The profiles P2 and P5 crossed the elongated geological anomaly that crosses the entire plateau area in a N-S direction. The measurements confirm a geological structure that can be assigned to a periglacial process at the current stage of research. The profiles P4 and P5 ran across the entire NNE-SSW and WNW-ESE extent of the site. The measurements document a largely crystalline bedrock over the entire plateau area. Profile P4 also clearly shows a wet area in NNE. Profile P3 confirmed the presumed wetland (Fig. 3). Archaeological fortification structures are also clearly visible in the geoelectric profiles.

The geoelectrical measurements have demonstrated a significant wet area with low resistivity values (low ohmic) in the NNE area of the fortification.

Discussion

The archaeological investigations already revealed some evidence of the presence of a wetland. The unusually large distance and the wide, fortificatory unfavorable area between the inner and the outer rampart-ditch-rampart systems in the north and east of the settlement has been irritating since the beginning of the research activities. A water spring discovered in the big outer ditch was obviously intended to be kept accessible to secure the water supply within the fortified area. Several other water springs in the near vicinity of the site are there.

In the southern part of trench 2, located near the water spring, an area with loosely placed stones was recorded. Their arrangement points to a levelling of a strongly soaked area. Wooden planks placed on top of the stones may have established a dry level of foot traffic along the southern flank of the rampart.

Finally, geoelectrical investigations did indeed provide evidence of a wetland area to the northeast of the site. Both the archaeological and geoelectrical surveys confirm a marsh area that strongly influenced the fortification conception.

Conclusion

The interdisciplinary investigations were efficiently designed in the Ratzersdorf project. Several factors indicate a strategically well-considered choice of location for the fortification at Ratzersdorf. Natural conditions, which include the steep slopes, the diverse resources of the surrounding area and also the excellent water supply from several springs, were among the decisive selection criteria. The fortification structures were largely adapted to the terrain and even extended towards a water spring. The outermost rampart-ditch constructions in the north were built exclusively in that section with the weakest fortification quality. They continue for some distance into the marshy area, but then run out to the east. The swamp may have extended over the entire area northeast of the fortification. Even today there are thick humus layers. All features clearly show that the wetland had been deliberately included in the defense conception for the Early Bronze Age central site. The marshy area obviously represented a sufficient obstacle to approach. The current, extremely heavy and impenetrable growth of blackberries in the swampy zones – blackberries are shallow rooted and require sufficient water – may well have been used as further additional natural protection at that time.

Based on several features documented by archaeology, a wet area was already suspected in the northeast area of the fortification. However, the significant proof of a marshy area was finally achieved very sucessfully by the geoelectrical measurements. Thus, for the first time, evidence of the integration of a marsh into a fortification concept of the Early Bronze Age in Austria was found.

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Pioneers of aerial archaeology: the *Bayerische Fliegerstaffel* in Palestine (1917-1918)

Roland Linck [1,2*]

1 Bavarian State Department for Monuments and Sites (BLfD), Munich, Germany
2 Ludwig-Maximilians-University, Department of Earth and Environmental Sciences, Munich, Germany
* Corresponding author: E-mail: roland.linck@blfd.bayern.de

Abstract
Bavarian military pilots were among the pioneers of aerial archaeology. The "Fliegerstaffel" documented a huge amount of archaeological sites especially in Palestine. Many of these sites nowadays are destroyed or not visible in its original shape anymore.

Keywords
aerial archaeology; Baalbek; Fliegerstaffel; Jordan; Middle East

Introduction

The history of aerial archaeology started in the second half of the 19th century, when first attempts were made by Franz Stolze to document his excavations on Persepolis (Iran) (Stolze 1882), or 1898/99 at the Foro Romano in Rome (Musson et al. 2013). Whereas these first surveys mostly were executed with balloons, the method avanced a huge step forward by the development of the first airplanes at the beginning of the 20th century.

First famous aerial archaeological findings in the Middle East are documented by Père Antoine Poidepard in the 1930s (Poidepard 1934). However, it is still quite unknown that already some decades earlier, during the First World War, several important sites were mapped from a bird's-eye perspective. A pioneering role played the *Bayerische Fliegerstaffel* that was sent to Palestine in 1917 to support the Turkish army in defending the Ottoman Empire from the British. The Ottoman Empire comprised, beside the modern Turkey, also Syria, Lebanon, Iraq, Jordan and Palestine (archivportal-d.de). Apart from their original task of generating military reconnaissance images, the Bavarian pilots also documented a multitude of archaeological sites in this area. The "Fliegerstaffel 304" was equipped with biplanes Albatros D.III and AEG C.IV (Fig. 1) (Dalman 1925). These airplanes offered a second seat for a pilot observer that acquired the lantern slide negatives. After the war, these photos were transferred to the Bavarian War Archive in Munich that still today stores nearly 3000 of them (archivportal-d.de).

Case studies

Baalbek (Lebanon)

Today, Baalbek is a provincial capital and is located in the 900-1500 m high Beqaa-Plain in the Eastern part of the Lebanon (van Ess and Rheidt 2014). Since 1984, the ancient ruins of Baalbek have been declared an UNESCO World Heritage Site. The Bavarian military pilots documented the area of the Jupiter temple, the most famous monument in Baalbek, from the air (Fig. 2). The Jupiter temple has a length of 270 m, and hence belongs to the largest ancient temples; already the smaller Bacchus temple (Fig. 2, upper part) is bigger than the Athena temple on the Acropolis in Athens (Greece).

The first systematic archaeological excavations started during the French Protectorate in the 1920s. Since this time, the archaeological surveys concentrated on the ancient remains of Baalbek and traces of younger building phases, like a Byzantine basilica and an Arab fortress have been largely removed (van Ess and Rheidt 2014). As the



Fig. 1: Biplane AEG C.IV of the *Bayerische Fliegerstaffel* at the airport Afule (former Palestine) in 1917/18 (© Bayerisches Hauptstaatsarchiv, BayHStA, BS Pal. 1256/a).

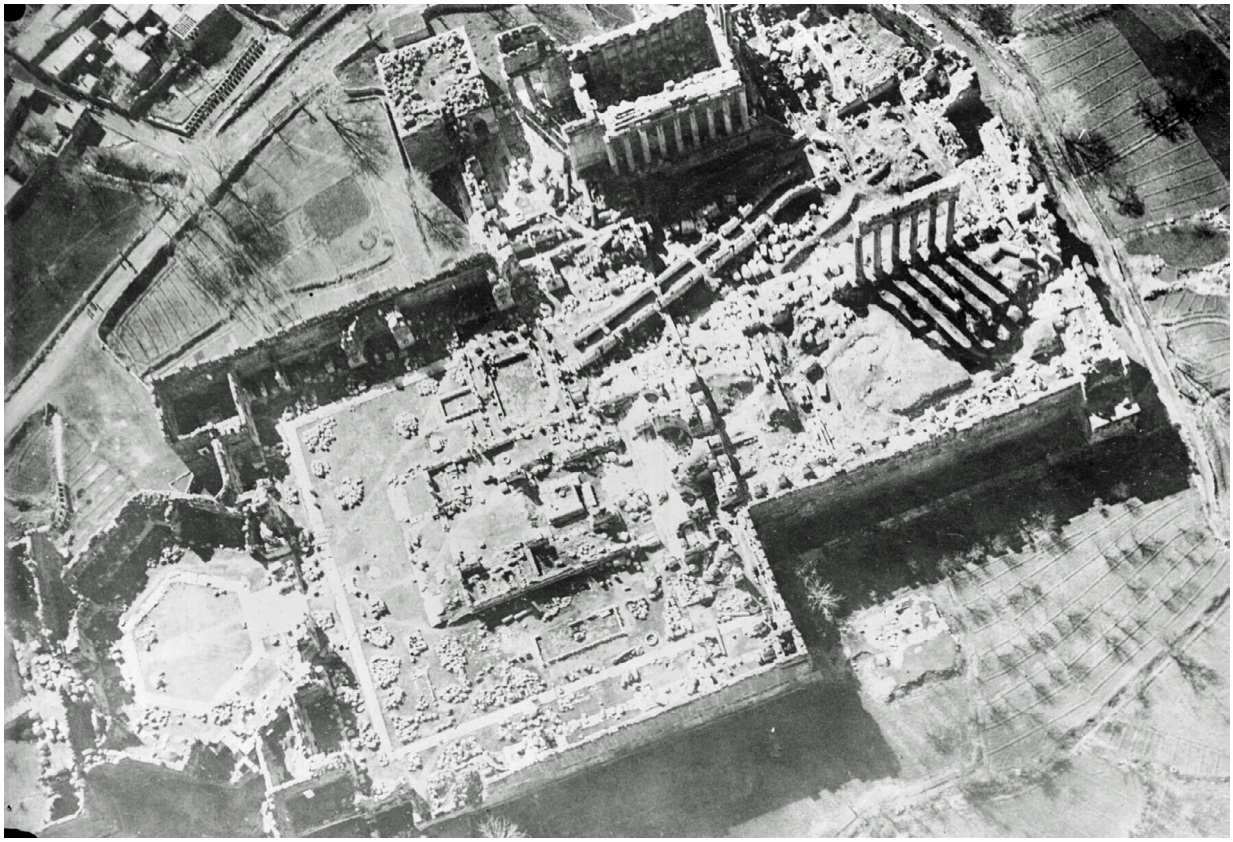

Fig. 2: Aerial view of the ruins of the Jupiter and Bacchus temple in Baalbek (Lebanon) from the north. As the photo was acquired in 1917/18, several now removed walls are still visible (© Bayerisches Hauptstaatsarchiv, BayHStA, BS Pal. 512).

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Fig. 3: (a) Aerial view of the desert fortress Qasr Mschatta (Jordan) from the northeast. The photo was taken on 09.04.1918 and shows the ruins located in the desert (© Bayerisches Hauptstaatsarchiv, BayHStA, BS Pal. 1224). (b) Modern satellite image showing that the character is lost due to the location inside the international airport area (© Microsoft, Bing Aerial 2022).

aerial photo of the "Fliegerstaffel" dates earlier, all these structures can be easily detected and mapped. Therefore, these images depict an important source for reconstructing, how the Jupiter temple in Baalbek looked like after Roman times. Especially in the Great court (Fig. 2, center) several demolished walls of the basilica and a huge stone-built water channel can be clearly identified. Of course, all the important parts of the ruin like the very well preserved Bacchus temple, the surrounding walls of the Jupiter temple as well as the entrance stairs and the octagon also are visible.

Qasr Mschatta (Jordan)

The Umayyad desert fortress Qasr Mschatta is located ca. 30 km south of Amman, the modern capital of Jordan. It was erected in the 9th century and belongs to a chain of more than 30 similar desert fortresses in Jordan, Iraq and Saudi Arabia. Already some decades after its construction it was abandoned again after an earthquake (smb.museum). The aerial photo in Figure 3a impressively shows the layout of Qasr Mschatta and its quadratic outline with 144 m length as well as the ruins of the 25 watchtowers along the outer wall. Additionally, in the interior, the remains of the former buildings like the palace still can be detected. In 1918, the original location in the middle of the desert, far away from any modern settlement was preserved, in contrary to today, when Qasr Mschatta is located inside of the Queen Alia International Airport and therefore is endangered to be completely demolished by future construction work related with the development of the airport (Fig. 3b). Furthermore, the original desert character is lost and the old aerial photography again provides an important historical source.

Conclusion

As the two exemplary case studies show, the military pilots of the *Bayerische Fliegerstaffel* can be regarded as aerial archaeology pioneers documenting several important sites in the Near East. During the First World War, this method still was in the fledgling stages and the biggest developments in the discipline started some decades later. The still preserved lantern slides of the archaeological sites in Palestine depict a real treasure, as many of these sites nowadays are destroyed by erosion, construction work, looting and military conflicts or are altered by growing settlements in the surrounding and extensive excavation campaigns in the meantime. The *Bayerische Fliegerstaffel* documented several further important archaeological sites in the Near East, like e.g. Damascus (Syria), the ancient ruins of Dscherasch (Jordan) or Milet (Turkey), the medieval Arab fortress Adschlun-Kalat er-Rabad (Jordan) and even the Pyramids of Gizeh (Egypt).

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Comparison of GPR results with UAV photogrammetry at a Roman *villa rustica* in *Noricum* (southern Bavaria)

Roland Linck[1,2*], **Andreas Stele**[1], **Tatjana Gericke**[1]

1 Bavarian State Department for Monuments and Sites (BLfD), Munich, Germany
2 Ludwig-Maximilians-University, Department of Earth and Environmental Sciences, Munich, Germany
* Corresponding author: E-mail: roland.linck@blfd.bayern.de

Abstract
Ground penetrating radar was used for mapping the layout of a Roman villa rustica. Adjacent rescue excavation results were mapped by UAV photogrammetry. The combination with a photogrammetric model enables a ground truthing of GPR results.

Keywords
ground penetrating radar; ground truthing; Noricum; Roman villa rustica; UAV photogrammetry

Introduction

Compared with other geophysical prospection methods, ground penetrating radar (GPR) has the huge advantage that it generates results in 3D due to the measurement of the signal travel time. Based on the travel time, the depth of the archaeological remains can be estimated. However, ground-truthing of the estimated depth rarely occurs by other methods like excavation maps. Some examples were published recently, e.g. by Baret (2021), Gamon et al. (2021), Paez-Rezende and Hulin (2021), Linck et al. (2022). Within this study a comparison of GPR depth slices with the digital imaging of excavation results will be presented.

The test site was a Roman villa rustica near Prien am Chiemsee in southern Bavaria. Despite several buildings of the villa having already been excavated during the first half of the 20th century, a small area was opened in 2021 during construction work surprisingly revealing a part of another Roman villa building. To evaluate the layout of the whole monument, the adjacent area was mapped by GPR in 2022. As the detected, but not yet archaeologically documented, remains were still uncovered during the survey, we used this opportunity to map the walls in detail and with high precision by an Unmanned Aerial Vehicle (UAV) flight. Hence, results from the geophysical survey can be compared with the directly adjacent excavation trench to gather an information on the accuracy of the estimated depth in the GPR data because some of the walls in the trench continue towards the survey area.

Survey instruments

The GPR survey was executed at an 80 x 34 m area directly adjacent to the archaeological excavation trench. The GSSI SIR-4000 was used with a 400 MHz antenna and a sample spacing of 6 x 50 cm was chosen to provide an ideal imaging of the buried archaeological remains within reasonable time. A Time-Domain-Reflectometry (TDR) measurement was also conducted once per hour to quantify relevant soil parameters. The TDR survey showed a quite high soil moisture level of averaged 51 vol% due to the local geology consisting of pseudogley-brownearth on top of gravel moraine. This results in a huge dielectric value ε_r of 20-35. The value fits to the estimated one at reflection hyperbolas in the GPR data. However, the measured soil conductivity with 1.1 dS/m was quite low and the area was still suitable for

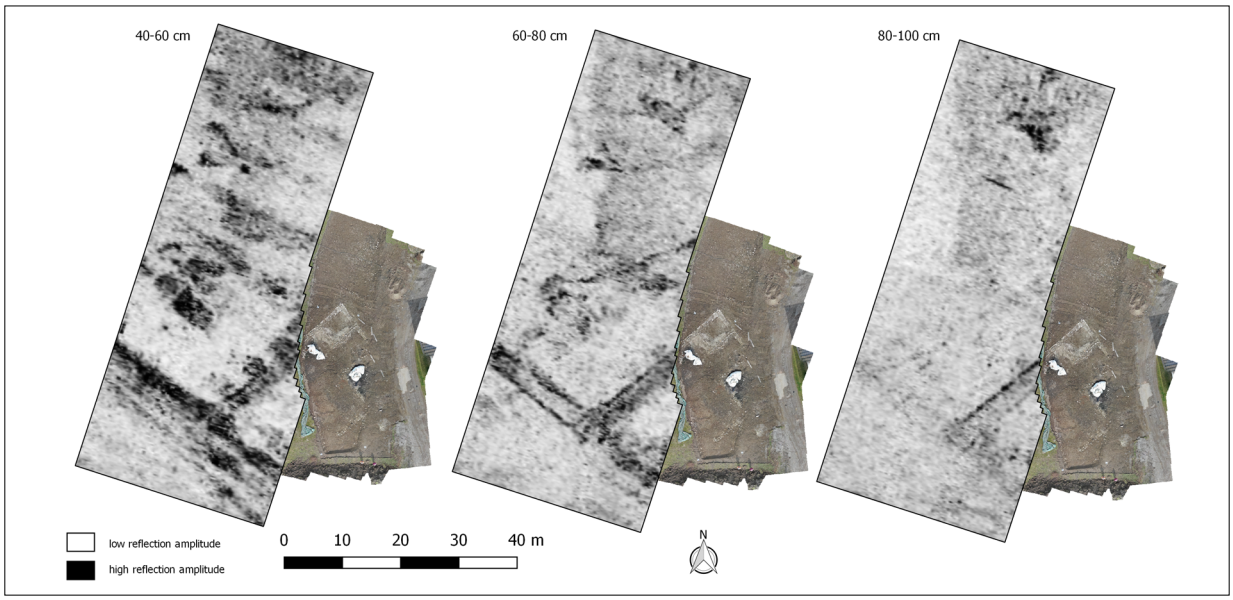

Fig. 1: Georeferenced overlay of selected GPR slices in the relevant depth range with the photogrammetric orthophoto of the excavated part of the building. GSSI SIR-4000 with 400 MHz antenna; sample interval: 6 x 50 cm (Archive No. Pri22rad). DJI Mavic 2 Enterprise; resolution: 3 mm, acquisition date: 18.03.2022 (Archive No. Pri22uav).



Fig. 2: Perspective view on the photogrammetric model of the excavated Roman remains showing the actual depth location of the walls. DJI Mavic 2 Enterprise; acquisition date: 18.03.2022 (Archive No. Pri22uav).

a successful GPR survey, as the archaeological remains were known to be quite shallow.

The photogrammetric survey of the excavated part of the Roman building was made with a DJI Mavic 2 Enterprise drone operating at 17 m flight altitude and covering the 980 m² large area with 71 densely overlapping images. This resulted in an orthophoto (DOP) with a resolution of 3 mm providing a detailed image of the visible remains. To ensure a 1-3 cm accuracy of the drone data, the relevant area was surrounded by four reference points surveyed with RTK-GNSS.

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Fig. 3: GIS-based interpretation map of the results of GPR and excavation showing the layout of the Roman buildings in this part of the villa rustica of Prien am Chiemsee.

Results and discussion

The radargram shows the Roman remains at a depth of 30-80 cm below the modern surface (Fig. 1) and therefore only 50 cm of the walls have been preserved. This is confirmed by the excavation results that reveal the first Roman remains in 40 cm below the top soil (Fig. 2). As visible in the trench, the walls seem to exist only of the last stone packages of the fundament (ca. 20-30 cm thickness), consisting of rubble and cobble stones. The bottom surface of the structures thus is overestimated in GPR. The reason is that inside the walls the physical parameters differ from the surrounding soil. Therefore, the parameters used for the depth estimation are not valid for the walls themselves. This is a serious concern for archaeologists and heritage management.

Combining the GPR depth slices and the photogrammetry results, a northeast-southwest oriented Roman building of 28.5 x 17 m size can be reconstructed (Fig. 1 and 3). Especially the depth slices of 60-80 cm and 80-100 cm below the modern surface show that the building consisted of a double wall structure, i.e. a ca. 70 cm thick outer wall and another parallel one in 2.5 m distance. In between the GPR data shows a strong reflective infill with smaller stones or a preserved floor. The same layout can be seen in the excavation results. Possibly these features can be interpreted as single rooms arranged in a row along the outer side of the building, whereas the separating walls have not been preserved. Only the northernmost of these rooms is clearly visible in the UAV DOP. The southern corner of the building is only vaguely detectable in the radargrams but can be reconstructed by the junction of the southwestern wall in the GPR data and the southeastern one visible in the DOP. This demonstrates how well both methods can be combined to assist with mapping the complete Roman building. Along the northwestern part of the monument, the 40-60 cm depth slice reveals a 2.5 x 3.5 m rectangular anomaly with a quite strong reflection amplitude. This feature can probably be interpreted as part of a collapsed wall that is buried in-situ.

Directly south and in the northwest of the stone building, the radargrams show further rubble concentrations. Two of the northwestern ones possibly also belong to stone buildings due to their rectangular shape. These subsidiary

buildings would have a size of 7 x 4 m and 5 x 8 m. The other reflective anomalies are not definitely of archaeological origin, but could also be of geological origin, e.g. parts of the moraine.

Directly adjacent of the described southernmost big stone building, a northeast-southwest aligned, 3 m wide linear anomaly with higher reflection amplitude is visible. This structure can be interpreted as a road. As its orientation does not fit to the detected Roman building and the structure lies a bit shallower, the road possibly dates to a later period; probably the Middle Ages or even Modern Period, as it is not marked on 19th century maps.

Conclusion

The presented integrated survey shows, how geophysical methods and drone photogrammetry fit together in creating a comprehensive map of an archaeological site. As the feature depth in the excavation and the GPR depth slices is similar, it can be concluded that the calculated values for GPR data fits quite well here, as both provide a value of 30-40 cm below the modern surface. However, a more precise analysis would require comparison between GPR survey data and a subsequent excavation of the same area, opposed to the adjacent areas shown here.

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Reconstructing a Romanesque church based on GPR results

Roland Linck [1,2*], **Andreas Stele** [1], **Tatjana Gericke** [1]

1 Bavarian State Department for Monuments and Sites (BLfD), Munich, Germany
2 Ludwig-Maximilians-University, Department of Earth and Environmental Sciences, Munich, Germany
* Corresponding author: E-mail: roland.linck@blfd.bayern.de

Abstract
We present an integrated prospection of the remains a medieval monastery in Lower Franconia (Germany) built over with a Renaissance castle. The geophysical data is combined with a photogrammetric model of the Renaissance castle. Based on the geophysical data, a virtual reconstruction of the medieval church was achieved.

Keywords
GPR; integrated prospection; medieval monastery; photogrammetric model; virtual reconstruction

Introduction and historical background

The ruin Schönrain is located in the Northwestern most part of Bavaria in Lower Franconia at a 103 m high ridge over the left bank of the Main river. Today's visible remains belong to a Renaissance castle erected in the 16th century by the local earls of Rieneck (Ruf 2008). The ruins comprise mainly the surrounding walls of the three-story residential hall of the castle with its monumental staircase tower at the Northeastern corner and the enclosure wall (Fig. 1). These upstanding parts were documented by a UAV survey to generate a photogrammetric 3D-model as base for an overlay with the geophysical results.

Prior to the Renaissance castle, a medieval monastery existed on the plateau. It was established in 1080 AD as a priory of the monastery in Hirsau (Baden-Württemberg). During the Peasant's Wars, the monastery in Schönrain was destroyed in 1525 (Ruf 2008). The buried medieval remains were target of an integrated geophysical survey with GPR and magnetometry. As the first method provides the best insights to the medieval remains, the following will mainly concentrate on these results.

Results

The archaeological remains appear in the GPR depth slices between 30 and 100 cm below the modern surface. Hence, they are preserved with 70 cm height and are lying quite shallow. The latter can be explained by the fact that already in 100 cm depth the sandstone bedrock is present, as the radargrams show. In the center of the survey area, the 34 m long Romanesque church can be identified (Fig. 1 and 2). It was constructed as a three-aisled basilica with a 7 m wide main nave and two 3.5 m wide side naves. This exactly corresponds to the typical ratio of 2:1 for early medieval churches. Between the naves, linear strip foundations as base of the former pillars can be detected. In the Southwest, two quadratic towers of 5 m lateral length and a porch in-between limit the church. This layout is also known from the mother monastery St. Aurelius in Hirsau. The chancel of the main nave is concluded by a semicircular apse in the Northeast that is coated in a rectangular shape at the outside. The side naves seem to have been concluded with rectangular closings. The untypical orientation of the church in Schönrain in Northeast-Southwest direction instead of exactly East-West is governed by the natural ridge layout.

Around the church, the other monastery buildings are grouped. Partly, the GPR depth slices even show distinct rooms of the buildings; especially in the South and the Northwest of the church. Regarding the structures near the

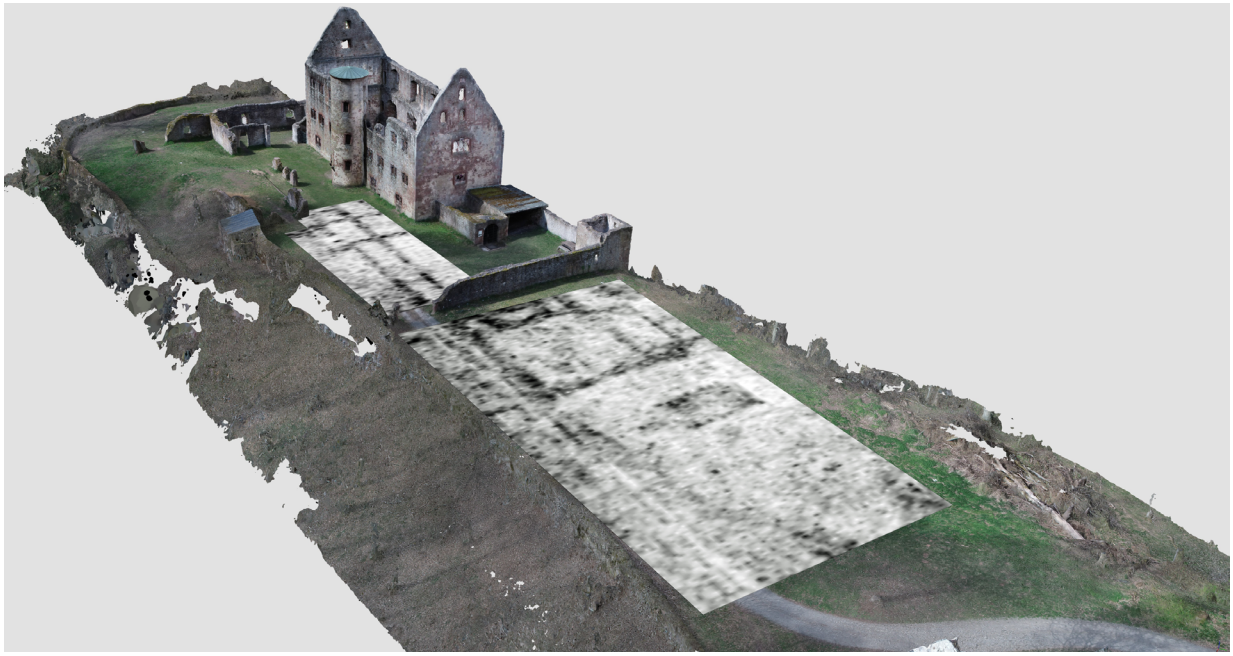

Fig. 1: Photogrammetric 3D-model of the Renaissance ruin Schönrain from Northeast. Overlay with the GPR depth slice of 60-80 cm to visualize the location of the Romanesque monastery on the plateau. For a better visibility, the modern trees were digitally removed in the model. DJI Inspire 2 with Zenmuse X4S-camera, flight altitude 45 m, acquisition date: 14.04.2021; Archive-No. Scn21uav. GSSI SIR-4000 with 400 MHz antenna; sample interval: 6 x 50 cm (Archive No. Scn21rad).



Fig. 2: GIS-based interpretation map of the medieval monastery based on the geophysical surveys. Colour coding: red = buried archaeological remains, grey = preserved walls of the Renaissance castle, black = survey grid. GIS-Plan-Nr. 5922/018.

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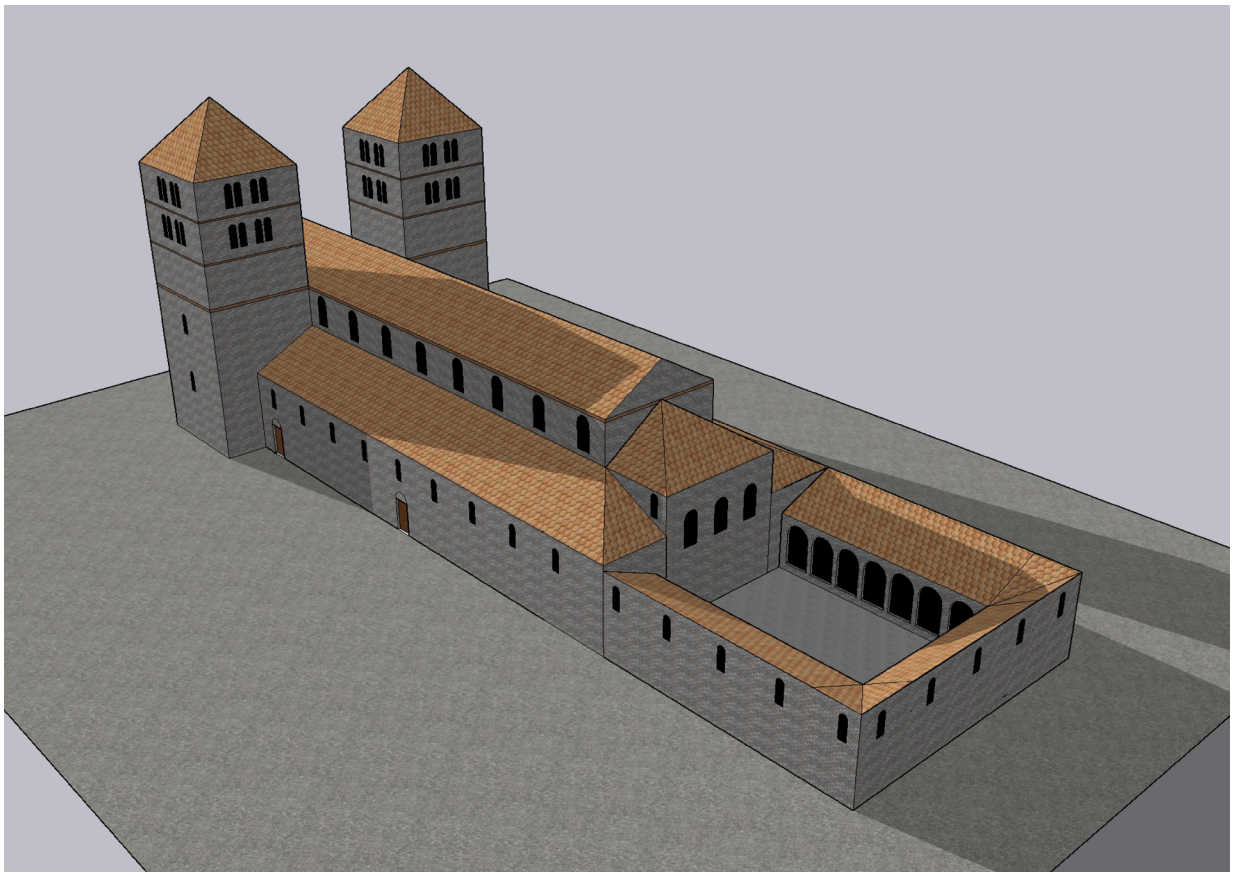

Fig. 3: Virtual reconstruction of the Romanesque Hirsau-type church with the possible cloistered court in Schönrain. View from Northeast.

church, a rectangular one Northeast of the apse with 12 m length is most striking. One can detect an enclosure wall, but no internal layout. Possibly, it can be interpreted as the cloistered court comparable to e.g. St. Aurelius in Hirsau. In this case, the structures North of the church belonged to the former cloister buildings and the ones South of it depict the farm buildings.

At a distance of 7 m north of the former monastery, the radargrams show another Northwest-Southeast oriented building of 10 x 5 m size. In the Northeastern corner, walls separate a small 2 x 2 m huge area; other internal walls are not distinguishable.

Near the northern boundary of the plateau, the magnetogram reveals two rectangular anomalies of 2 x 1.5 m and 2 x 1.3 m size. The enhanced magnetization indicates an interpretation as refilled well pits. A detailed mapping of the stone walls with magnetics fails in most parts due to the modern technical disturbances at the plateau.

Virtual reconstruction

Based on similar monastery churches of the Hirsau type in Heiligenberg (Baden-Württemberg), Kastl (Bavaria) and St. Aurelius Hirsau (Baden-Württemberg), a virtual reconstruction with Trimble SketchUp Pro 2022 was executed (Fig. 3). The reason for using the above-mentioned churches is that there are published reconstructions or drawings in von Moers-Messmer (1964) (Heiligenberg), Dehio and von Bezold (1887-1901) (Hirsau) or are still preserved (Kastl). These materials gave an impression on how the rising walls in Schönrain could have looked like during Romanesque times. Characteristic features for Hirsau-type monastery churches were two massive towers with double round arch windows separated by small pillars and pyramidal roofs as well as a nave with round arch windows of two different sizes and an extremely flat-angled roof (Fig. 3).

Conclusion

The GPR data provide an explicit layout of the Hirsau-type monastery in Schönrain for the first time. The controversially discussed appearance of the Romanesque church could also be clarified and the thesis of a three-nave basilica was substantiated. The presented results are a solid base for further research as e.g. the above presented virtual reconstruction and a touristic development of the site.

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Fore! GPR survey of the Belhus Tudor water gardens

Neil Linford[1*], Paul Linford[1], Andrew Payne[1], Matthew Bristow[2], Sarah Newsome[2]

1 Geophysics Team, Historic England, Portsmouth, Hampshire, United Kingdom
2 Landscape Archaeology, Historic England, Cambridge, Hampshire, United Kingdom
* Corresponding author: E-mail: neil.linford@historicengland.org.uk

Abstract
Covid-19 restrictions allowed unique access to this site on a temporarily closed golf course. Vehicle towed ground penetrating radar survey provided rapid coverage of the site. Geophysical survey helped support local volunteer research groups. Significant remains survive despite demolition of the Tudor mansion and landscaping for the golf-course. Detailed topographic data was generated from UAV based photography through Structure from Motion.

Keywords
Elizabethan water gardens; garden archaeology; ground penetrating radar (GPR); structure from motion (SfM); tudor mansion; UAV

Introduction

Belhus Park is in the borough of Thurrock, east of London where the site is bounded by the M25 orbital motorway. A manor house was first tenanted here from the 14th century and passed through marriage to the Barrett family who rebuilt Belhus House towards the end of the 16th century, obtaining a licence in 1618 to create an extensive park and elaborate parterre garden, shown on an estate map of 1619 and a bird's-eye view of the property in the early 18th century (Fig.1). Following a period of neglect, the house and grounds were brought up to date by Lord Dacre between 1744 and 1777, with Lancelot 'Capability' Brown commissioned to remodel the grounds between 1753 and 1763 (Historic England 1987). During the Second World War Belhus was damaged by military occupation, and the house was demolished in 1957. The site has been used as a municipal golf course and leisure complex since 2000, with renewed interest in the historic designed landscape generated through a volunteer research project run jointly by 'Land of the Fanns' and the Gardens Trust. A subtle, circular depression was identified during the research project on one of the golf course fairways to the west of the demolished mansion, possibly associated with the Tudor garden design. Geophysical survey was requested to help support the project and has proved successful for the identification of similar garden remains (Cole et al. 1997).

Methods

Access to the site is normally very limited as the active golf course is in use continually throughout the year. A brief window of opportunity occurred in March 2021 immediately prior to the lifting of covid-19 pandemic restrictions that had kept the course closed for the preceding year. Given this limited access a vehicle towed gound penetrating radar (GPR) survey was conducted with a 3d-Radar (Kontur) MkIV GeoScope Continuous Wave Step Frequency (CWSF) system with a multi-element DXG1820 vehicle-towed, ground-coupled antenna array (Eide *et al.* 2018, Linford *et al.* 2010) 2010. Data were acquired at a 0.075 m by 0.075 m sample interval across a continuous wave stepped frequency range from 40 MHz to 2.99 GHz in 4 MHz increments using a dwell time of 3 ms (Bristow et al. 2021).

Additional aerial photography was acquired using a DJI Mavic Pro quadcopter Uncrewed Aerial Vehicle (UAV) capturing 305 overlapping 12-megapixel JPEG images each from an altitude of about 50 m above ground level, resulting in a ground resolution of 1.54 cm per pixel. These images were processed in Agisoft Metashape to create a high-quality orthomosaic photograph and a Digital Terrain Model (DTM) of the wider survey area. Targeted analytical earthwork survey was used to record the circular garden feature and the outline of the house foundations, using a Trimble R8 survey grade GNSS receiver (Fig. 2).



Fig. 1: a) Belhus Mansion Painting, c1710 unknown artist in the style of Jan Siberechts with permission from Thurrock Museum. Formal gardens are shown to the north and west of the central mansion incorporating elaborate water features, together with b) the site of the water gardens under the golf course today.

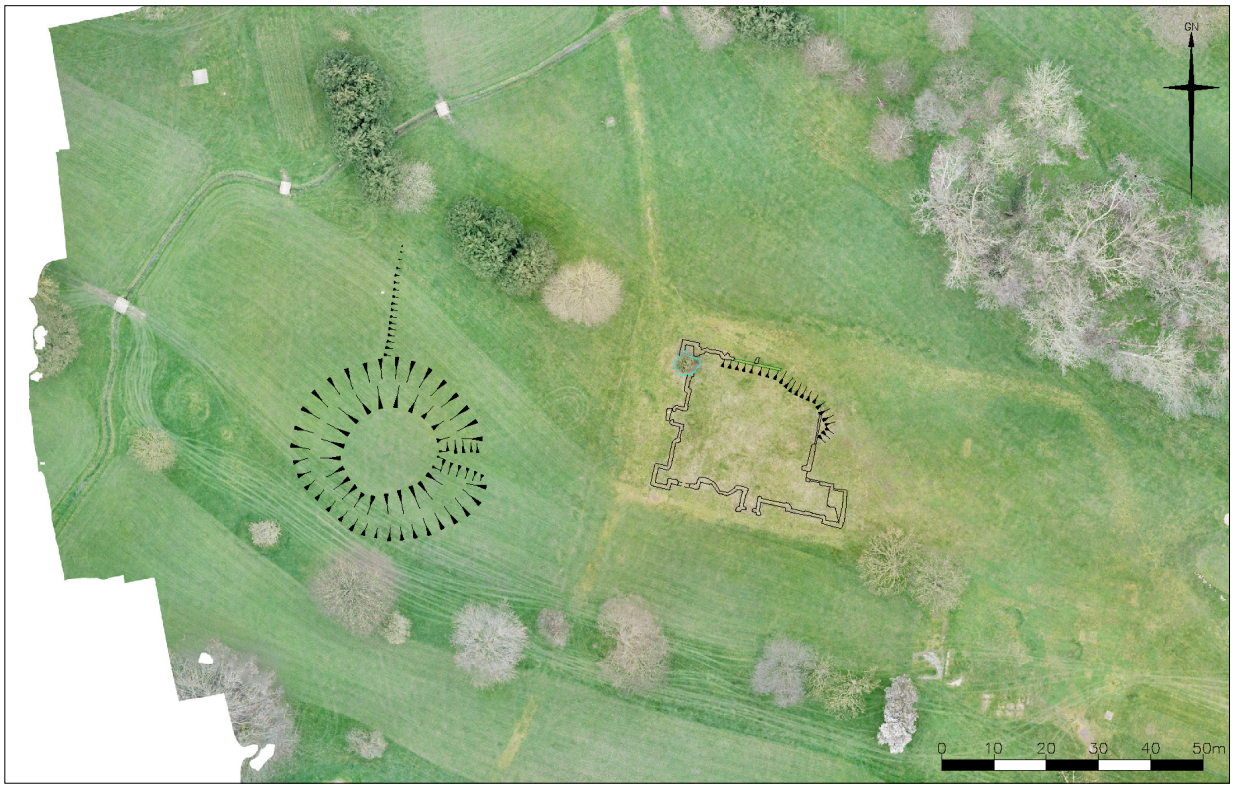

Fig. 2: Analytical earthwork survey hachures superimposed over an extract from the orthomosaic photograph.

Results

Figure 3 shows an extract of the GPR time slice where high-amplitude anomalies confirm the survival of significant elements from the original Tudor garden. The central circular anomalies correlate with the slight depression recorded by the earthwork survey (Fig. 2) and corroborates detail shown on the contemporary, false perspective painting of the gardens. The GPR survey suggest the location of the gardens to the north are slightly offset to the west compared to the painting and the survival of structural remains to the east is more fragmented, perhaps due to the later remodelling of the gardens together with the Second World War activity at the site. The GPR survey has also

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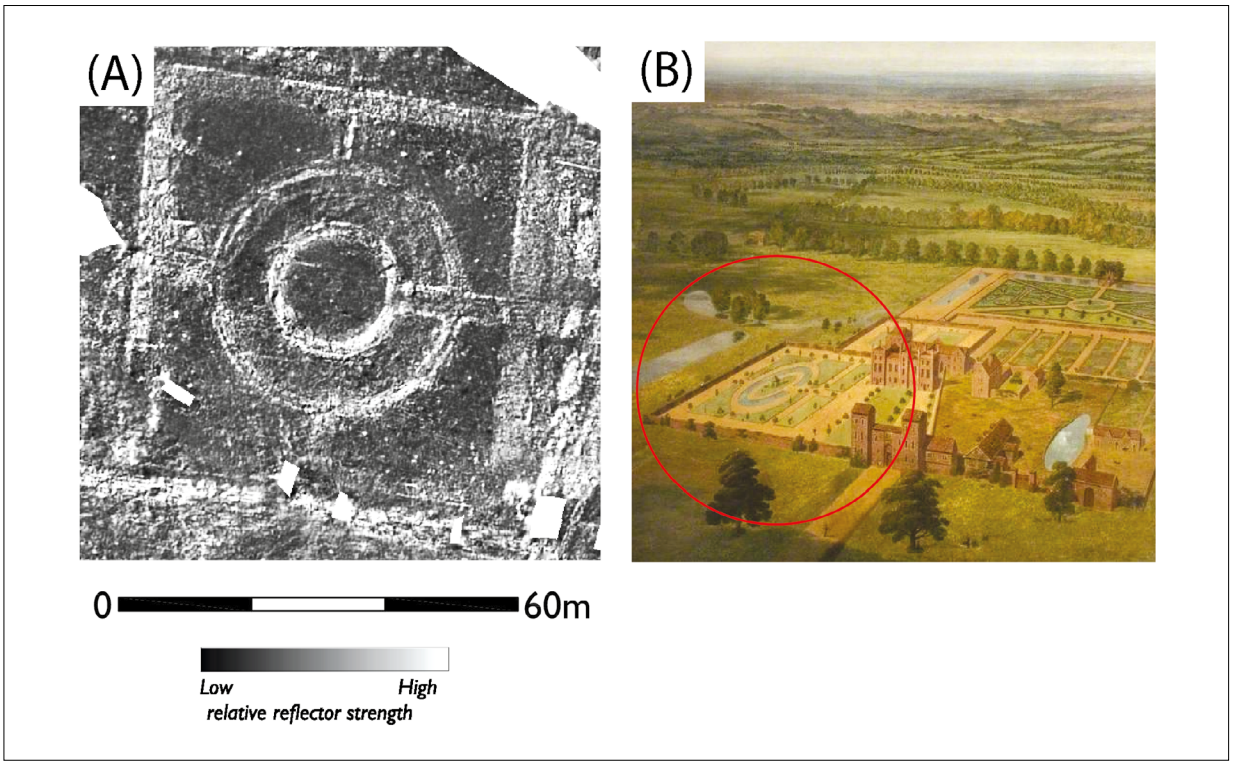

Fig. 3: a) Extract from the GPR survey from between 10.0 and 12.5 ns (0.53 to 0.66 m) showing the survival of garden features in comparison to b) detail from the contemporary painting.

revealed a substantial network of buried conduits and services that may well, in part, be associated with the water supply or drainage from the original house and water gardens. Surviving architectural elements in the wider landscape, including a brick built Tudor 'stench pipe' may also be associated with the drainage conduits.

Conclusion

Actively managed landscapes, such as golf courses, can often pose a threat to unrecognised historic design features, through remodeling to incorporate the necessary greens, fairways and bunkers. Access for geophysical survey is also often limited necessitating the use of rapid acquisition vehicle-towed systems to provide accurate location of any surviving remains compared to the use of more traditional, hand-held instrumentation. The GPR survey at Belhus Park has proved particularly successful in confirming the fidelity of a contemporary painting together with additional details of the wider Tudor garden and designed landscape. The survey results suggest an exceptional level of survival that will assist with the ongoing management of the site.

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Recent geophysical survey of English monastic sites

Neil Linford[1*], Paul Linford[1], Andrew Payne[1], Sarah Newsome[2], Matthew Bristow[2]

1 Geophysics Team, Historic England, Portsmouth, Hampshire, United Kingdom
2 Landscape Archaeology, Historic England, Cambridge, Hampshire, United Kingdom
* Corresponding author: E-mail: neil.linford@historicengland.org.uk

Abstract
Geophysical survey can provide additional detail even from well understood monastic sites. Extended landscape survey in rural settings can reveal wider semi-industrial monastic activity. Vehicle towed ground penetrating radar used to complement earth resistance and magnetic survey.

Keywords
abbey; earth resistance; ground penetrating radar (GPR); magnetic survey; priory

Introduction

Geophysical survey can provide a useful means of investigating monastic sites, particularly the use of Ground penetrating radar to complement earth resistance and magnetic coverage (Linford and Payne 2017). This paper will focus on two recently surveyed monastic sites: Dunstable Priory, Bedfordshire, situated in an urban municipal park where the standing remains still function as an important parish church; and Sibton Abbey, Suffolk, a romantic ruin set in an open pastoral landscape where the relationship between the monastic complex and the river Yox immediately to the south can be more readily discerned. Dunstable Priory was an Augustinian order founded in 1132 where on the 23 May 1532 in the former Lady Chapel of the conventual church the marriage of Henry VIII and Catherine of Aragon was pronounced null and void. The Manshead Archaeological Society have previously conducted extensive earth resistance surveys and targeted excavation at Dunstable Priory, and the interpretation of the data is marked out in white paint on the grass. Sibton was an early Cistercian abbey founded by 1150 and grew rich from animal husbandry, including the export of Suffolk wool to Flemish weavers. Only the refectory and south walls of the nave survive today, with no trace of the later 18th Century manor house, built by the Levett-Scrivener family who have owned the site since 1610.

Methods

A vehicle-towed ground penetrating radar (GPR) survey was conducted at both sites using a 3d-Radar (Kontur) MkIV GeoScope Continuous Wave Step Frequency (CWSF) system with a multi-element DXG1820, ground-coupled antenna array (Cuenca-García et al. 2020; Eide et al. 2018; Linford et al. 2010; Stamnes and Kiersnowski 2021). Data were acquired at a 0.075 m by 0.075 m sample interval across a continuous wave stepped frequency range from 40 MHz to 2.99 GHz in 4 MHz increments using a dwell time of 3ms (Linford et al. 2022). In addition, a magnetic survey using Bartington 601 fluxgate gradiometers at a 0.25 m x 1.0 m sample interval and a targeted earth resistance survey using a Geoscan RM85 earth resistance meter at 0.5 m x 1.0 m sample interval were conducted at Sibton Abbey.

Results

Figure 1 shows extracts of the data collected at Dunstable Priory, including surface evidence of the former buildings, previous earth resistance results, together with the GPR survey where a series of fragmented anomalies suggest the apse and ambulatory immediately to the east of the standing remains of the church. The earth resistance from this area was less clear and, perhaps, indicative of rubble deposits associated with the demolition of the former Lady Chapel. The GPR data certainly suggests some potential

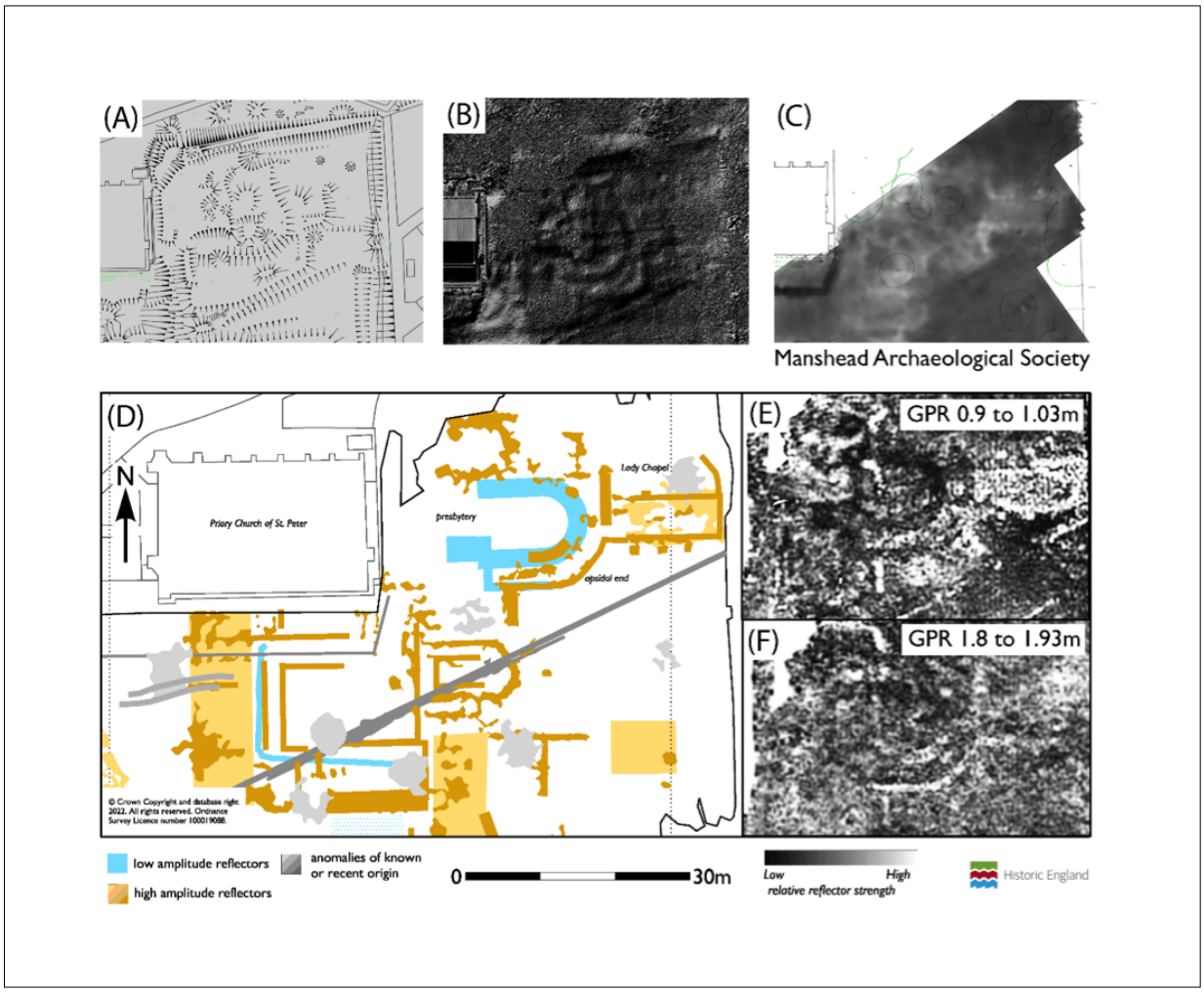

Fig. 1: Dunstable Priory (A) analytic earthwork survey and (B) digital elevation model derived from UAV photogrammetry over the site showing surface evidence for further monastic buildings. Extracts from (C) the previous local society earth resistance survey (high resistance plotted as lighter tones) is shown together with (D) a graphical interpretation of the GPR survey and data from two selected time slices that reveal (E) the robbed-out ambulatory and (F) deeper wall-footings of the apse leading to the former Lady Chapel.

robbed out wall footings and presents a much more elaborate church building on the site than has been previously recognised. Wider area GPR survey was constrained by more recent paths and planting associated with the modern park but did successfully reveal additional detail to complement the earth resistance data and suggest the slight realignment of buildings to the south of the monastic range. Survey beyond the Priory gardens was hampered by surrounding urban development, and the landscaping of the school playing field to the south of the gardens.

In contrast, investigation of the wider landscape beyond the immediate monastic range was possible at Sibton Abbey, where the standing remains are found within a series of pasture fields running alongside the river Yox (Linford and Payne 2022). The wider GPR survey here revealed evidence for a large building containing a series of internal circular anomalies. Further regular groups of circular anomalies were found immediately to the north, both apparently free standing and some with evidence for surrounding walls, and the magnetic survey data suggests the presence of strongly magnetized, semi-industrial anomalies within the same area. Comparison with the recent GPR survey conducted at Fountains Abbey, Yorkshire (National Trust 2021), suggests a similar interpretation for these anomalies providing evidence for either a tannery or, perhaps the processing of Suffolk wool, a lucrative export from Sibton.

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Fig. 2: View of the standing remains at Sibton Abbey, Suffolk.

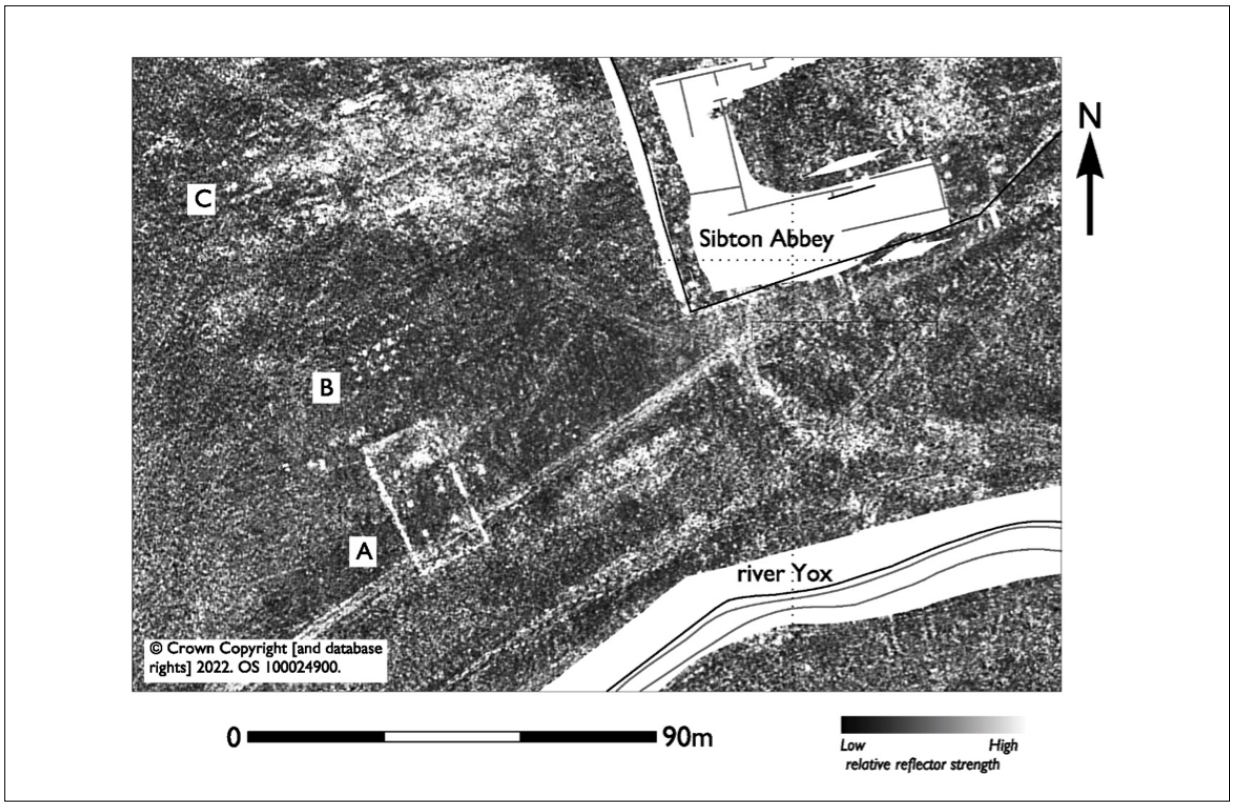

Fig. 3: Extract from the GPR survey at Sibton Abbey between 22.5 and 25.0 ns (1.23 to 1.36 m) showing a ~15 m x 30 m possible tannery building marked 'A' with internal circular pits or processing vats. A group of twelve pits are found immediately to the north at 'B' and a further structure containing pits or processing vats at 'C'.

Conclusion

The application of vehicle-towed GPR arrays to the investigation of monastic sites provides additional complementary detail to support the use of more conventional geophysical techniques. Investigation of the wider landscape surrounding the standing remains of the abbey at Sibton has proved particularly successful and provided further evidence for the scale of industrial activity associated with the religious community.

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Protected by shooting at it – the *Öde Kloster* and an associated Roman settlement within the military training area Bruckneudorf, Austria

Klaus Löcker [1]*, Jakob Gallistl [1], Christian Gugl [2], Alois Hinterleitner [1], Hannes Schiel [1], Ingrid Schlögel [1], Mario Wallner [1], Ralf Totschnig [1], Tanja Trausmuth [1], Immo Trinks [3], Jürgen Zeitlhofer [4]

1 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
2 Department of Classical Studies, Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria
3 Vienna Institute for Archaeological Science, University Vienna, Vienna, Austria
4 Armaments and Defence Technology Agency, Austrian Armed Forces, Federal Ministry of Defence, Vienna, Austria
* Corresponding author: E-mail: klaus.loecker@geosphere.at

Abstract
The archaeological prospection focused on a multiphase fortified settlement. It was conducted as an integrated survey using airborne laserscanning (ALS) data, aerial photography, magnetics and GPR. The results show among other things that restricted military areas provide outstanding conditions for the preservation of archaeological sites.

Keywords
aerial photography; ALS; ground penetrating radar; magnetics; multi-method

Introduction

The so-called *Öde Kloster* is a long known archaeological site within the military training area Bruckneudorf. This restricted military area has been established in 1867 and used by the Austrian Armed Forces ever since. So, the site has been protected from intensive agricultural use by ploughing or levelling and thus the massive, fortified structure is still preserved, even though it sometimes was aim of target practices and maltreated by tank driving throughout the last 150 years.

A first archaeological investigation of the *Öde Kloster* took place in 1903 under the direction of Maximilian von Groller-Mildensee (Groller 1905). The *Öde Kloster* is a roughly square complex of about 135 by 165 m, which is enclosed by an early medieval rampart and a ditch (Fig. 1). Inside the complex there are some Roman buildings of different phases which were partly covered by the medieval bank. In the 9th century AD, a probable Carolingian royal court was created with the construction of the ditch and bank, an interpretation that seems uncertain, since Carolingian finds are very poor and ambiguous. The buildings in the southern part of the complex are associated with the medieval-monastic use. The only recognizable access to the complex is a gate in the middle of the eastern section of the fortification.

Materials and methods

In summer and winter 2020 and 2021 geophysical measurements were carried out using magnetics and GPR inside and around the *Öde Kloster*. The main aim of these measurements was to examine the area northeast of a shooting range of the military training area for unexploded ordnance in the ground. The survey was additionally carried out using orthophotos and airborne laserscanning (ALS) data provided by the Austrian Federal Office of Metrology and Surveying. The ALS data have been processed using the Relief Visualization Toolbox (RVT) (Zakšek et al. 2011; Kokalj et al. 2019). A motorized measurement system with eight FEREX CON650 probes in a line of 25

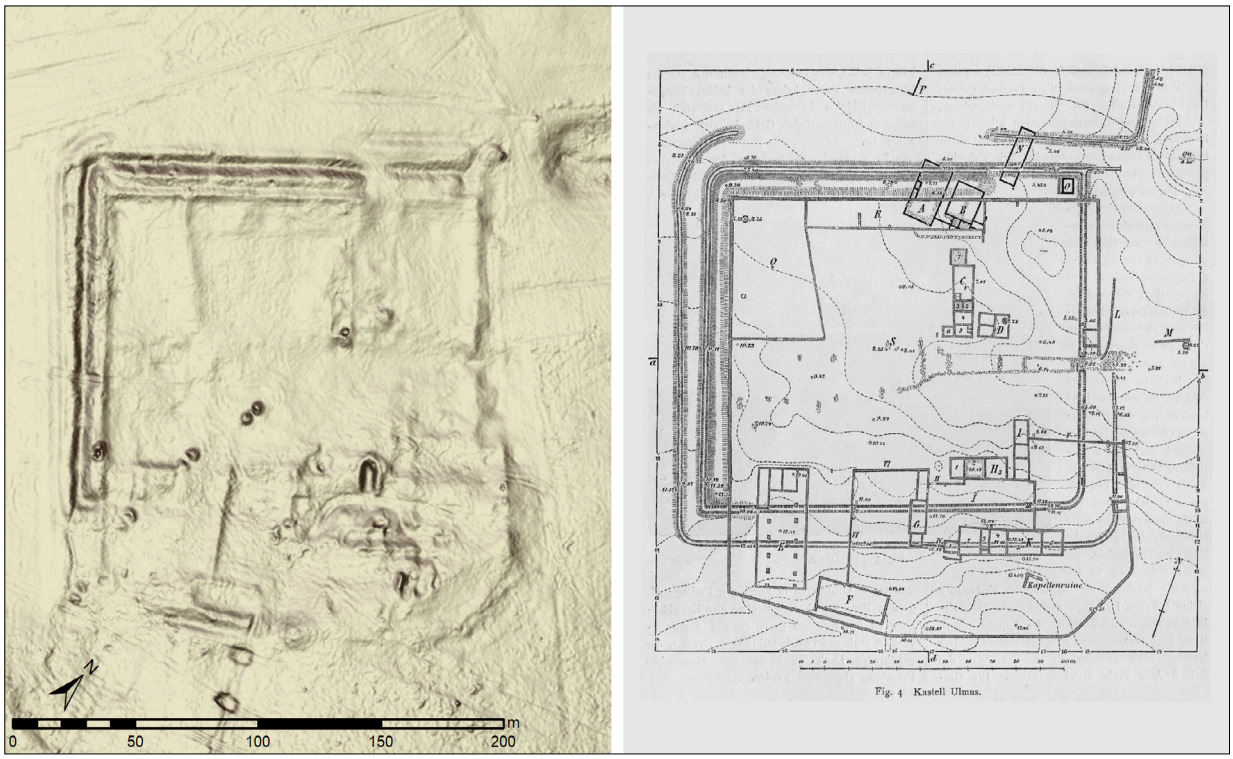

Fig. 1: The ALS data of the *Öde Kloster* complex (left, data provided by INSPIRE BEV) and the excavation map of Groller 1905 (right).

cm was used for the magnetic surveys. The GPR data were collected using a Sensors & Software SPIDAR multichannel system with six 500 MHz antenna pairs with a line spacing of 25 cm, and a Malå MIRA multichannel system with 16 channels of 400 MHz antennas with 8 cm line spacing.

The geophysical data have been processed using the APSoft software package by ZAMG (Trinks et al. 2018) and the resulting images and data integrated into ArcGIS Pro together with the orthophotos and the ALS data.

The Roman settlement with a potential villa

The newly discovered structures comprise the extensive area of a Roman settlement around a Roman villa, which is located next to a road connecting the south of the Leitha mountains to the Roman town of Carnuntum.

About 200 m northeast of the *Öde Kloster*, where the remains of already known settlement structures could be identified by the survey, a potential main building of a Roman villa, about 15 by 22 m in size, was discovered in the data of the geophysical measurements (Fig. 2). The villa is situated inside of a large, trapezoidal area enclosed by a wall of approximately 140 to 200 by 150 to 180 m. In this enclosed area are numerous other buildings such as possible residential buildings, farm buildings (both stone and wooden buildings), a drying kiln, a potential bathhouse, and – in the south of the complex – three remarkable buildings, which could probably be addressed as stables. These three buildings have sizes of about 14 to 15 by 24 to 25 m each and, due to their interior layout, allow comparisons with similar buildings for auxiliary troops.

If these three large buildings really are stable buildings, then a function of the settlement as a place of horse breeding might be reasonable. A connection to the Roman army in Carnuntum or perhaps even as a mansio (Roman road station) is imaginable. Groller had associated the *Öde Kloster* with the Roman mansio of "Ulmo", but this was denied by later publications. Perhaps the discovery of this new site will bring new momentum to this discussion.

Due to its structure, the newly discovered settlement also has similarities with the rural settlement (vicus) of Vienna-Unterlaa (Adler-Wölfl 2015). Wooden and stone buildings were found there, although the wooden buildings are older and were built as early as the 1st century AD. The stone buildings date from the 3rd century and the settlement ends at the beginning of the 5th century AD. The same can be assumed for the settlement at the *Öde Kloster*, which has been

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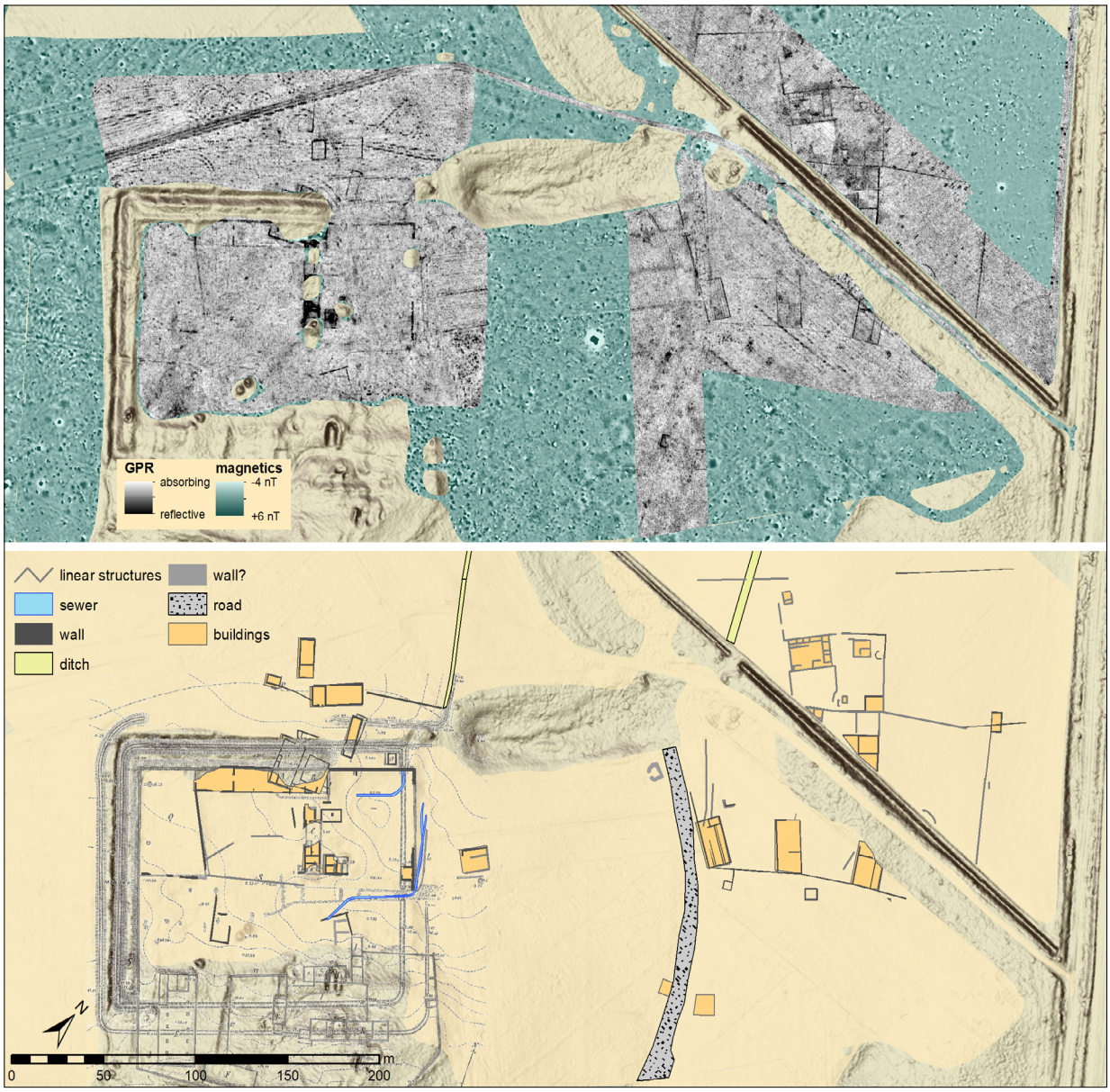

Fig. 2: Magnetics (green scale) and GPR (grey scale) data (above, data provided by INSPIRE BEV) and the interpretative map of the *Öde Kloster* complex 2022 (below, data provided by INSPIRE BEV).

built towards the end of the 1st century AD and certainly extends to the end of the 4th century. During the recovery of unexploded ordnance discovered based on the survey, two coins were found dating to the middle of the 4th century.

Conclusion

In addition to the well-known *Öde Kloster*, geophysical investigations northeast of the complex have discovered an associated large Roman settlement (vicus). A Roman settlement well comparable has been excavated in Vienna-Unterlaa. Based on the types of buildings, it is also likely to have been a place of horse breeding, which could be connected to the needs of the Roman army situated in the near town of Carnuntum.

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The unique settlement microregion of the Lusatian Urnfield culture in Łazy (SW Poland): fieldwalking and geophysical survey results

Maksym Mackiewicz [1*], **Paweł Madera** [2], **Dagmara Łaciak** [3], **Agata Hałuszko** [1, 4]

1 Archeolodzy.org Foundation, Wrocław, Poland
2 Archaeological Museum, The City Museum of Wrocław, Wrocław, Poland
3 Institute of Archaeology, University of Wrocław, Wrocław, Poland
4 Institute of Archaeology, Maria Curie-Skłodowska University, Lublin, Poland
* Corresponding author: E-mail: max@archeolodzy.org

Abstract
Cremated cemetery and three settlement sites were surveyed. Magnetics and electrical resistivity provided a suggestive location for the cemetery. Magnetic prospection of the surrounding settlements provided a less clear picture. Surface material indicated the presence of previously unregistered episodes of settlement.

Keywords
cremation cemetery; electrical resistivity survey; Lusatian urnfield culture; Lower Silesia; magnetic survey

Introduction

In the region of Łazy village (Wińsko Commune, Lower Silesian Voivodeship, SW Poland) there is a unique settlement microregion of the Lusatian Urnfield culture (Fig. 1A), dated to the period between *Montelius' Period* IV and Hallstatt D (ca. 1100-400 BC). The cremation cemetery (site 1) located on a parabolic dune is one of the central places of this area. The site was discovered at the end of the 19th century as a result of sand extraction. At the time, a unique urn with a narrative scene depicting deer hunting was found. In the following years, numerous accidental finds as well as salvage excavations were reported. Altogether 187 cremation graves were discovered, mostly with stone constructions, some of which had the form of paving (Fig. 1B). Among them, especially interesting is the chambered grave (no. 4/95) dated to Hallstatt C (Fig. 1C). The grave is considered to be a burial of a noble warrior connected with the Hallstatt culture area (Madera 1999, 2002).

Our knowledge about the settlement network in the area ich much poorer and chronologically unprecise. Therefore, in 2020-2021, we undertook a new non-invasive survey aimed at verifying the sizes and shapes, as well as functions and chronology of selected sites (site 1, 7, 18 and 25) that belong to this settlement cluster.

Methods

The core of the fieldwork agenda comprised fieldwalking and geophysical prospections with the use of magnetic and electrical resistivity method. The burial ground is forested, whereas neighbouring settlement sites are located on crop and wastelands, which made us adjust the methods.

The surface survey was completed during the fall 2021 by using the transect walking method with 10 m intervals between the parallel lines. The location of each find was recorded using a handheld GPS. Their spatial distribution was visualized with the use of QGIS as a *heatmap*. As no stray artefacts were found on the surface of the cemetery, only pebbles were recorded poking up through the leaf litter and thereby probably marking the presence of burial constructions – the dune composition should not contain larger stones originally. Considering measurements made

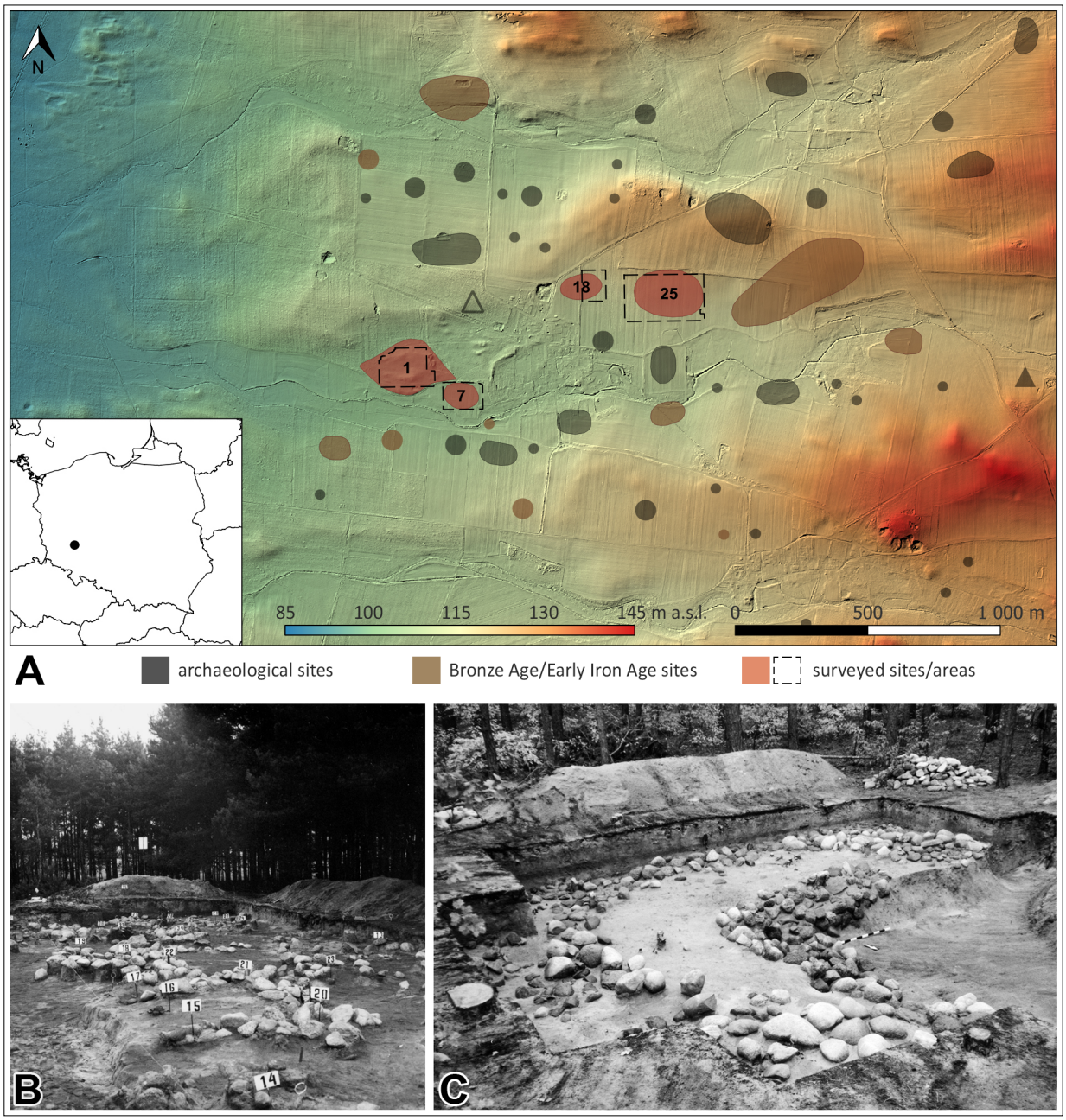

Fig. 1: (A) Microregion near Łazy. The sites marked in orange and red are associated with the Lusatian Urnfield culture. Surveyed in 2020 are marked in red (base map: hillshaded DTM based on National Geodetic and Cartographic Resource datasets); (B) stone structures recorded during excavation in (1974, WOAK Wrocław, author unknown); (C) chambered grave 4/95 (1995, photo P. Madera).

with the handheld GPS units to be insufficiently precise for correlations with the results of geophysical prospections, the localization of stones was recorded with the use of a total station, which turned out to be quite time-consuming in dense forest conditions (Fig. 2A).

The magnetic survey with the use of Bartington Grad 601-2 fluxgate gradiometer was performed on the area of about 11 hectares. The survey was conducted with a traverse interval of 1 m in the woodland and 0.5 m in the open areas. All the data recorded were processed with the use of DW Consulting TerraSurveyor Lite software.

The electrical resistivity survey covered approximately one hectare within the area of the burial ground. A RM

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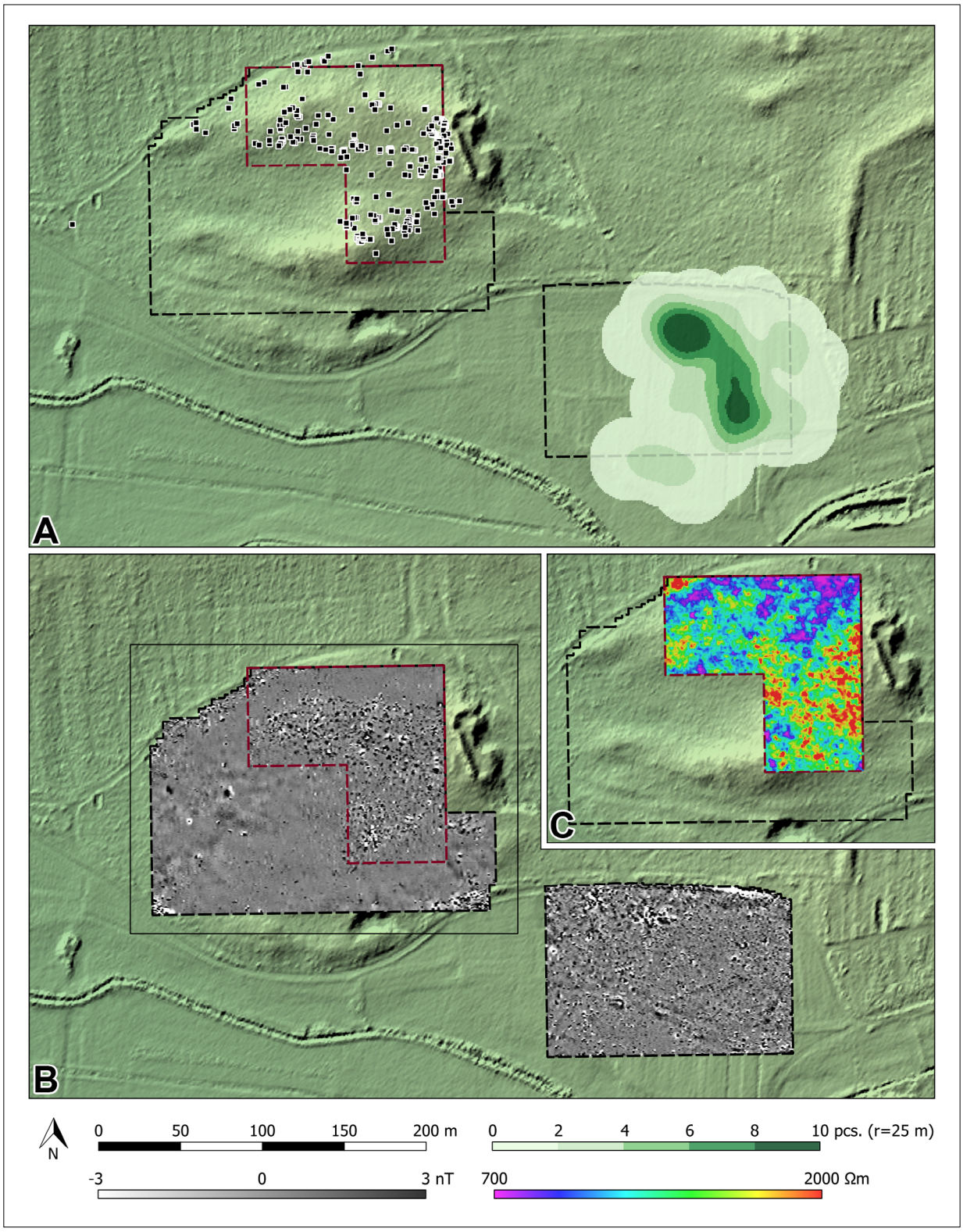

Fig. 2: Sites 1 and 7: (A) distribution of stones on the surface (black rectangles) and Bronze Age and the Early Iron Age ceramics (heatmap, r = 25m); (B) magnetic map; (C) resistivity map (base map: hillshaded DTM based on National Geodetic and Cartographic Resource datasets).

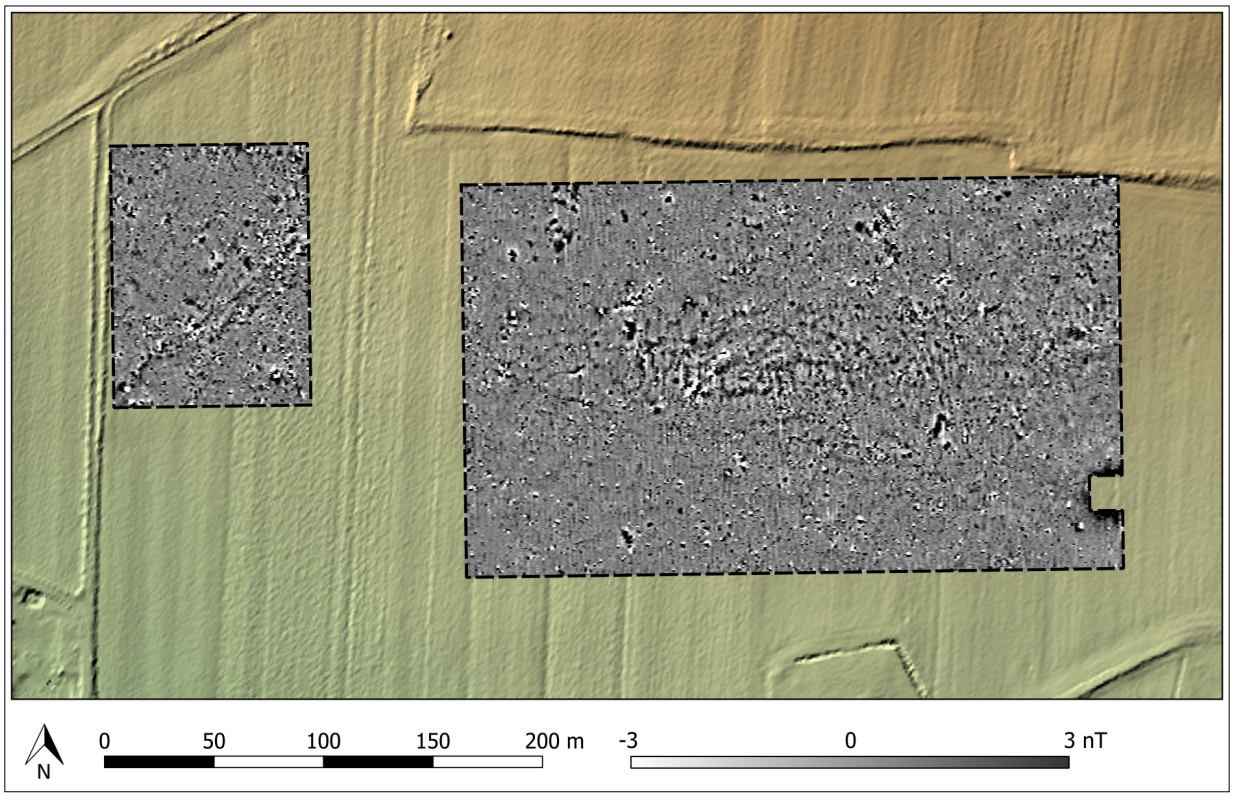

Fig. 3: Sites 18 and 25: magnetic map (base map: hillshaded DTM based on National Geodetic and Cartographic Resource datasets).

Frobisher TAR-3 system was used to perform measurements with a 1 m × 1 m resolution. Thanks to the use of the 0.5 m probes spacing Wenner array, there was no need to handle additional cables, which made it easier to move within the trees and bushes. The data processing of the results was completed using the Snuffler 1.3 software.

Results

The magnetic survey provided quite a suggestive picture of the burial ground, revealing its shape, dimensions and arrangement (Fig. 2B). The sandy substrate of the dune made it possible to obtain good magnetic contrast. Positive and highly dynamic readings were recorded mainly at the top of the horseshoe-shaped dune. These were probably induced by erratics commonly used for construction of graves and pavings. The distribution of anomalies corresponds well with the dispersion of stones occurring on the surface of the site. It must be stressed though, that different rocks had different magnetic susceptibilities, which resulted in quite a variability of magnetic signatures recorded. The recorded anomalies constitute a few apparent clusters of different densities, which seems to indicate that the area was used with varying intensity.

The main aim of the electrical resistivity survey was to record structures undetectable with the use of the magnetic method (e.g. pavements or chambers made of low magnetic susceptible stones). In the general picture obtained, an apparent variability of recorded values resulting from topographic and ground moisture conditions was revealed (Fig. 2C). On this background, more local, sometimes just one-point anomalies could be distinguished. The locally increasing values could indicate the presence of stone features; again, they often correspond with the dispersion of erratics on the surface.

The magnetic survey on the ”settlement area” provided us with a less clear picture (Fig. 3). The sites were located in a valley on sands and sandy loams, or on the valley‘s slopes built of boulder clays. Indicating readings that could be undoubtedly correlated with remains of a given human activity was quite difficult, and must have been limited to distinguishing larger and stronger signals. Such anomalies were relatively scarce and usually sparse, which may indicate a low density and generally poor preservation conditions of anthropogenic features.

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Due to the small number, low frequency and strong chronological differentiation of ceramic finds, the field-walking provided no firm basis for clarifying the question of the nature and intensity of the settlement processes. Nevertheless, the collected material definitely changes the pre-established shapes and extents of the sites, consequently extending the local preservation area. Also, they indicate the presence of previously unrecorded prehistoric cultural phenomena.

Conclusions

The effectiveness of non-invasive geophysical methods for investigating cremation cemeteries depends on many factors. Despite difficult field conditions (i.e. the dense forest cover), which not only made the research more difficult but also strongly affected the quality of the resulting data, the picture obtained for Łazy is quite detailed and revealing. This was possible thanks to the presence of easily detectable grave constructions (i.e. stone linings and pavings). The magnetic and electrical resistivity surveys carried out on the dune as well as the documentation of erratics dispersed on its surface, provided a highly valuable package of complementary spatial data reflecting the shape and size of the burial ground and the varying density of features, at least of those detectable in this manner. Also, it was often possible to distinguish particular graves. On the contrary, the quality of analogue data obtained for neighbouring settlement sites are somewhat unsatisfactory. Observation conditions precluded the recording of more subtle anomalies, for which the picture obtained seems to be incomplete.

Acknowledgments

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Strongholds of the south-eastern Greater Poland: a regional non-invasive survey

Maksym Mackiewicz [1*]

1 Archeolodzy.org Foundation, Wrocław, Poland
* Corresponding author: E-mail: max@archeolodzy.org

Abstract
The aim of the project was an inventory of strongholds in SE Greater Poland. Datasets included archive queries, remote sensing data and geophysical surveys. Two aerial surveys were carried out, numerous sites were recorded. Magnetic prospection was conducted for seven sites. For most of the sites prospection provided very suggestive results.

Keywords
aerial survey; Greater Poland; magnetic prospection; regional studies; strongholds

Introduction

The south-eastern Greater Poland belongs to the regions that are outstandingly rich in relics of prehistoric and medieval fortified sites. The oldest ones are commonly connected with communities of the Lusatian Urnfield culture of the Early Iron Age; these are just a few features of very diversified dimensions and constructions. The most numerous group consists of single- and double-ringed forts constructed during the early reign of the Piast dynasty at the turn of the 10th and 11th centuries AD that constituted a well-developed system of chokepoints. Younger defensive structures are represented by late medieval and early modern knights' seats in the motte castle type, some of which took the form of motte-and-bailey (Teske 2000).

In 2019, a project of a detailed inventory of strongholds in SE Greater Poland was initiated. The action had two key objectives: (i) to satisfy basic research needs, collect the data about form and structure of the strongholds, building materials used for their construction, and patterns of use of space within the fortifications and in their vicinity; (ii) to complete documentation for conservation and preservation including, among others, record and assessment of sites' condition and factors threatening their preservation.

The focal area was delimited to the administrative boundaries of eight districts, with over one hundred fortified features already recorded within the area (Fig. 1A). Presuming systematic character of the works and possible extension of the agenda in the forthcoming seasons, the surveys were initially limited to two neighboring districts of Pleszew and Ostrów Wielkopolski, and only in 2020 expanded onto another one (Krotoszyn county).

Methods

The scenario was to complete exclusively non-invasive actions involving archive queries, analyses of remote sensing data, and geophysical surveys.

The analyses of remote sensing data started from products available as web services that could be directly linked to in QGIS. Satellite imaging of Google Earth as well as aerial orthophoto maps and hillshade visualizations based on airborne laser scanning (ALS) provided by National Geodetic and Cartographic Resource as web map services were used. Kilometer after kilometer, we went through the digital data marking and describing different types of anthropogenic structures (not only fortifications). Already a cursory survey revealed that the overall number of earthworks is much higher than presumed. It yielded another few dozens of spots that called for field verification. For each fortification feature, there were obtained sequences of archival aerial photographs as well as clouds of points

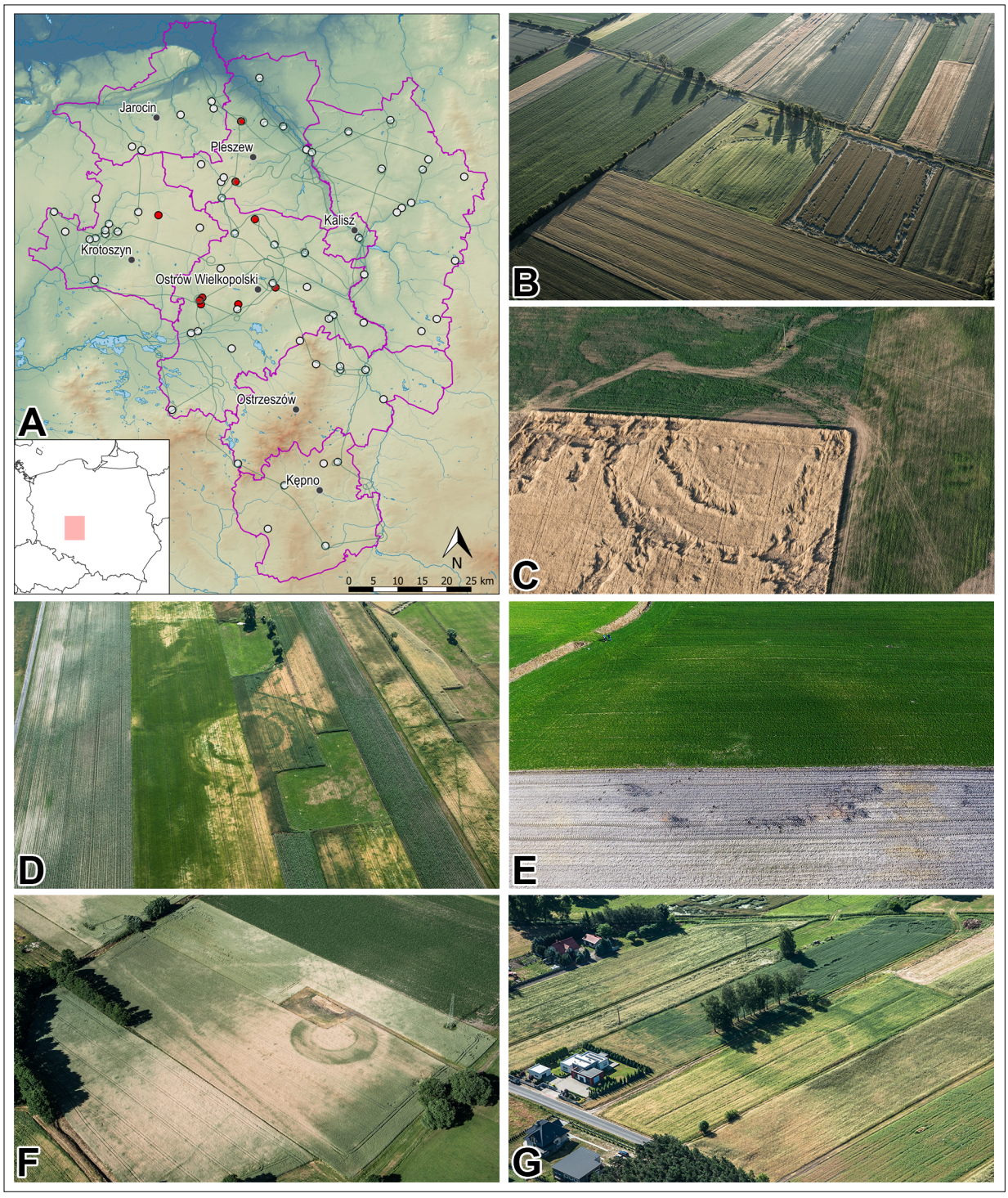

Fig. 1: Study area. White points indicate strongholds, red dots mark surveyed ones. The green lines mark the flight routes. Aerial photos taken in 2019: (B) Taczanów Drugi, (C) Lisewo, (D) Chlewo, (E) Grudzielec, (F) Ostrów Wielkopolski-Krępa, (G) Topola Wielka (base map: hillshaded DTM based on National Geodetic and Cartographic Resource datasets).

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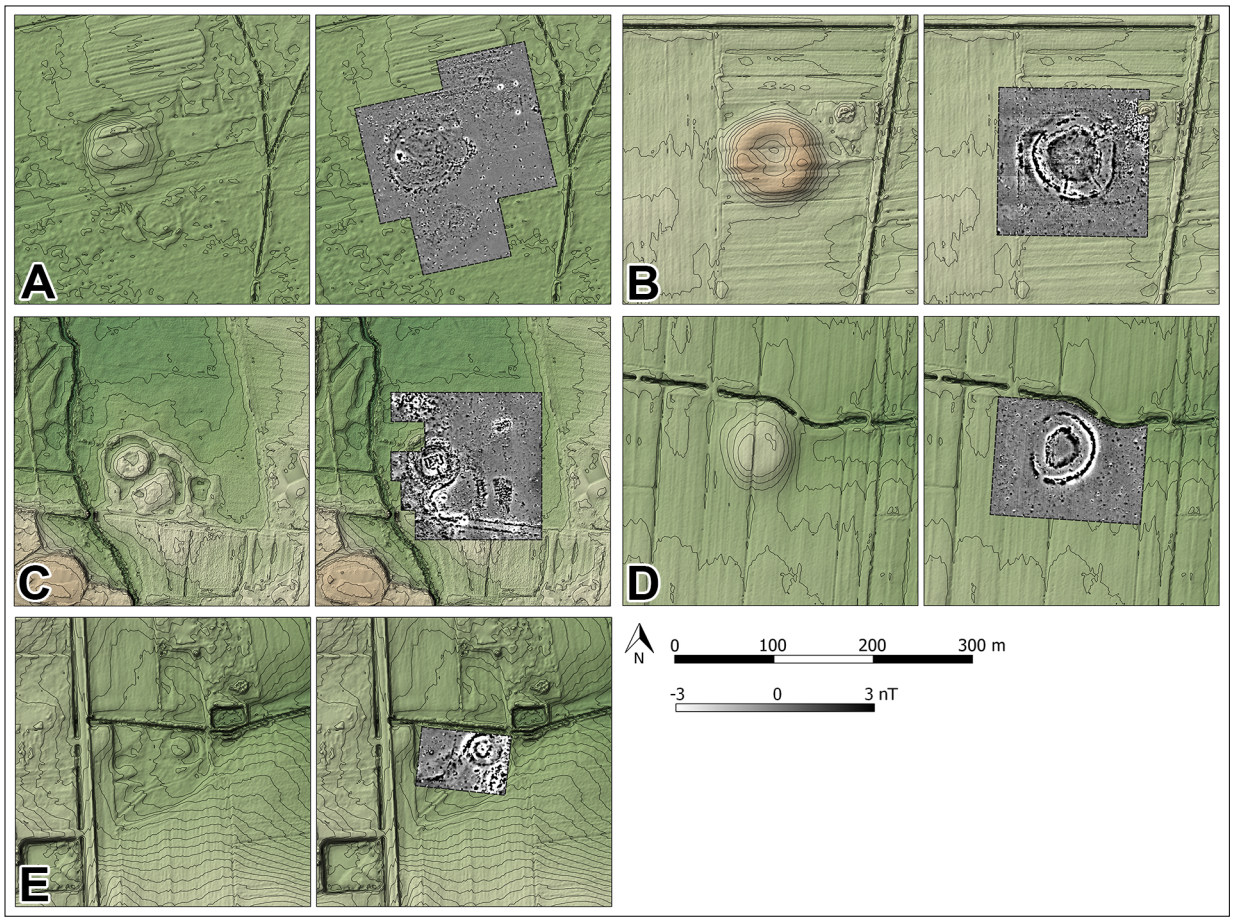

Fig. 2: Magnetic survey results: (A) Nabyszyce, (B) Taczanów Drugi, (C) Rozdrażew, (D) Grudzielec, (E) Czermin (base map: hill-shaded DTM based on National Geodetic and Cartographic Resource datasets).

from ALS, which were then reclassified and visualized with the use of different algorithms.

Aerial surveys were made twice – in June and July 2019, during a strong drought, which made it more likely to detect vegetation marks, generally manifesting themselves rather poorly in the region (Fig. 1). Altogether 25 strongholds and a number of sites of different character were documented. Better visibility of flat sites and earthworks with no longer distinguishable above-ground parts was noticeable.

Monitoring of the sites made with the use of a drone was an important addition to the aerial survey. It allowed for repeated visits to selected places and their documentation in varying conditions and at different vegetation stages. Detailed photogrammetric models and orthophoto maps were made for chosen sites. The latter data precisely documented up-to-date topography, which was then compared with ALS data obtained a few years earlier or with older contour maps. This way, a process of erosion of terrain features could often be noticed even within a short period of time.

Seven features were chosen for magnetic prospection. All of them were localized in open areas intensely used for agricultural purposes, and thus subject to plough damage. The surveys were done with the use of Bartington Grad 601-2 fluxgate gradiometer. The undertaken actions were aimed, among others, at assessing the current condition of the relics and the dynamics of their degradation.

Results

The five investigated sites were present in the Polish Archaeological Record. Moreover, some of them have been already excavated. New data on the actual localization of defensive features or materials used for their construction

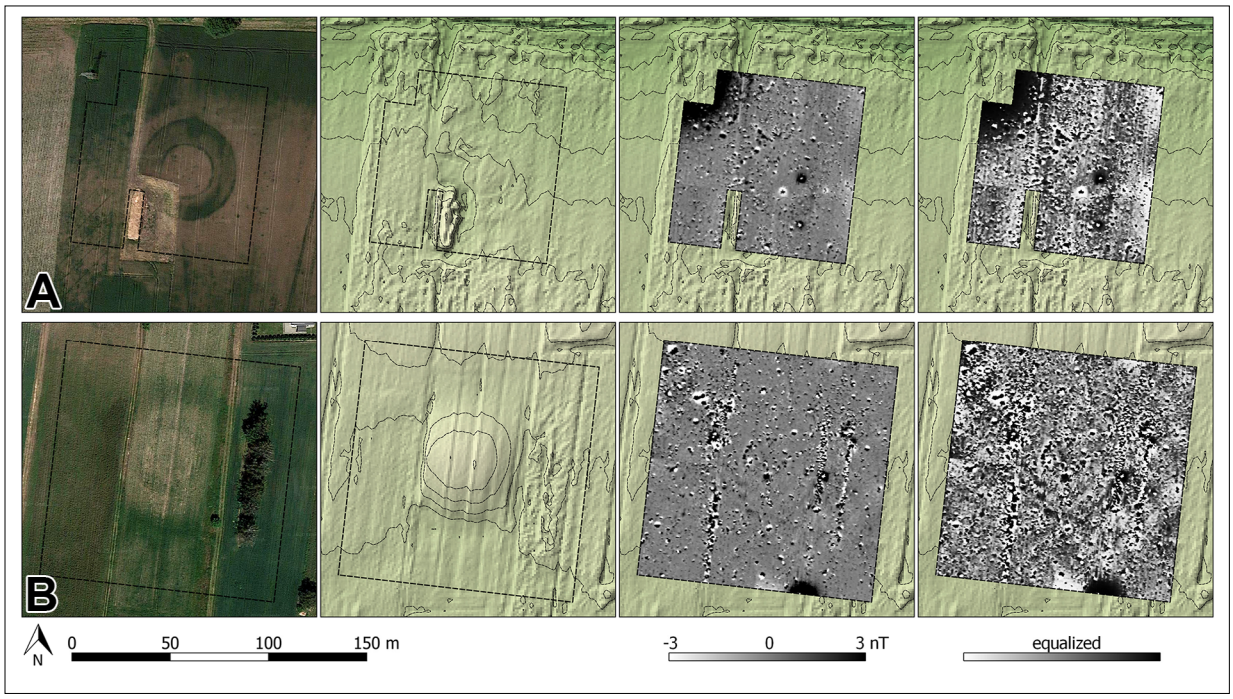

Fig. 3: Satellite imagery (Google, Image Landsat/Copernicus) and magnetic survey results: (A) Ostrów Wielkopolski-Krępa, (B) Topola Wielka (base map: hillshaded DTM based on National Geodetic and Cartographic Resource datasets).

made it possible to extrapolate some of the earlier findings. Quite often though, the resulting picture was more sophisticated, than the initial one. It can be exemplified by the case of the stronghold in Nabyszyce, initially recorded as a single early medieval feature (Fig. 2A). However, aerial photographs and ALS-based visualizations already revealed two probably younger features adjacent to it – a motte and another somewhat enigmatic rectangular structure. Geophysical survey showed that there had also been an additional artificially separated area within the early medieval gord. Geophysics of the early medieval stronghold at Taczanów Drugi revealed quite an interesting architectonic solution with additional radially arranged buttresses reinforcing ramparts or gateways (Fig. 2B). Field pebbles, still numerously occurring on the surface of the site, but also collected and reused for hardening local dirt roads, had been used for their construction. An exceptionally detailed picture was provided as the result of surveys conducted in Rozdrażew, where the course of fortifications surrounding a gord's hill and an ancillary settlement, as well as relics of buildings located therein were recorded (Fig. 2C).

Also, magnetic prospections were completed for two previously unknown features. Already the first observations made in Grudzielec confirmed the find to be relics of a gord – remains of charred wood and burnt clay on the surface of a plowed field marked the course of earthworks (Fig. 2D); furthermore, there were numerous early medieval sherds. The arrangement of the site was perfectly recorded by magnetic measurements. In Czermin, the alleged late medieval motte was not that clearly visible in the landscape (Fig. 2E). The dam was silhouetted though due to different vegetation.

Magnetic surveys within early medieval strongholds in Ostrów Wielkopolski-Krępa and Topola Wielka yielded no clear pictures (Fig. 3). Both sites are strongly eroded and hence the possible layers of high magnetic susceptibility are rather thin. Still, their location could be clearly seen thanks to vegetation marks.

Conclusions

The scenario involved applying a fast-paced and effective fieldwork procedure, which made the realization of the project's objectives possible while maintaining reasonable costs. In doing so, a rich package of complementary information, shedding new light on a number of sites, was obtained. At present, for the two districts, there is a complete and detailed documentation of all (28) strongholds recorded in the area. For a quarter of them (7) a full doc-

umentation procedure, involving i.a. photogrammetry and magnetic survey, was performed. Considering the whole country, this is quite a result. Where necessary and possible, the works are to be continued with the use of the current methodology as well as other tools.

Acknowledgments

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Pliska and Veliki Preslav: non-invasive research into the urban planning of two early medieval centers

Peter Milo [1]*, Andrey Aladzhov [2], Petar Dimitrov [2], Jan Havelka [1], Maria Manolova Voykova [3], Beáta Milová [4], Anna Mária Rekemová [1], Dávid Šálka [1], Tomáš Tencer [1], Michal Vágner [1]

1 Department of Archaeology and Museology, Masaryk University, Brno, Czech Republic
2 National Archaeological Institute with Museum, Bulgarian Academy of Science, Sofia, Bulgaria
3 Varna Regional Museum of History, Varna, Bulgaria
4 Archaeological Institute, Slovak Academy of Science, Nitra, Slovakia
* Corresponding author: E-mail: peter.milo@mail.muni.cz

Abstract
Geophysical surveys in Pliska and Veliki Preslav (Bulgaria) brought a breakthrough in our view of the appearance of early medieval centres in the Balkans. Urban planning on a scale of dozens of hectares has been documented for the first time. It has been found that wooden buildings massively accompany masonry architecture. Using a magnetic survey, we have been able to define the road network and functionally specific areas.

Keywords
Bulgaria; central sites; early Middle Ages; geophysical survey; settlement structure

Introduction

The two metropolises of early medieval Bulgaria – Pliska and Veliki Preslav, belonged to the largest cities of their time in the world. Their history and archaeology graphically illustrate the rise and fall of the First Bulgarian Kingdom as well as the re-occupation of the Eastern Balkans by the Byzantine Empire between the 8th and 11th centuries. Despite archaeological investigations spanning more than a century, fundamental questions concerning the nature, structure and settlement intensity of these cities remain unanswered. Our recent geophysical surveys (2019-2022) promise to shed new light not only on the functioning of these cities but also on the economic and socio-cultural lives of their inhabitants.

Materials and methods

Combining geophysical survey with previous archaeological field walks and excavations proved to be adequate and valuable for expanding our knowledge of the researched sites. Given the nature of the archaeological structures excavated in Pliska and Veliki Preslav such as stone buildings and wood-clay features, we decided to conduct a magnetometer and GPR survey. While magnetometry investigates vast areas quickly and identifies a wide range of archaeological features, GPR can estimate the depth of the features.

The magnetic survey in Pliska covered an area of 775 ha. The surveyed area in Veliki Preslav reached 76 ha. The prospection was carried out with a fluxgate magnetometer LEA MAX (Eastern Atlas, Germany) with ten fluxgate probes (FEREX CON 650, Foerster, Germany). The instrument was designed as a gradiometer for measuring the vertical gradient of the local magnetic field. Sampling density was 0.5 m x 0.1 m. Data positioning was provided with an RTK GNSS (Real-Time Kinematic Global Navigation Satellite Systems), and gathered data were processed using the standard procedure in the LEAD2 programme.

The GPR survey covered only small parts of both sites. The surveyed area in Pliska was 1 ha, in Veliki Preslav it was 1.7 ha. The prospection was conducted using the multichannel georadar Raptor–45 (Impulse Radar, Sweden) with eight antennas with a central frequency of 450 MHz.

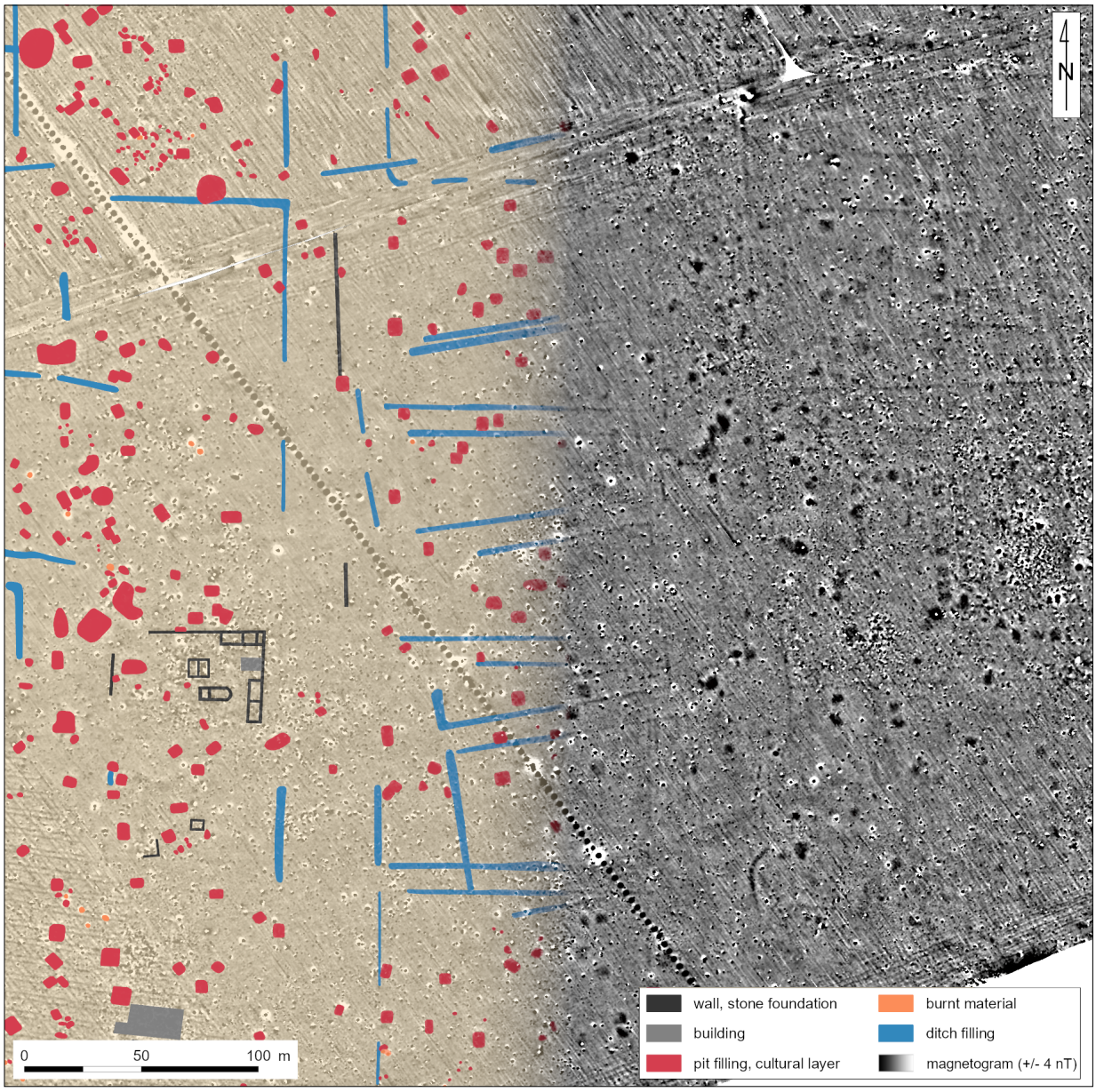

Fig. 1: Pliska: Results of magnetic prospection in the western part of the Outer City and archaeological interpretation of the survey.

The resolution of the measurements was 0.1 m x 0.1 m. The obtained data were processed using GPR Slice (Geophysical Archaeometry Laboratory/Screening Eagle) software.

The results of the geophysical measurements were processed and further visualised in the GIS environment (ArcGIS; ESRI). The identified anomalies were interpreted as features with archaeological potential and transformed into a digital vector format. Based on the physical properties of these anomalies, their shape, dimensions and the overall context or distribution in space, they were further classified as settlement pits, trenches, burnt features, fortifications, stone architecture etc.

Results

Pliska, the assumed first capital of early medieval Bulgaria (681-1018), consists of two components. The Inner City represents a stone fortification with dozens of monumental stone buildings such as palaces, administrative and

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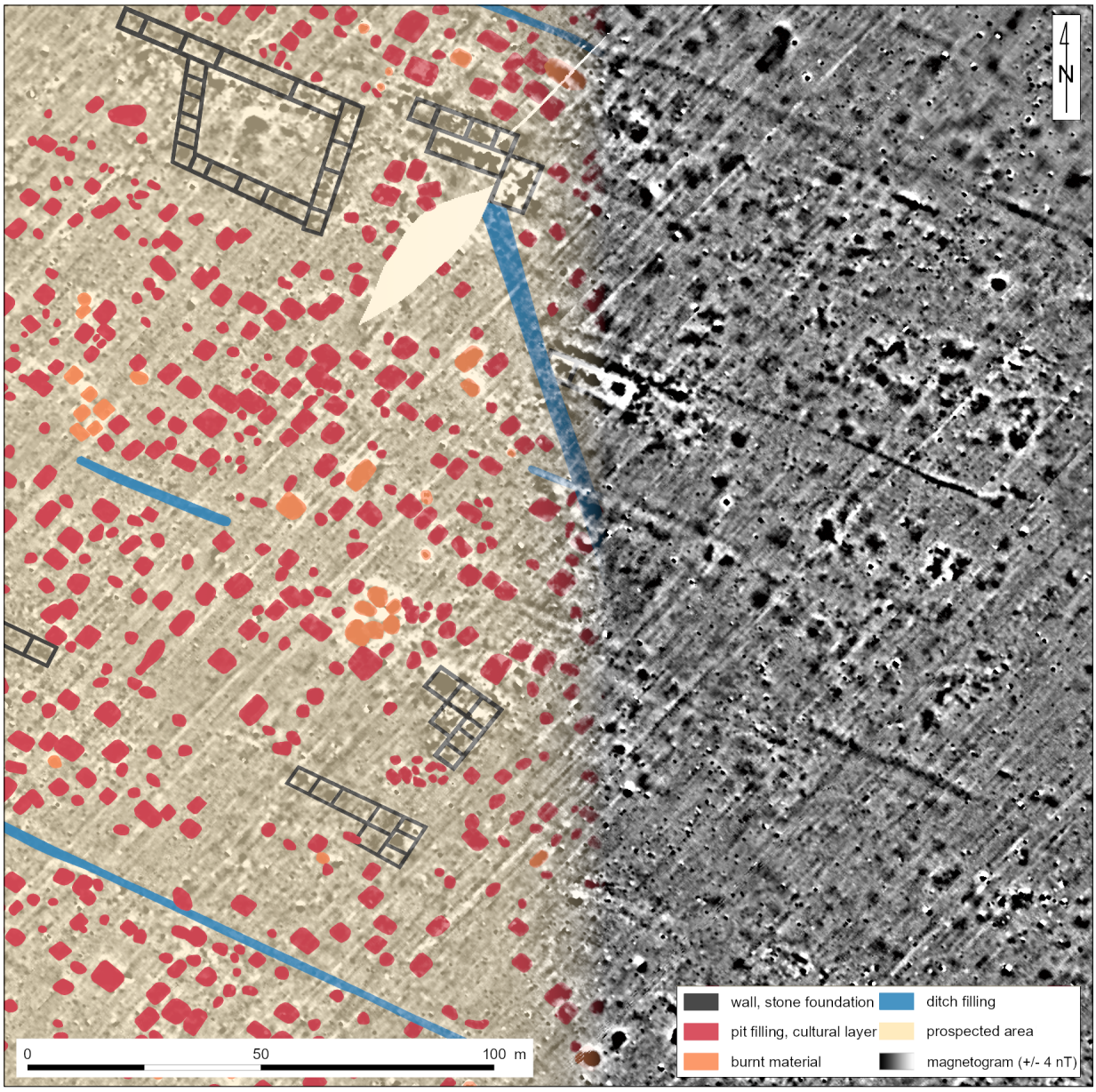

Fig. 2: Veliki Preslav: Results of magnetic prospection in the eastern part of the Outer City and archaeological interpretation of the survey.

aristocratic buildings, and churches. It is surrounded by the Outer City, a huge settlement complex protected by earthen ramparts. Together, the whole territory of Pliska covers an area of 2188 ha (Aladzhov 2013). After the Bulgarian ruler Simeon I moved his headquarters from Pliska to Veliki Preslav, this city grew in size enormously in less than 80 years (893-971). From a purely military fortress, Veliki Preslav developed into a "three-tier" agglomeration consisting of the Palace City spread over an area of 24 ha, an Outer City of over 300 ha and the suburbs (Totev 2001).

In terms of area, Pliska and Veliki Preslav were comparable to the megacities of the era such as Constantinople and Baghdad. Due to the rapid reduction of their occupied areas in the eleventh century and beyond, they also represent the best-preserved metropolises from the Middle Byzantine period in the Balkans. As a result, many important parts of both cities have been archaeologically excavated – the Ruler's and Patriarchal complexes, aristocratic mansions, production and monastery ensembles, as well as numerous church buildings. However, after nearly 125 years

of archaeological excavations, several questions remain unanswered, especially about the Outer Cities and suburbs. It was generally assumed that the Outer City was in both cases sparsely built up, chaotic and without firmly set urban planning rules. Such an idea was also confirmed by a large-scale geophysical survey carried out in the field to the north of the Great Basilica in Pliska in 2016 (Filzwieser et al. 2019). However, the latest geophysical survey found that large parts of both sites show organised residential development. In Pliska, we discovered a regular settlement structure with a network of roads oriented in the north-south and west-east directions (Fig. 1). Some have the character of boulevards with a width of tens of meters. They are lined with fenced courtyards of regular rectangular shape with a size of 0.4 to 2 ha. The fences are mostly wooden palisades, but exceptionally, also stone walls. Our survey shows buildings of various kinds in individual courtyards, including multi-room stone houses or even large complexes with a square courtyard in the middle. The main buildings are often surrounded by a large number of simple sunken huts. Although the same features were identified in Veliki Preslav (Fig. 2), the character of the settlement structure there is diametrically different than in Pliska. The most interesting is one city district with a size of approx. 60 ha. It shows no fences like in Pliska. It is characterised by a regular network of narrow streets and extremely dense occupation. There are numerous stone houses and churches, but most objects are small wooden cottages with a square floor plan. Furthermore, we discovered two large building complexes – probably a monastery and military barracks – in the peripheral zones.

Discussion and conclusion

The structure of the built-up areas in Pliska and Veliki Preslav reveals a system for which we do not know a direct analogy. Although sunken huts are a common type of house in the Balkans, as well as in Central and Eastern Europe, the sacral and profane stone architecture – despite its local antecedents – has its roots outside the territory of the Bulgarian state. The buildings and fabric of settlement we have so far recognised we can search both in the territory of Byzantium and in the steppe regions of the Black Sea and Central Asia. New information about the urban fabric in Pliska and Veliki Preslav obtained by geophysical survey significantly expands our existing knowledge, obtained mainly through archaeological excavations. To truly understand the character and development at both sites, an additional large-scale geophysical survey is needed as well as the involvement of other non-invasive survey methods. Subsequent validation of the obtained data using precisely targeted archaeological trenches will also be necessary. Such research is already underway, and we can hope in a significant breakthrough in the knowledge of these important early medieval metropolises.

Acknowledgments

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Combined geophysical surveys on medieval and post medieval build structures

Joep Orbons [1*]

1 ArcheoPro, Eijsden, The Netherlands
* Corresponding author: E-mail: j.orbons@archeopro.nl

Abstract
The goal of this paper is to precisely locate medieval or post-medieval buildings. A method is suggested to quickly zoom in by using combined geophysics. Seventeen cases are compared in a study to check the proposed integrated method. The work is carried out in cooperating with local historical societies.

Keywords
archaeological prospection; EMI; magnetometry; Medieval buildings; resistivity

Introduction

Finding a castle, monastery or church is one of the most visible and satisfying works in archaeology. Very often, local historical societies have a rough knowledge of that old, medieval building where the location is known to an accuracy of about 1 to 2 ha. The exact location is unknown. Excavating is not an option but knowing and visualizing the building adds value to the local heritage. A nice way to find these buildings is the use of geophysics. In the Netherlands, many villages and regions have local historical societies with a broad knowledge of the local history. These local societies very often initiate a search for a lost medieval of post medieval building but lack the instrumentation for a prospection survey. A good cooperation between the local historical society and the professional archaeologist can produce some good results.

Over the last 5 years, 17 surveys have been done on medieval and post medieval sites with moats and walls, very often in cooperation with local historical societies (Fig. 1).



Fig. 1: Surveyed sites in The Netherlands and Belgium.

Materials and methods

A standard way of working has been created for these medieval and post medieval sites with walls and moats where the area to be studies is mostly 1 to 2 ha in size. It always starts with a desktop study, carried out by the professional archaeologist using the knowledge gathered by the local historians matching the EAC Guidelines (Schmidt et al. 2015).

The field work is usually a one- or two-day field survey where the volunteers of the local historical society assist the professional archaeologist during the field work.

The standard way of working is to split a field day in two. The morning session is an EMI survey of the complete site, normally 1 to 2 ha. The instrument used for the



Fig. 2: Surveying with the CMD Mini Explorer.

EMI survey is a CMD Mini Explorer with RTK GPS positioning (Fig. 2). Depending on the field conditions, the survey lines are 1 to 2.5 m apart. The measurements take place at 5 measurements per second. With a normal walking speed, this results in one measurement every 25 cm.

At the end of the morning, the EMI data is downloaded and visualized during the lunch break. Out of the EMI data, an area is selected for a detailed survey with resistivity and magnetometry. Usually, 0.25 ha is more than enough to fit the building being prospected.

After the lunchbreak, the selected area of 0.25 ha is surveyed with resistivity and magnetometry. The resistivity measurements are taken with the RM15 in single electrode spacing modus with an electrode spacing of 0.75 or 1 m. The measurements are taken in a 1x1 m grid survey. The same area is then surveyed with the Bartington Grad 601 Dual magnetometer to gain information on the magnetic properties in the underground. The measurements are taken in a 1x0.25 m grid survey. Most medieval buildings fit within these constraints so a full survey is possible in one day.

At the end of these two detailed surveys, that data is quickly reviewed in the field. First to check if all went well and secondly to satisfy the curiosity of the volunteers.

Very often, the geophysical survey is carried out in combination with an augering campaign to gain even more information.

The field data is reported and shared with the local historical society, usually resulting in a publication in the local historical magazine. The results are satisfying to add knowledge to the local history, but also to add methodological knowledge to the local people for them to know how to prospect for archaeology.

Results

The 17 surveyed locations form a nice database to check the effectiveness of the method. The results are given in Table 1. All sites were surveyed with the CMD Mini Explorer for a first scan. All but one site were then surveyed with the RM15 in either single electrode mode or in ERT

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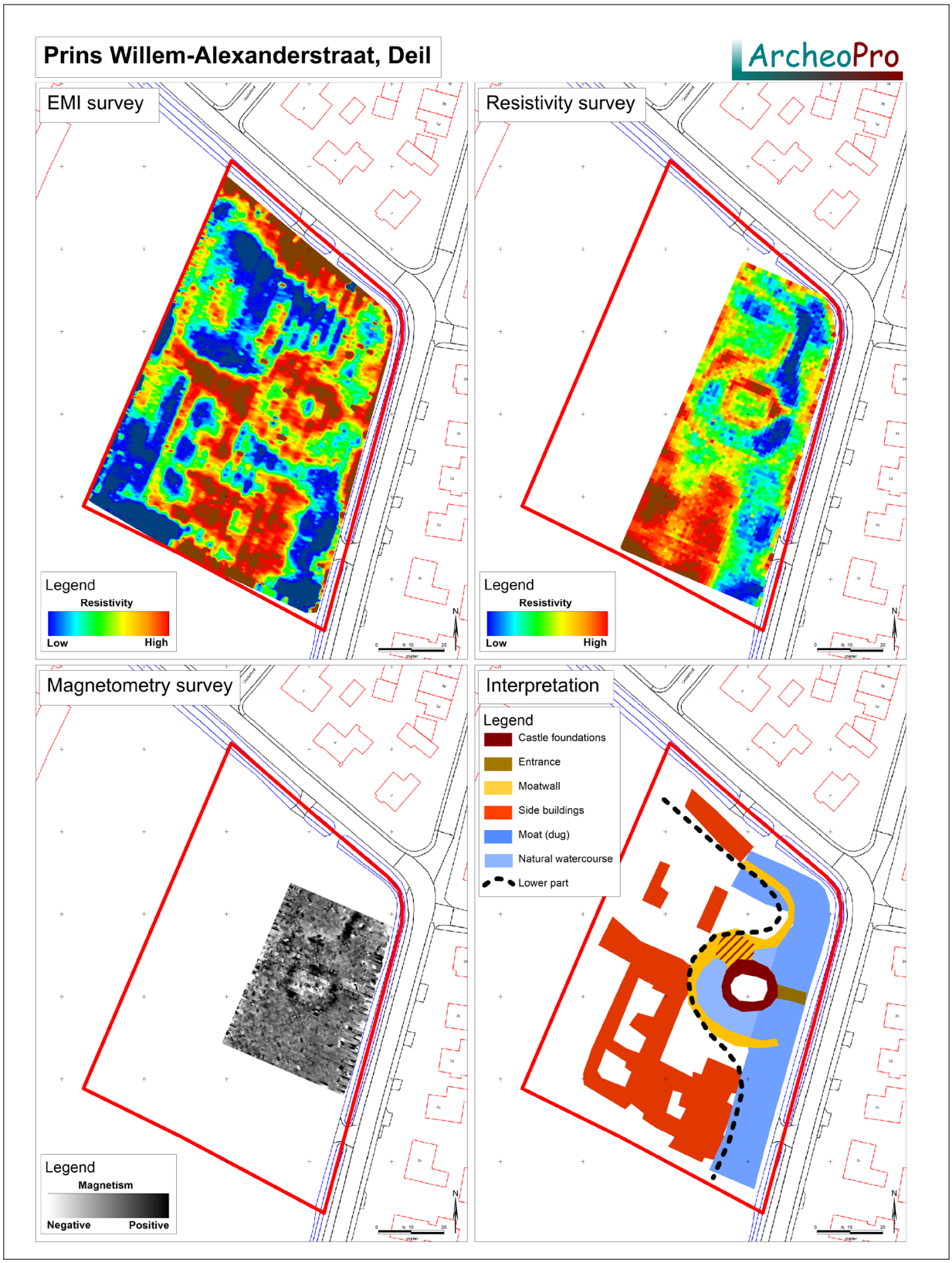

Fig. 3: Results of Castle Bakersbos, Deil Survey, Site 13 (Orbons 2021).

Site	Projectname	CMD Mini	RM15	RM15_ERT	Magnetic	Urban	Result
1	Twee Getuigen, Brielle	X			X		1
2	Laathof, Schey	X	X		X		1
3	Kasteelterrein, Vlijmen	X	X		X		1
4	Landgoed Steenenburg	X	X		X		1
5	kartuizerklooster Olland	X	X		X		0
6	Stift Kekerdom	X	X		X		1
7	Hof van Maarland, Eijsden	X	X	X	X		2
8	Bastion IX, Brielle	X		X		X	2
9	Kapelstraat Lith	X	X		X		2
10	Terp Kerkbrink, Groet	X	X			X	1
11	Brigittenpoortje, Brielle	X	X			X	1
12	De Stuyver, Ten Esschen	X		X	X		1
13	Kasteel Bakersbos, Deil	X	X		X		2
14	Dorpshart, Zonhoven	X	X			X	1
15	Kasteel Spaldorp	X	X		X		2
16	Steegstraat, Eijsden	X	X		X		2
17	Abdij Berne, Nederhemert	X	X		X		2

Table 1: Surveyed sites.

mode. 13 sites were also surveyed with the magnetometer. The 4 sites that were not surveyed with the magnetometer were the sites located in an urban setting with a lot of metal objects in and around the site.

The results of the surveys can be categorized in 3 divisions:

Only one site (Site 5) was surveyed with no indication of the expected early medieval monastery, probably because the monastery is not present at the given location.

Nine sites (Sites 1, 2, 3, 4, 6, 10, 11, 12 and 14) gave a good indication of the presence of the walls and moats, indicated in table 1 with a "1" in the result column. The results are not very clear features because of the complexity of the situation, disturbance of the soil or other unfavorable situations for geophysical prospections. 3 of the 4 urban sites (Sites 10, 11 and 14) fall within this category confirming the complexity of urban geophysics (Trinks et al. 2009).

Seven sites (Sites 7, 8, 9, 13, 15, 16 and 17) produced some very clear and beautiful images of the walls and moats, indicated in table 1 with a "1" in the result column (Fig. 3). One of the urban sites (Site 8) was very successful.

Conclusion

From these 17 cases, it can be concluded that the chosen method of working is effective and efficient. The one site that did not produce the expected monastery (Site 5) is probably at the wrong location. All other surveys produced a result that added knowledge to the site. 7 out of the 17 sites even produced some beautiful images that are very publishable for the general public.

The speed of working works well for these sites. The cooperation with the local historical society is effective, not only to assist during fieldwork but also in publishing and presenting the results to the local population.

The zooming-in method from EMI to resistivity and magnetometry is very efficient. Most medieval buildings fit within the 50x50 m size and can thus be surveyed, even if the exact location is not known within a couple of hectares. The EMI survey works very well for a quick scan, pointing to the interesting location. The combination of resistivity and magnetometry prove very helpful in understanding the nature of the archaeological features under investigation.

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Geophysical and UAV surveys on Konya Karahöyük (central Anatolia, Turkey)

İnci Nurgül Özdoğru [1*], Gonca Dardeniz [2], Orkan Özcan [3], Fırat Yiğit [4], Serkan Özçelik [4]

1 Department of Ecology and Evolution, Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey
2 Department of Protohistory and Near Eastern Archaeology, Istanbul University, Istanbul, Turkey
3 Department of Ecology and Evolution, Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey
4 SER Engineering Co., Istanbul, Turkey
* Corresponding author: E-mail: ozdogru@itu.edu.tr

Abstract
Geophysical prospection and unmanned aerial vehicles (UAV) were applied systematically to improve excavation strategies. Magnetic results were verified using GPR in the suitable areas.

Keywords
Bronze Age Anatolia; GPR survey; magnetic prospecting; remote sensing; thermal image

Introduction

The archeological site of Konya-Karahöyük is located in the Konya plain of central Anatolia, Turkey (Fig. 1). Situated almost 8 km southeast of modern Konya, the site is at the crossroads from Syro-Mesopotamia to the Aegean (Alp 1994). The archaeological material collection collected from the site dates to the 3rd-2nd millennia BC and displays Anatolian, Syrian, and Aegean influences confirming it as a dynamic hub of the Bronze Age.

The mound of Konya-Karahöyük covers an area of 33 ha. With its lower town, which is heavily filled with alluvial deposits, the site spans almost 100 ha. Previous excavations at the site (from 1953 to 1994 with breaks) yielded remains of monumental architecture, yet, there is a lack of a systematic understanding of the architectural patterns. Excavations reinitiated at the site in 2022 aim to expose architectural remains of the upper and lower towns as well as to investigate the expansion of the site via using interdisciplinary methodologies. Thus, in the first season of the new round of excavations, a combined methodology of ground penetrating radar (GPR), magnetic prospection, and unmanned aerial vehicles (UAV) including thermal imaging was applied systematically to unfold the architectural layout of this multilayered archaeological site. The results of this combined methodology, applied only at a small section of the mound, yielded promising results to detect architectural remains made of mudbrick and stone.

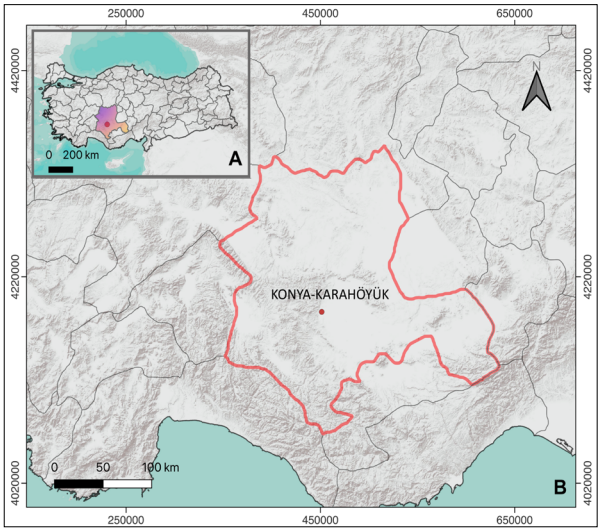

Fig. 1: The maps show the locations of A) Konya in Turkey, B) Konya in the region. Red color line shows the Konya province in Turkey. The red color dot denotes the Konya-Karahöyük.

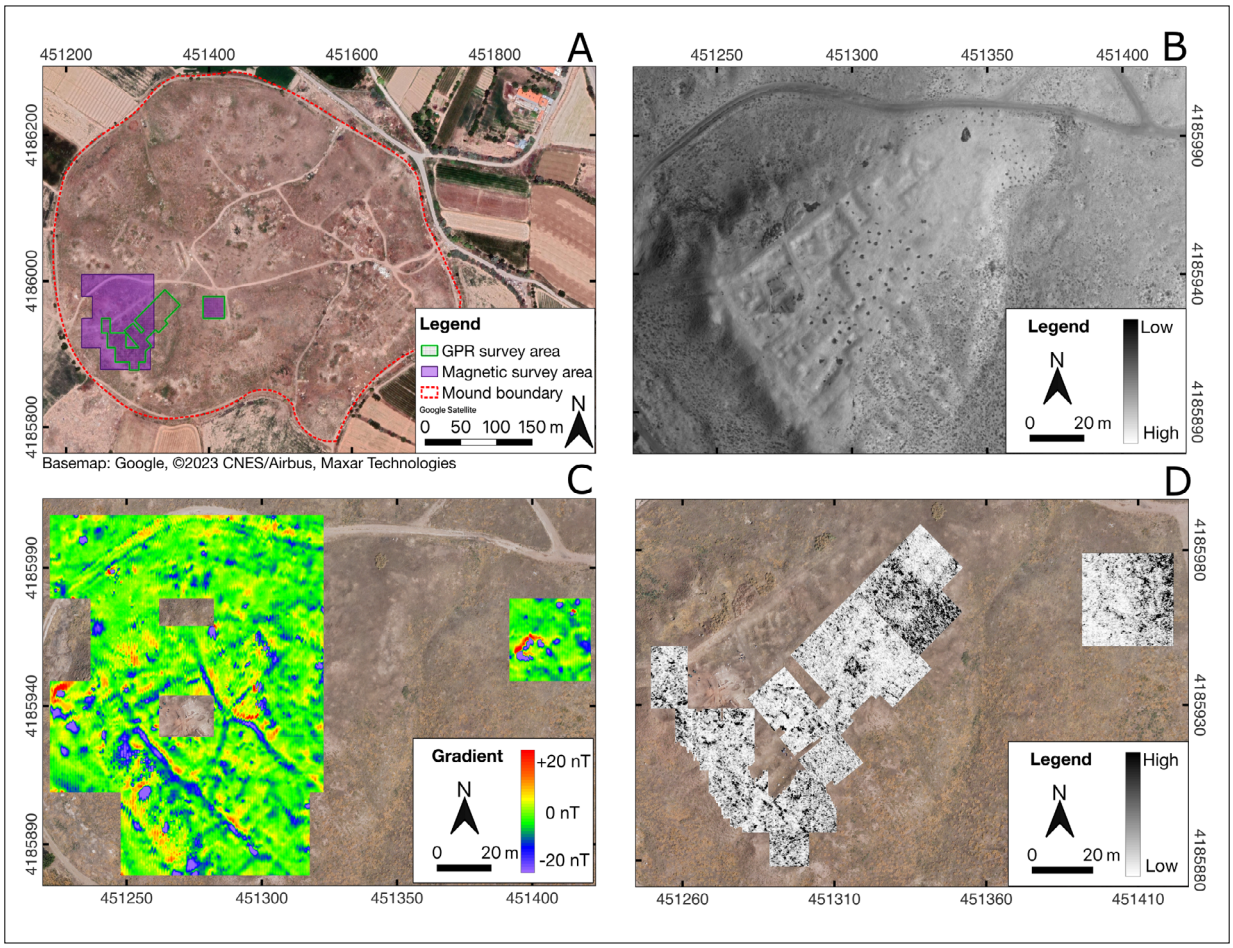

Fig. 2: The area that the mound of Konya Karahöyük covers is illustrated with red color dotted line and geophysically covered areas are displayed on the figure (A). The results of the thermal imagery (B), magnetic (C), and GPR (D) surveys are shown respectively.

Methods

The fieldwork involved applying a combination of newly acquired aerial and geophysical survey data that include GPR and magnetic methods. The GPR used was GSSI UtilityScan with 350 MHz central frequency, and the magnetometer was Geometrics G-858 MagMapper cesium vapor magnetometer. The profile spacing was 0.25 m for GPR and 0.5 m for the magnetic survey.

The mound rises 19 m above sea level, and it shows varying elevations at different parts due to archaeological as well as alluvial accumulation. Considering the complex morphology of the mound, the magnetic survey was favored for the detection of mudbrick and stone architecture. GPR was used in areas where the method is applicable morphologically and is comparable to magnetic survey results. Approximately an area of 4400 m^2 was covered by GPR with a selected penetration depth of 3 m. Magnetics was applied approximately to 1.2 ha. The duration of data collection was two weeks. For the process of the GPR and magnetic datasets, ReflexW and MagPick software were used respectively.

The aerial survey involved capturing both multispectral and thermal images using a DJI Mavic 2 Enterprise Advanced drone (Dual Imaging: 640 × 512 px Thermal Camera, 48MP Visual Camera). A high-resolution Digital Elevation Model (DEM) and aerial thermography were applied to emphasize crop marks on the mound utilizing the spectral information contained in the solar radiation (Casana et al. 2017). The images were processed via Agisoft software for creating point clouds, mosaicking, orthorectification, georeferencing, multispectral processing, and creating DEM. QGIS was used to visualize the results of the geophysical and aerial survey data.

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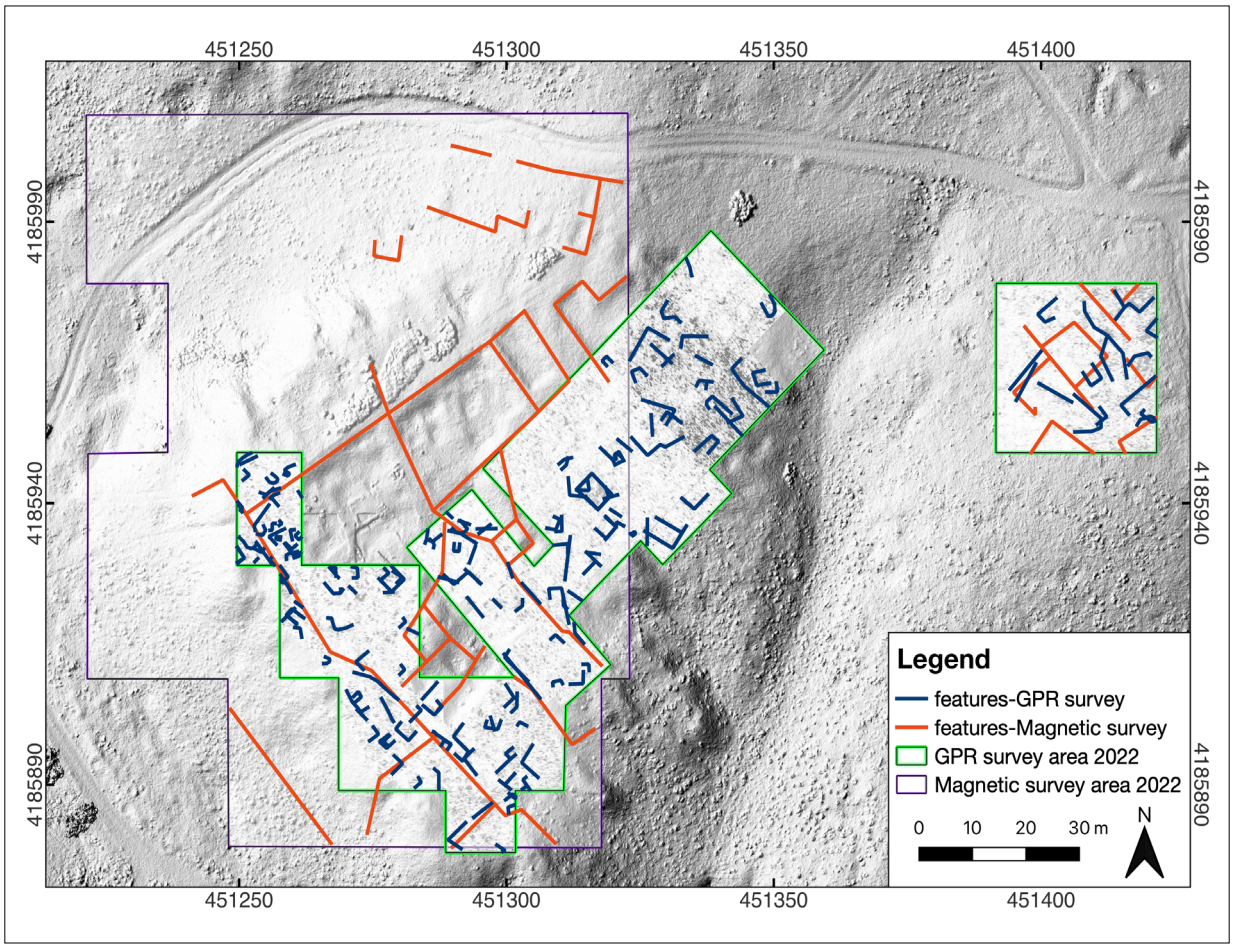

Fig. 3: Interpretation of geophysical surveys in comparison with thermal imagery and DEM is illustrated.

Results and discussion

This project applies a combination of geophysical and UAV surveys at a central Anatolian Bronze Age site in the first archaeological excavation season after 30 years of break. The objectives of the interdisciplinary research in this very first season were to 1) investigate possible architectural remnants with various methods to understand the best working techniques for the following field seasons; 2) provide a brief view of below surfaces before opening new excavation squares.

This study mainly focused on the southwestern part of the mound to provide general information for future excavation seasons. The preliminary results of the geophysical exploration identified several architectural remnants at different depths (Fig. 2). Along the NW-SE direction, the produced profiles identified two linear marks that could possibly be the walls of a monumental structure extending approximately 70 m (Fig. 3). The results are in accordance with the thermal images and DEM. Between these linear structures, nearly perpendicular walls were also identified. The structures were mostly starting from 0.25 m – 0.5 m below the surface. The 2023 season at the site will ground-truth the results via excavation.

Conclusions

In conclusion, the preliminary results of this multi-technique survey demonstrate that methodologically different remote sensing methods have broad prospects for studying Bronze Age mound-like settlements with mudbrick and stone architecture such as Konya-Karahöyük. The site with its diverse morphology, various architectural remains (mudbrick, different types of stones, etc.), and complex archaeological strata require a combination of geophysical and UAV survey methods.

In the next excavation seasons, a similar methodology will be applied to the other sections of the mound. Yet, the results of our first survey season -especially DEM- indicate that the rest of the mound requires further attention in the following years. Subsurface structures revealed by the thermal images and DEM need to be confirmed with geophysical methods and test trenches. Only after the test trenches, post-excavation reevaluation of UAV and geophysical data will be possible. The following excavation seasons and further research will lead to a more precise processing and accurate interpretation while combining UAV and geophysical datasets.

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Experiences from microgravity and GPR surveys for subsurface cavities detection – case studies from SW- and central Slovakia

Roman Pašteka [1*], Dennis Wilken [2], Tina Wunderlich [2], Erik Andrássy [1], Ema Nogová [1,3], Dominika Godová [1,3], Lenka Ondrášová [1,3], Jozef Bódi [1,3]

1 Department of Engineering Geology, Hydrogeology and Applied Geophysics, Comenius University in Bratislava, Slovakia
2 Institute of Geosciences, Kiel University, Kiel, Germany
3 Earth Science Institute of the Slovak Academy of Sciences, Bratislava, Slovakia
* Corresponding author: E-mail: roman.pasteka@uniba.sk

Abstract
Combination of microgravity and GPR method constrains each other and help to detect subsurface cavities in a very effective way. Several examples are presented, some of the data-set were acquired during common summer schools between Kiel University and Comenius University in Bratislava.

Keywords
cavity detection; georadar; joint interpretation; microgravity

Introduction

In archaeological prospection, for the detection of subsurface cavities mainly geoelectrical and electromagnetic methods have been and are commonly used. Among them, especially the GPR method (ground penetrating radar) can very well recognize subsurface cavities due to their intensive differences in geoelectrical properties to the subsurface (e.g. Leucci 2006). Beside geoelectrical methods, microgravimetry represents a very important tool for the detection of cavities – due to their intensive density contrast with surrounding soils and rocks (e.g. Pašteka et al. 2020). Very effective is a joint use of these two methods, as it has been shown in many studies (e.g. Pánisová et al. 2013; Pašteka et al. 2019). Here we present results from several surveys, performed in medieval churches in SW- and central Slovakia. Some of them were acquired during common summer geophysical schools, organized by Christian-Albrechts University in Kiel and Comenius University in Bratislava – as an example we can bring forward the Erasmus IP project INCA (International Course on Archaeogeophysics; Rabbel et al. 2010).

Methods

In this contribution we present mainly results, acquired by means of GPR instrument GSSI with 400 MHz antenna and gravimeter Scintrex CG-5. Distance between GPR lines was 0.3 m, gravity points were acquired in nets of 1 x 1 m. GPR data were processed by standard way, where mainly gain control, removal of multiples and filtration played important roles. Microgravity data were processed in a form of incomplete Bouguer anomalies, where the so-called building corrections (removal of the gravity effect of the building masses) are very important (e.g. Pašteka et al. 2020). Results from both methods (GPR and microgravimetry) were interpreted together in a joint qualitative and quantitative interpretation. In the following section we shortly describe selected aspects from achieved results during acquiring both used methods in several churches from Slovakia.

Results

In the frame of the geophysical summer school INCA and also other local projects, several churches in SW- and cen-

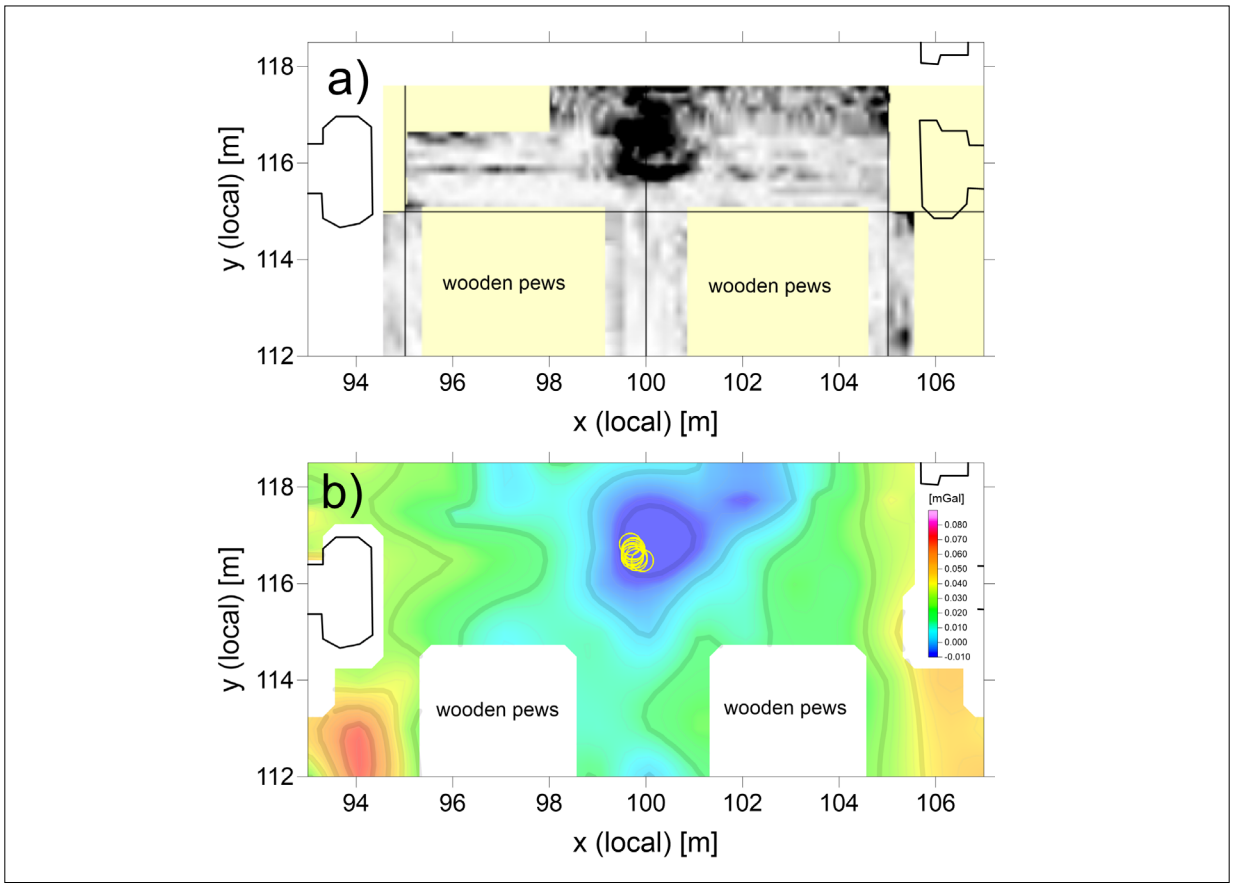

Fig. 1: Results from archaeogeophysical survey in the St. Catherine's church in Banská Štiavnica. a) horizontal GPR slice for the depth 1.0 m, b) incomplete Bouguer anomaly for the correction density 2.0 g*cm^{-3}, together with the results of the 3D Euler deconvolution (yellow circles).

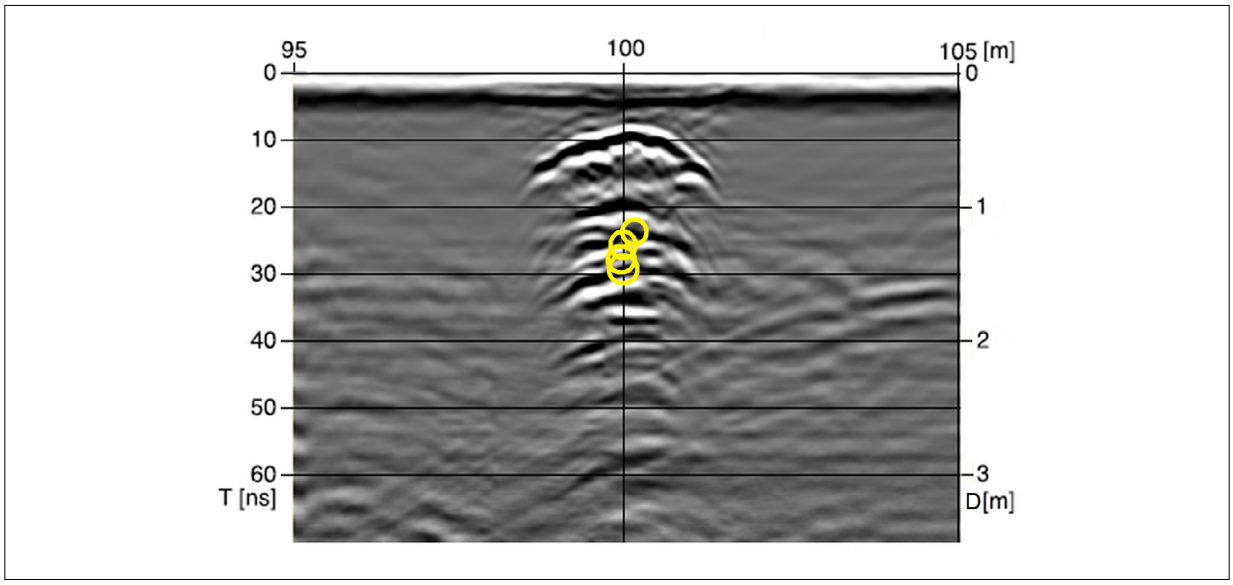

Fig. 2: Vertical GPR slice, crossing the central part of the detected anomaly in Fig. 1. Positions of the 3D Euler deconvolution depth solutions (structural index = 2) are displayed as yellow circles.

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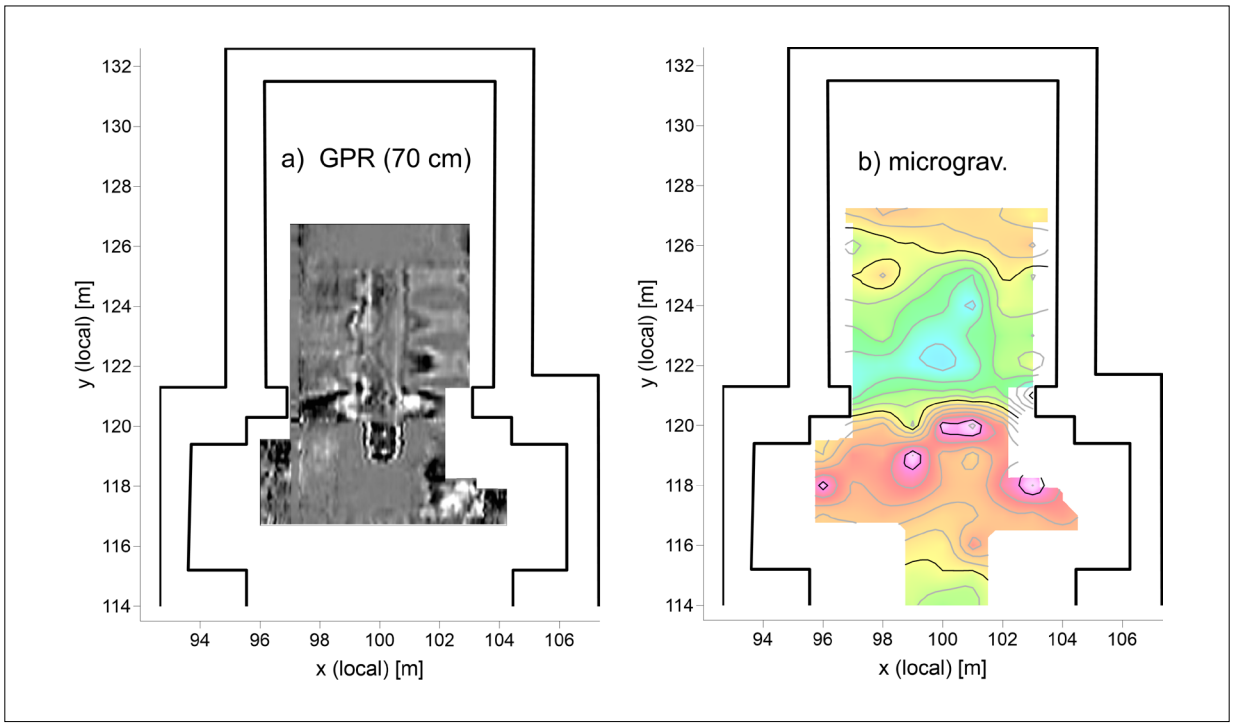

Fig. 3: Results from archaeogeophysical survey in the St. Joseph's church in Beckov. a) horizontal GPR slice for the depth 0.7 m, b) incomplete Bouguer anomaly for the correction density 2.0 g*cm^{-3}.

tral Slovakia were explored by means of GPR and microgravity methods. In the interior of St. Catherine's church in Banská Štiavnica (central Slovakia) the major part of the aisle (beside the places with large wooden pews) and a part of the presbytery was covered by GPR and microgravity measurements. In the transition area between aisle and presbytery (Fig. 1), both methods detected an important cavity, with high probability a crypt. In the horizontal reflection amplitude section from the GPR method it is characterized by a dominant symmetric anomaly in the centre of the figure (Fig. 1a). The map of incomplete Bouguer anomalies shows a little more complex character (Fig. 1b) – beside the central anomaly over the cavity of interest, there are is also a small low on the right-hand edge of the main negative anomaly. This aspect is not well explained until today, probably it is connected with a density weak part below the floor in the church. Estimation of the depth extent of the detected cavity was performed from both methods. Depth of the upper edge (approx. 0.35 m) can be very well recognized from vertical GPR sections (Fig. 2), but the bottom edge estimation is strongly influenced by the existence of multiple reflection in the interior of the cavity and can be hardly determined from the GPR results. For this estimation we have used the quantitative interpretation of microgravity data – 3D Euler deconvolution method (Reid et al. 1990) has estimated the depth of the centre of cavity in approx. 1.3 m (Fig. 2) and 3D density modelling has confirmed the depth extent of the cavity from approx. 0.35 m to 2 m below the floor of the church (in the case of an air-filled cavity).

Very similar results were acquired in the St. Martin's church in Bratislava and Joseph's church in Beckov (SW-Slovakia). In St. Martin's church a system of several crypts with irregular organisation was confirmed and one unknown cavity was interpreted (in the SE corner of the presbytery – not shown as a figure here). In the St. Joseph's church the GPR method has found a central crypt in the presbytery (in a form of so-called columbarium – Fig. 3a), which was the first case in Slovakia that the small spaces for coffins could be recognized in horizontal GPR sections (Pašteka et al. 2019). Microgravimetry method could confirmed only the total effect of this crypt (Fig. 3b; not the separated coffin spaces in the columbarium - these objects were too small). No one from these three sites were explored by means of archaeological survey yet (shallow drillings with video-inspection). We are looking forward to obtain the feet-back from this kind of verification in the future.

Conclusion

In this contribution we show results from case studies from various churches in SW- and central Slovakia. Combination of microgravimetric and GPR can be very effective in the detection and study of subsurface cavities such as crypts: these are manifested in horizontal GPR sections as intensive reflectors and in incomplete Bouguer anomaly maps as dominant minima. In the majority of cases, central positions of anomalies from both methods are laterally identical. From the GPR vertical sections it is possible to estimated very well the upper depth limit of detected cavities and from quantitative interpretation of microgravity data (by means of density modelling and Euler deconvolution) we can determine the centres and vertical extents of interpreted cavities. In this study, we present also a case with the limitations of microgravity method: in the St. Joseph's church in Beckov the GPR method has found a central crypt in the presbytery (in a form of so- called columbarium) and microgravimetry could confirmed only the total effect of this crypt (not the separated coffin spaces in the columbarium - these objects were too small).

Acknowledgments

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Understanding the anomaly: reinterpreting *Porolissum* Roman town with emerging GPR and ER data

Michał Pisz [1,2*], **Vlad-Andrei Lazarescu** [3], **Alexandru Hegyi** [4]

1 School of Archaeological and Forensic Sciences, University of Bradford, Bradford, United Kingdom
2 Faculty of Geology, University of Warsaw, Warsaw, Poland
3 Institute of Archaeology and History of Art, Romanian Academy – Cluj Branch, Cluj-Napoca, Romania
4 Maritime Asia Heritage Survey, Center for Southeast Asian Studies, Kyoto University, Kyoto, Japan
* Corresponding author: E-mail: m.pisz@bradford.ac.uk; michal.pisz@uw.edu.pl

Abstract
The Roman *Porolissum* (Romania) was first surveyed with magnetics in 2010. Local geology is propitious for magnetic prospection. In 2021 the Polish-Romanian team carried out a complementary ER and GPR survey. Emerging geophysical data allowed reinterpretation of the previous survey results. Complementary survey data and geological setting analysis yet enhanced the archaeological interpretation.

Keywords
archaeological prospection; earth resistance; ground penetrating radar; magnetometer survey; Roman *limes Porolissensis*

Research background

In this paper, we present the case study of a multi-method archaeo-geophysical survey carried out in the extent of a Roman fort and *municipium Porolissum*. The first magnetometer survey carried out in 2008 by a team of geophysicists from Eötvös Loránd University showed very good responsiveness. Hence, investigations were continued in collaboration with multiple teams from different institutions, focusing on the area of the Roman town (Ștefan 2016; Fiedler et al. 2018; Opreanu and Lăzărescu 2018). Captured anomalies clearly outlined buried archaeological structures due to the use of strongly magnetic construction material (andesites and dacites). The Polish-Romanian team carried out supplementary earth resistance (ER) and ground penetrating radar (GPR) surveys in 2021. We argue that despite the seemingly unambiguous results of the magnetic survey, the application of complementary geophysical methods, GPR in particular, allowed improving the analysis, led to emerging discoveries and enhanced the interpretation of previous results.

Porolissum Roman fort and town

The site is located in NW Romania (Salaj county), in the Moigrad-Pomăt-Citera magmatic-volcanic complex. The fort is partly set on and surrounded by several Neogene hillocks, the genesis of which is associated with a phenomenon of hot-spot intrusions into Oligocene deposits, laying magmatic bodies consisting of dacites and andesites that were later brought to the surface by selective erosion (Fig. 1) (Mac 2010).

As a strategic frontier province, *Dacia Porolissensis* was a Roman territory with a strong military presence. The core of the *Porolissum* military complex was the Pomăt Hill fort, the largest auxiliary fort in the Dacian provinces, measuring 230 × 300 m. The civilian settlement at *Porolissum* was located around the fort, and due to its position at the fringes of the Empire, it developed into an important commercial hub allowing for complex connections with the *Barbaricum* (Opreanu and Lăzărescu 2016).

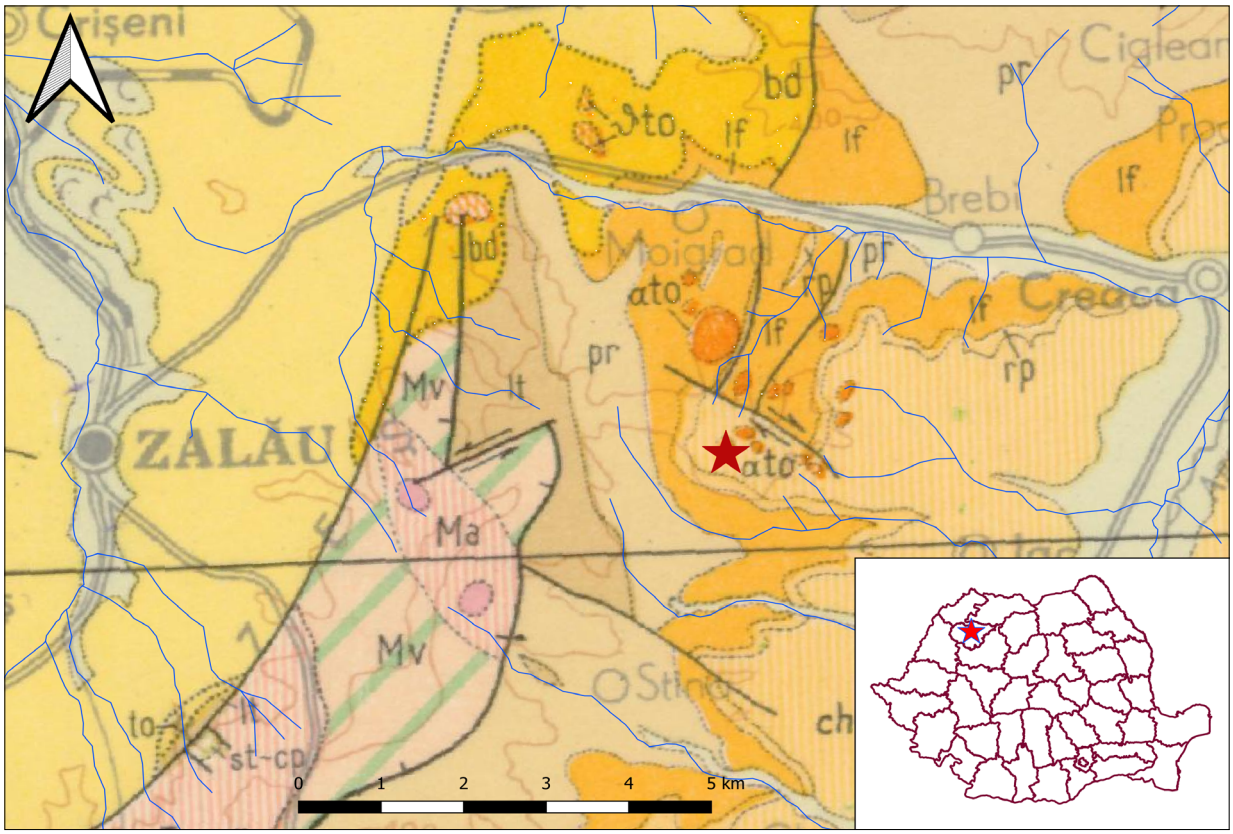

Fig. 1: The location of the Roman fort and town of *Porolissum* on the 1:200000 Geological Map of Romania (Raileanu et al. 1968).

Methods

The magnetic survey in the *municipium* area was carried out between 2010-2016 by Dan Ștefan, with a Bartington Grad601 dual sensor fluxgate gradiometer (Ștefan 2016). In 2021 we carried out a complementary survey with ER and GPR methods (Schmidt et al. 2015).

ER survey was carried out with Geoscan Research RM85 meter in a multiplexed measurements mode. Multi-depth twin probe array has been used with three mobile probes separation distances set at AM = 0.5, 1.0 and 1.5 m. Measurements were carried out within a 20 × 20 m grid, with 1 m crossline and 0.5 m inline. The ER data were processed in Geoplot 4 software. Recorded resistance values have been despiked and multiplied by the value of the K geometry factor relevant for each of multiplexed arrays, to calculate the values of the apparent resistivity for each maximum depth of prospection. Subsequent filtering procedures (e.g. low pass, interpolation) were applied.

GPR survey was carried out with a Malå GX radar with a shielded 450 MHz antenna in the same 20 × 20 m grid, with a 0.5 m crossline and 0.05 m inline. The GPR data was processed in SubGeo WAVE GPR processing software and exported as time slices.

Rendered geophysical maps were georeferenced and uploaded to QGIS along with up-to-date UAV orthophoto, DSM, satellite imagery and Romanian Geological Map 1:200000. In addition, Magnetic Susceptibility readings of the soil surface and materials used for construction have been taken on the site with Bartington MS3 meter and MS2D sensor.

Results

ER (Fig. 2) and GPR (Fig. 3) survey results matched to some extent, GPR being considerably more detailed. Numerous electrical anomalies were captured, high resistant zone and linear being the most commonly encountered. The latter corresponded with highly reflective features detected with the GPR.

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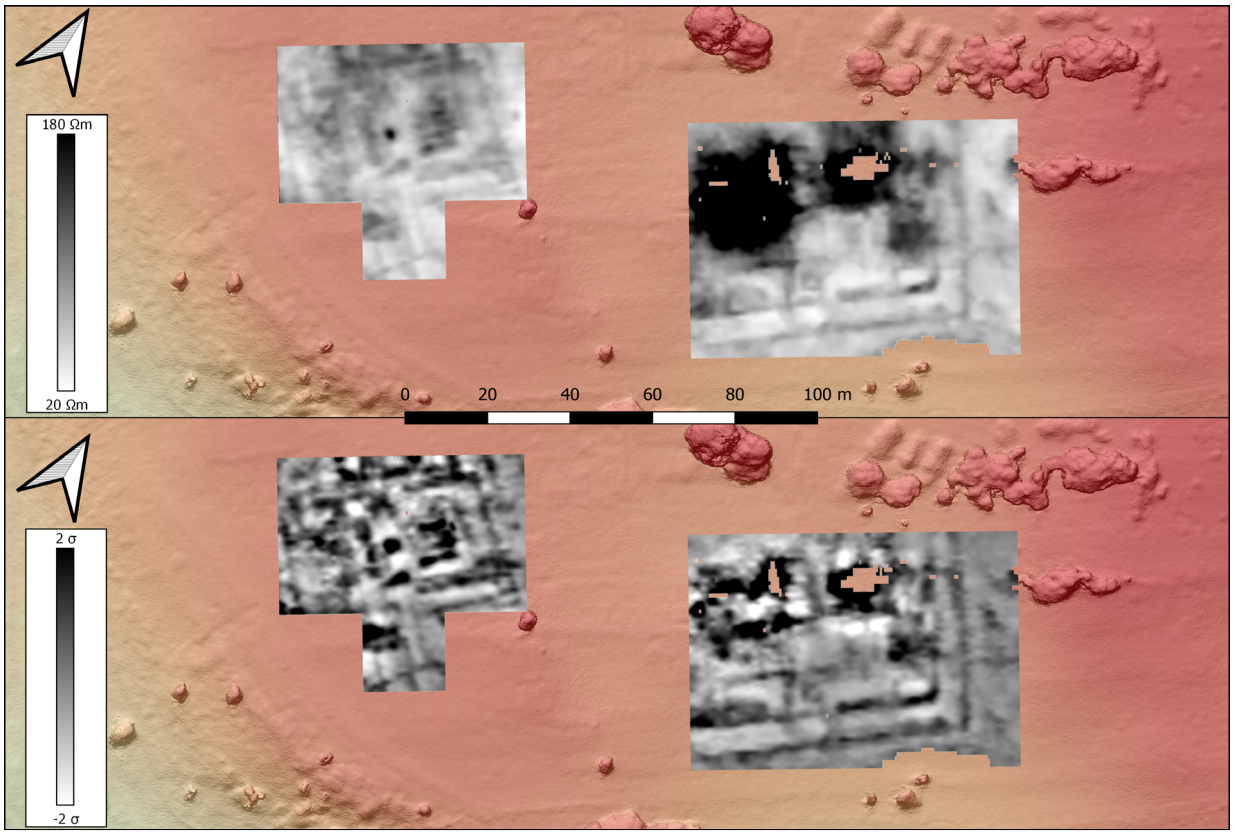

Fig. 2: The results of the 2021 ER survey. Resistivity map at AM=0.5 m (above), and high pass filtered AM=1.0 m (below).

Discussion

The previous geophysical survey results proved magnetics to be very effective in the geological conditions of *Porolissum*. Excellent contrasts triggered by strongly magnetic linear features (i.e. walls built of andesites and dacites) resulted in clearly pronounced structures. On the other hand, magnetic maps looked blurred at spots where building material was scattered above archaeological structures.

The same distortion burdens the shallower and lower-resolution prospection with ER. Scattered highly resistive material prevented us to capture some anomalies of linear structures lying under the rubble in the very low resistive subsoil (Fig. 2).

The latter property of the soil tends to be an obstacle for the GPR survey. Nonetheless, we argue that the GPR survey presented even better effectiveness and satisfyingly complemented magnetic survey results. It was less affected by scattered rubble and clearly depicted preserved structure foundations, providing a such level of detail as preserved *hypocausta* (Fig. 3). This allowed us to improve the existing interpretation and attribute particular functions to structures.

The considerable depth and good state of preservation of buried features, along with a fortunate geological setting of the site, may suggest the magnetic method be applied exclusively in such conditions. However, complementary methods, apparently the GPR being the best choice, should be considered to improve the archaeological interpretation.

Conclusion

A few conclusions might be drawn based on the results of this study.

1. Resurveying the area of the previous apparently unambiguous magnetic survey, with complementary geophysical methods, was very effective in providing additional information about archaeological features and structures.

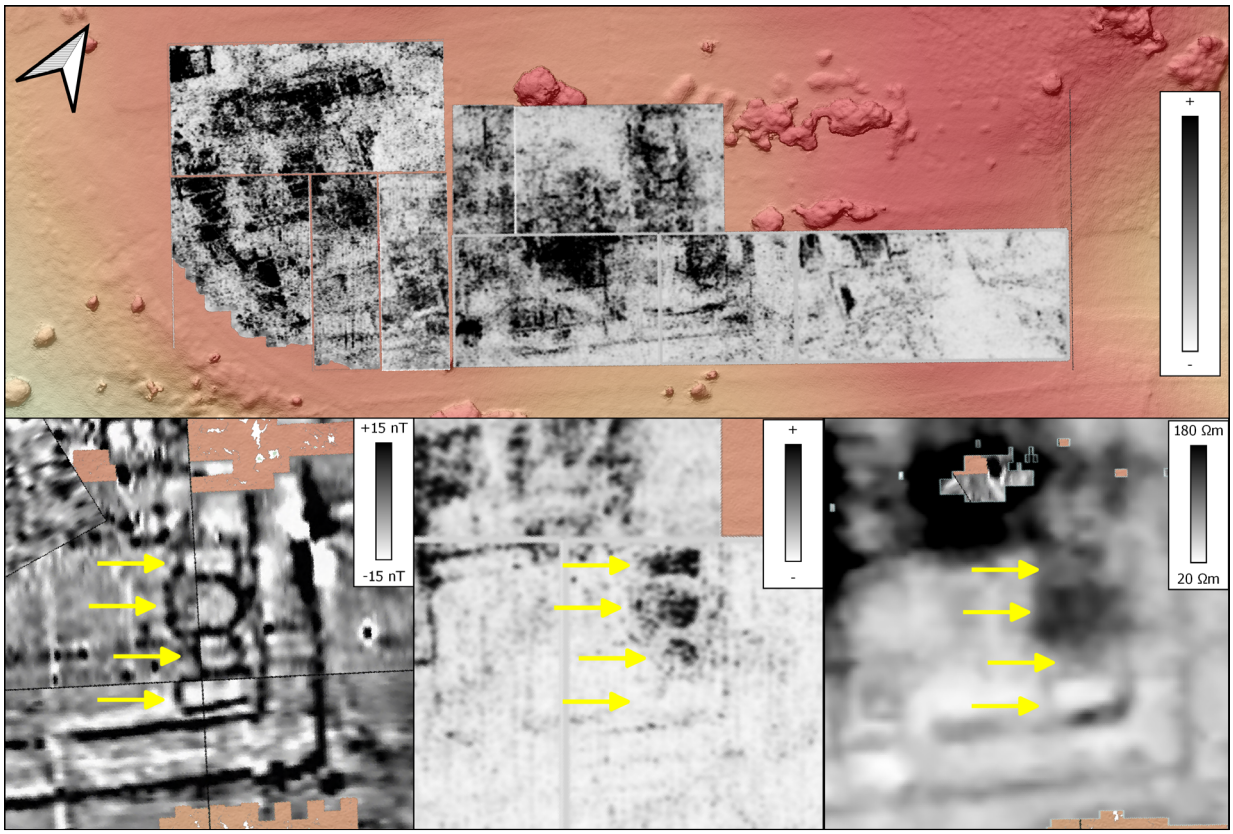

Fig. 3: The results of the 2021 GPR survey (above) and the baths as seen in the magnetic (below left), GPR (below centre) and ER (below right) imaging.

2. Even if applied in theoretically unfavourable conditions, complementary geophysical measurements allowed us to improve the archaeological interpretation, e.g. attribute functions to particular archaeological structures.
3. The analysis of the geological map and Magnetic Susceptibility values of the soil and rocks used on site as a construction material, helped to enhance the interpretation of the existing magnetic survey results and to explain the phenomena recorded in this data. Strongly magnetic rocks, besides feature-related anomalies, produce considerable noise.
4. Strongly magnetic archaeological features may deliver clear results, however, in certain situations, they may also distort the overall image of surveyed features and lead to interpretive pitfalls. Properties of soils and rocks should be tested and taken into account at the stage of analysis and interpretation of archaeo-geophysical data.
5. Based on the results presented in this paper we plan to carry out a further GPR survey with a multi-channel array.

Acknowledgments

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Combining teaching and research: a BIP on geophysical and archaeological prospection of North Frisian medieval settlement patterns

Wolfgang Rabbel [1*], Sarah Bäumler [1], Fabian Benedict [4], Andrea Bielikova [6], Sara Dannemann [1], Philippe De Smedt [2,3], Pablo De Weerdt [2], Dominika Godova [6], Hanna Hadler [5], Martina Hulmanova [4], Doris Jetzinger [4], Ingrid Kowatschek [4], Valentina Laaha [4], Gaston Mendoza Veirana [2], Bente Sven Majchczack [1], Lenka Ondrasova [6], Marieke Paepen [2], Artur Papp [4], Roman Pasteka [6], Gerhard Pichler [4], Antonia Reiß [5], Klara Sauter [4], Isabel Seilern-Moy [4], Julia Straßberger [4], Martin Thorwart [1], Susanne Tötzel [4], Immo Trinks [4], Basiel Van Rillaer [3], Jeroen Verhegge [2,3], Andreas Vött [5], Dennis Wilken [1], Timo Willershäuser [5], Tina Wunderlich [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Department of Environment, Ghent University, Ghent, Belgium
3 Department of Archaeology, Ghent University, Ghent, Belgium
4 Vienna Institute for Archaeological Science, University of Vienna, Vienna, Austria
5 Institute of Geography, Johannes Gutenberg-University, Mainz, Germany
6 Department of Engineering Geology, Hydrogeology and Applied Geophysics, Comenius University, Bratislava, Slovakia
* Corresponding author: E-mail: wolfgang.rabbel@ifg.uni-kiel.de

Abstract
We performed a research-oriented EU Erasmus+ Blended Intensive Program (BIP) with participants from four countries focused on North Frisian terp settlements from Roman Iron Age and medieval times. We show that the complex terp structure and environment can be efficiently prospected using combined magnetic and EMI mapping, and seismic and geoelectric profiling and drilling. We found evidence of multiple terp phases and a harbor at the Roman Iron Age terp of Tofting. In contrast, the medieval terp of Stolthusen is more simply constructed, probably uni-phase. The BIP proved to be a suitable tool for high-level hands-on education adding value to the research conducted in on-going projects.

Keywords
archaeological prospection; education; integrated geophysical interpretation; wetlands

Introduction

A Blended Intensive Program (BIP) is an international university teaching format promoted by the European Union ERASMUS + program. It has been created to foster the international connectivity of students and teachers and to stimulate inventing and practicing ways of hybrid teaching and learning. We tested the BIP format as a tool for combining geophysical and geoarchaeological teaching and research. Through a cooperation of the universities of Bratislava, Ghent, Kiel, Mainz and Vienna we realized a BIP in the form of a hands-on field and online course. The thematic focus was set on the geoarchaeological prospection of North Frisian medieval settlement patterns using geophysical methods and downhole sediment sampling. Scientifically, the course was embedded into major on-going research projects.

The investigated sites are located in a clay and peat district colonized in several waves that transformed the natural landscape. Settlers of the Roman Iron Age and the Early Middle Ages favored elevated river embankments and formed large village terps. Terps are artificial dwell-

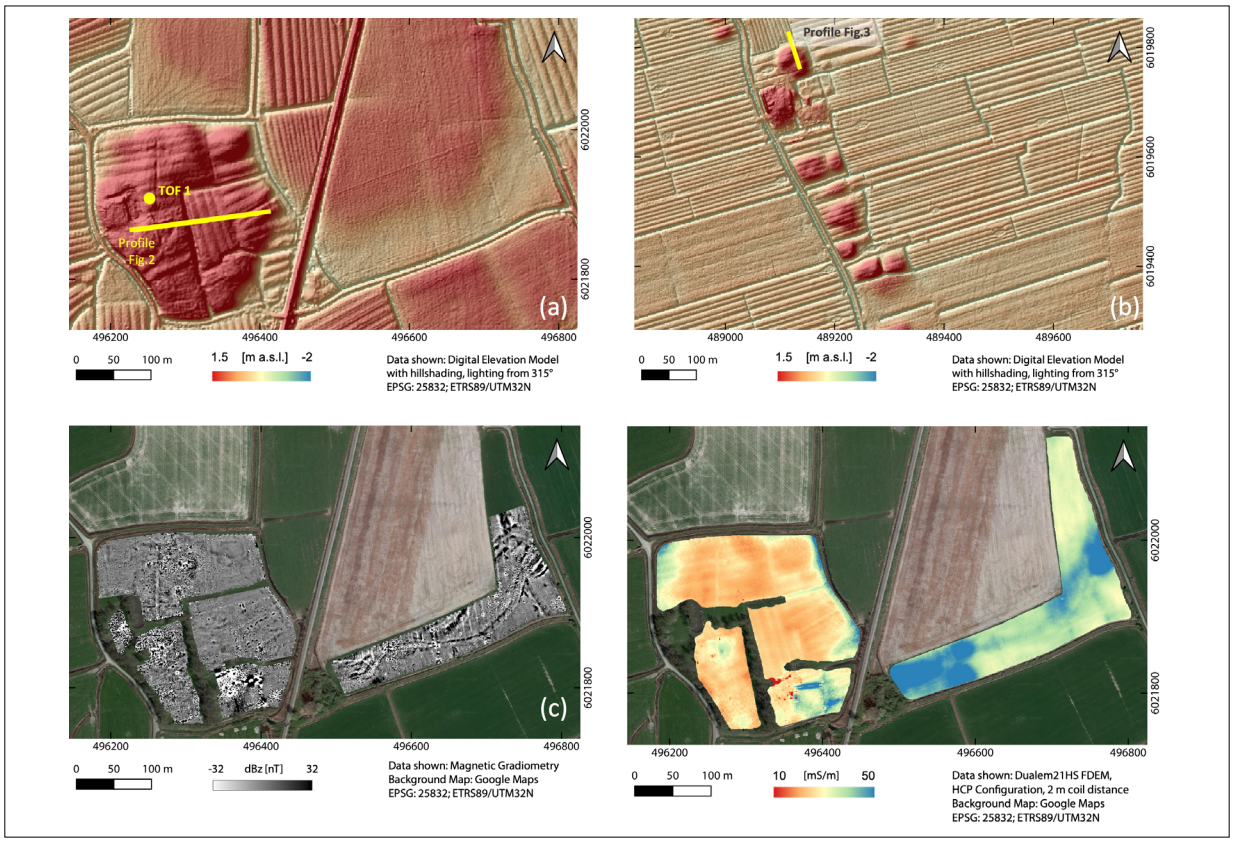

Fig. 1: General setting of the investigated terps: a) Lidar microtopography scan at Tofting, the yellow line and dot show the location of the profile and drill hole (TOF 1) in Figure 2, b) LiDAR microtopography scan at Stolthusen, the yellow line shows the location of the profile in Figure 3, c) magnetic map of Tofting (vertical component gradiometer), d) EMI conductivity map of Tofting (HCP 2m coil spacing). Both Lidar scans: ©GeoBasis-DE/LVermGeo SH/CC BY 4.0, Datengrundlage: DGM1. Background maps: ©2023 Google, Pictures ©GeoBasis-DE/BKG, GeoContent, Maxar Technologies, Map data ©GeoBasis-DE/BKG (©2009).

ing mounds to protect settlements from storm surges. In the High Medieval Period, new settlers reclaimed the large peat bog areas. Starting from straight chains of small farm terps, they transformed the landscape significantly (Bantelmann 1975; Bazelmans et al. 2012). During the course, we investigated an early village terp founded in the 1st century BC and a medieval chain of small terps from the 12th/13th century AD with respect to their environmental setting, internal construction, especially multiple phases, and to their archaeological remains.

Educational goals and set-up of the BIP

The educational goals of the BIP were the following:

- bring relevance to teaching contents through conducting field research on targets that had been the subject of little or no previous investigation,
- practice context-related teaching through refreshing students' methodical knowledge on-site, using instruments under field conditions, demonstrating pros and cons of field methods and practicing targeted integrative data interpretation,
- produce relevant scientific output presentable to the scientific public.

The course was set up in the following way:

- The field part was scheduled for one week, while the obligatory online part was held in the semester after the field course. It comprised eight combined lectures and practical work of three hours each, covering data interpretation and preparing the presentation of results.
- Working groups of four to five persons each with participants from each country were formed for field and online work. The number of participants was restricted to 20 persons.

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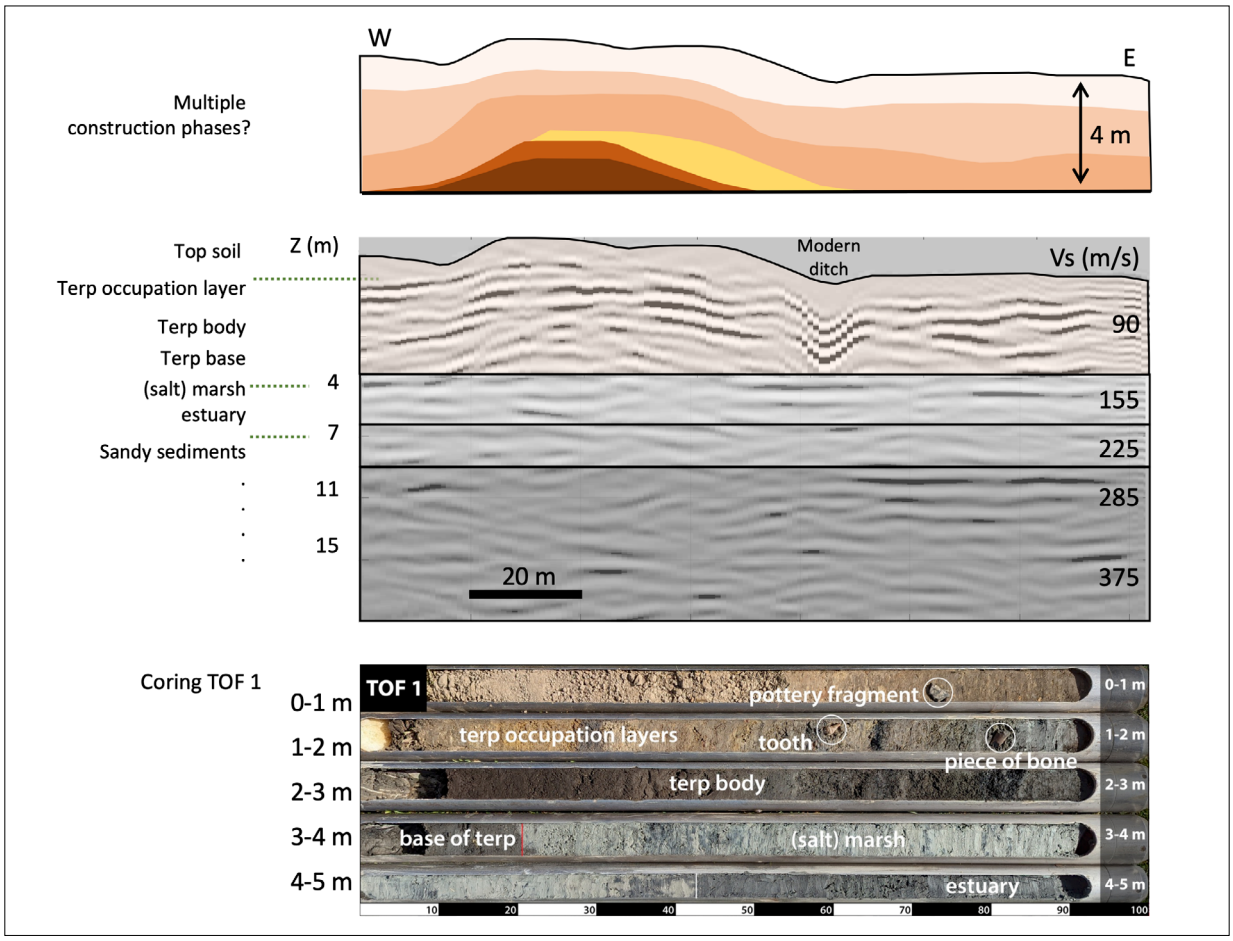

Fig. 2: Seismic and geological depth structure of the Tofting terp along the profile in Figure 1a (yellow line). Middle: Average shear wave velocity-depth function (grey layers, Vs indicated) overlain by seismic reflection image (migrated CMP-stack). Vs-depth function determined from refracted waves using the slowness-intercept time method. Bottom: Nearby drill core; the interpretation on the left of the seismic profile is based on this core. Top: tentative interpretation of the seismic reflections of the upper 4 m showing possible construction stages of the terp.

- As a final goal we defined the creation of scientific posters showing the results of the course to be presented at the ICAP 2023 conference.

Field methods applied

For the field measurements the working groups provided magnetic fluxgate-gradiometer arrays (six probes on a cart, 0.5 m crossline and 0.65 m gradient distance), electromagnetic induction (EMI) devices, multi-electrode geoelectric unit, ground penetrating radar (GPR), 72-channel seismograph with horizontal crossline-oriented geophones, drilling equipment for sampling and geophysical down-hole measurements. Differential GNSS was applied for positioning.

For investigating archaeological remains we applied magnetic, EMI and GPR mappings. Positions of the invasive geoarchaeological investigations were chosen based on geophysical measurement results. For ground truthing we applied drillings and direct-push electric conductivity measurements.

Results

General setting of the terps of Tofting and Stolthusen

LiDAR scans of the microtopography (Fig. 1) reveal that the investigated terps differ in size and structure: Tofting (Fig. 1a) is originally a cluster of smaller terps that were merged to a large village terp over time. In its final exten-

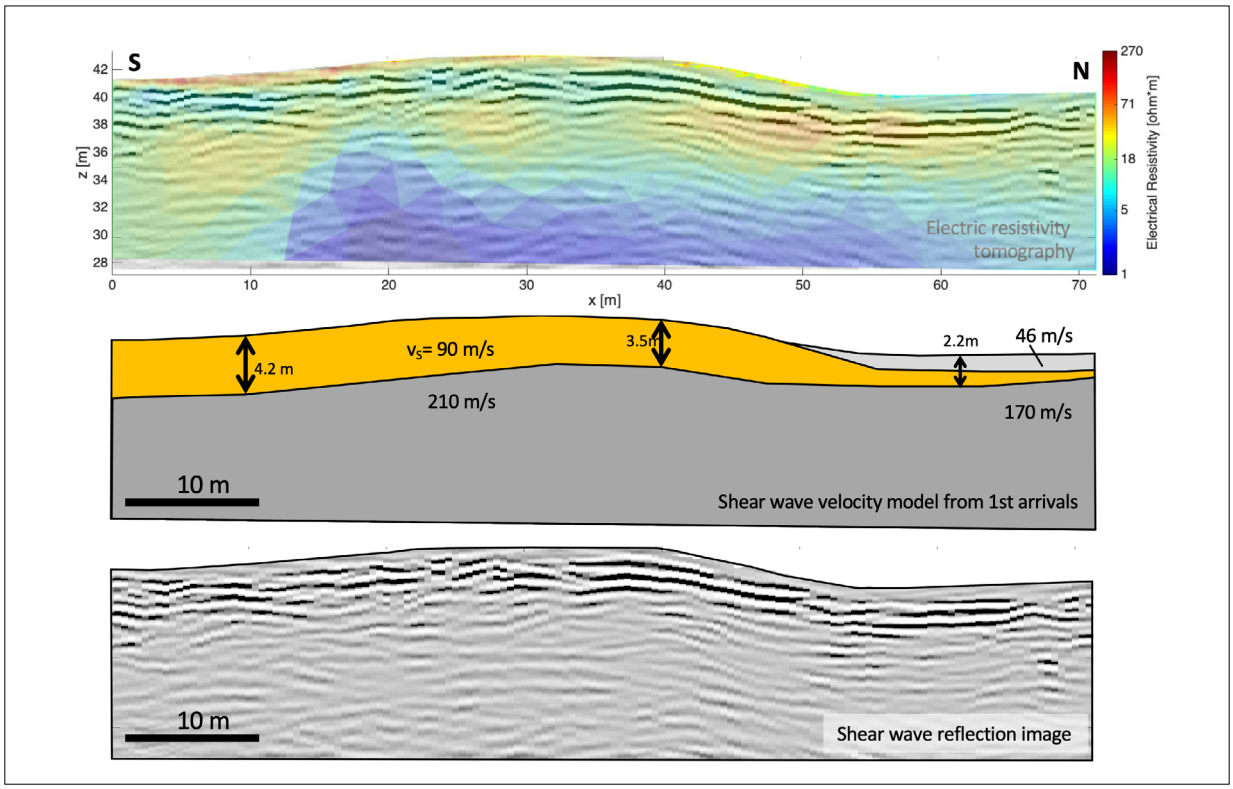

Fig. 3: Seismic and geoelectric depth structure of the Stolting terp. The data was acquired along the profile in Figure 1b (yellow line). Bottom: Seismic reflection image (migrated CMP-stack). Middle: Shear wave velocity structure from first arrivals using the slowness-intercept time method. Top: Electric resistivity tomography (ERT, Wenner-ß-configuration inverted using Res2dinv software) overlaying seismic reflection image.

sion the Tofting terp is four times as large in diameter as the single terps of Stolthusen aligned along a traffic route (Fig. 1b). The Tofting site is covered with clusters of small-scale magnetic anomalies (Fig. 1c) originating from modern building debris mainly. The electric conductivity map (Fig. 1d) shows some lows (brownish areas), which coincide with microtopographic highs and may indicate the initial terps. East of the terp, the magnetic map (Fig. 1c) shows two WSW-ENE directed, curvilinear anomalies, which correspond to a high in electric conductivity (blue in Fig. 1d). These could indicate a silted riverbed or channel leading to a small harbor at the SE tip of the terp.

Depth structure of the Tofting terp

The Tofting terp was investigated with shear-wave profiling, EMI, GPR, ERT and drilling. The stratigraphy shows up best in the W-E directed seismic depth section (Fig. 2 and 1a, yellow line). It consists of four units identifiable in terms of shear wave velocity (Vs) and in a core drilled near the seismic profile (Fig. 2 middle and bottom): The terp body (Vs ~ 90 m/s) is a 3-4 m thick layer of clay-ey sediments enriched in organic construction material (dung, sods) and archaeological findings (sherds, bones). It was erected on the original salt marsh consisting of fine-grained sediments (Vs ~ 155 m/s). Underneath follow coarser-grained, silty to sandy laminated layers (Vs = 225-375 m/s).

The corresponding seismic reflection section, overlain on the velocity diagram (Fig. 2 middle) shows that the terp body (upper 3-4 m) has an internally variable stratification. We interpret it as evidence of different construction phases and materials (Fig. 2 top). The dark brown layer at the bottom may represent an initial stage, next expanded into the yellow layer, then to the middle-brown layer etc.

Geophysics and coring agree well with archaeological excavations from 1949–1952. These found stratified settlement terps with multiple house phases, thick layers of dung and settlement debris and applied clay layers. The top meter is made up of applied clay layers, which merge the initial terps to one large terp body and may date to the early medieval to early modern periods (Bantelmann, 1955).

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Depth structure of the Stolthusen terp

The uppermost layer of the Stolthusen terp is also 3-4 m thick and shows an average shear wave velocity of 90 m/s (Fig. 3 middle). A nearby drilling clarified that it is composed of the actual terp body underlain by peat and the original salt marsh. This sequence is underlain by a sandy layer (Vs = 210 m/s), which gets more fine-grained only outside the terp (Vs = 170 m/s). The seismic reflection image (bottom) shows the layering of the heterogeneous construction material and the peat and marsh units underneath. In Stolthusen this layering is laterally more continuous than in Tofting. Different construction phases are not obvious. This may be due to the shorter lifetime of the Stolthusen terps compared to Tofting.

The electric resistivity tomogram overlain on the seismic reflection section (Fig. 3 top) shows that seismics and geoelectrics agree well in stratigraphy and structural detail. At ~5 m depth the electric resistivity anomalies can be associated with lateral changes in grains size that are visible in the reflection image, too, but are not resolved in the seismic velocity model.

Discussion

Through combining personnel and equipment of five universities we could familiarize the students with a wide variety of state-of-the-art instrumentation. The concept of a BIP field course in the frame of on-going research projects proved to be justified, first, because the participants confirmed that it increased the motivation and demonstrated the relevance of the undertaken steps, and second, because the scientific results considerably contributed to the projects. However, it must be noted that five days duration of the field course was too short given the complexity of the investigated targets leaving too much of the discussion to the online part of the BIP, which is difficult to transmit even with modern communication technology. Still, we feel it confirmed that the general course layout was successful in educational and scientific terms, even though details would have to be improved for follow-up runs.

Conclusion

The investigations have shown that the terps' structure and environment can be efficiently prospected using a combination of magnetic and EMI mapping complemented by seismic and geoelectric profiling and drilling. GPR turned out to be of only little depth penetration due to the high conductivity of terp and marsh soils. We found evidence of multiple terp phases and a harbor at the Roman Iron Age terp of Tofting. The medieval terp of Stolthusen has a rather simple uni-phase construction.

Acknowledgments

We gratefully acknowledge support of the BIP course through the European Union Erasmus + Program, the ROOTS Cluster of Excellence (EXC 2150 390870439), the RUNGHOLT project (German Research Foundation grant HA 7647/3-1). We thank Ghent University for supporting the PROSPECT International Thematic Network (www.prospect.ugent.be), which enabled developing this BIP, and the AXIO-NET PED-Service for providing free SAPOS GNSS correction data.

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Archaeology at the Danube using non-invasive ground and aerial prospection methods to document prehistoric settlement traces at the Bisamberg near Vienna, Austria

Franziska Reiner[1*], Jakob Gallistl[2], Roderick B. Salisbury[1], Katharina Rebay-Salisbury[1], Ingrid Schlögel[2]

1 Austrian Archaeological Institute (ÖAI) of the Austrian Academy of Sciences (ÖAW), Vienna, Austria
2 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
* Corresponding author: E-mail: franziska.reiner@oeaw.ac.at

Abstract
To link prehistoric settlement activities with a modern mapping of existing monuments on the site, non-invasive aerial and terrestrial prospection methods are used. The LiDAR data catches the course of the presumed prehistoric rampart. The geomagnetic measurements display, among other things, the course of a 250 m long prehistoric ditch. Furthermore, ERT measurements reveal the rampart's inner construction.

Keywords
archaeological prospection; Bisamberg; LiDAR; prehistoric settlement traces

Introduction

The Bisamberg is an approximately 358 m high rise north of Vienna (Austria), with the southernmost foothills reaching into Vienna's 21st district. Together with the Leopoldsberg flanking the Danube across the river, the two hills form the Vienna Gate. Geologically, the Bisamberg is the north-easternmost extension of the Central Alps and is a continuation of the Flysch zone of the Wienerwald. Traces of settlements around and on the Bisamberg date from the Mesolithic around 8000 BC (Kmoch 1966; Neugebauer-Maresch 1993) to the Modern Era. Matthäus Much described a 3-4 m high prehistoric rampart enclosing the Elisabethhöhe, the highest plateau of the Bisamberg, as early as 1874. Prehistoric finds from the settlement were assigned to the Middle Bronze Age in the 1980s (Much 1874; Kaus 1986).

Objective of the study

In the course of the project "Archaeology at the Danube - Pilot Study Bisamberg" conducted by the Austrian Archaeological Institute (ÖAI) of the Austrian Academy of Sciences (ÖAW), a survey of the archaeological monuments on the Bisamberg was carried out using modern non-invasive aerial and terrestrial prospection methods (Fig. 1). Magnetometry yielded information about the current state of the archaeological monuments and prehistoric settlement activities. Electrical Resistivity Tomography (ERT) was used to gain insights into the structure of the rampart, which is still visible in the terrain. In addition, high-resolution LiDAR terrain surveys were carried out in order to better show the course of the rampart.

Topographical situation and challenges

Most of the survey area is designated for landscape conservation and serves mainly as a recreational area. The meadow south of the prehistoric enclosure is dominated by a south-facing slope and is used for agriculture. The steep slope made geomagnetic measurements difficult, which is why only the northern part of the area was measured so far. The conditions for geoelectric investigations

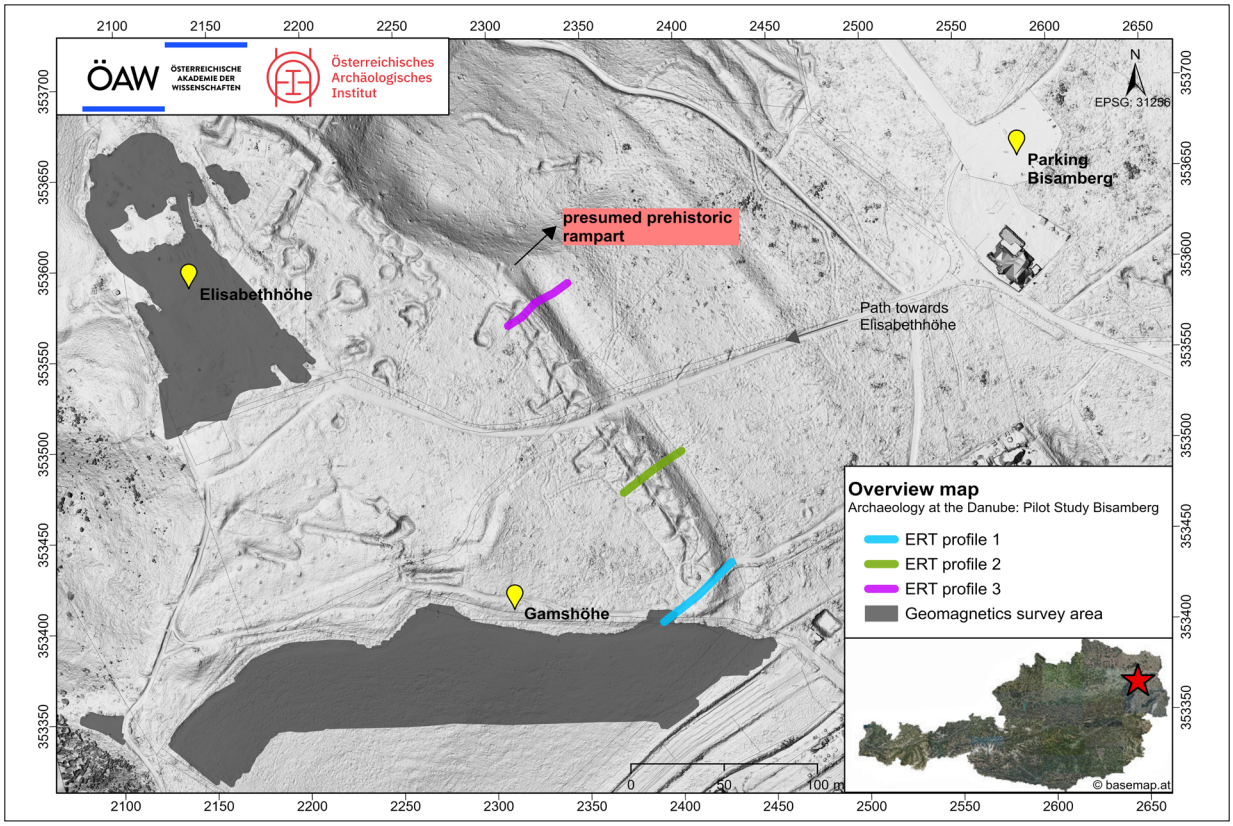

Fig. 1: Overview map of the geomagnetic survey area and the geoelectric profiles with background terrain model (copter-supported, vegetation-cleaned LiDAR data © ÖAW/ÖAI, Ch. Kurtze) (© ÖAW-ÖAI/F. Reiner).

also proved to be difficult, as the recurring remains of the (presumed prehistoric) rampart serve as a mountain bike trail and thus suffer recent deformations and modifications of the terrain relief. The area where the rampart is located carries dense vegetation in spring/summer, which is why the geoelectrical measurements as well as the LiDAR flights were mainly carried out before the growth season.

Survey methods

The geomagnetic measurements were carried out with a 5-channel fluxgate gradiometer system Magneto MXPDA from Sensys (survey width 1.0 - 2.0 m, sensor spacing 0.25 - 0.5 m, sampling rate 100 Hz). Total area surveyed was approx. 1 ha around the Elisabethhöhe and 1.6 ha south of the Gamshöhe. Due to the direct integration of an RTK-DGPS, georeferenced measurements of the survey area could be carried out. The data were georeferenced, managed and analyzed in ArcGIS Pro in form of digital greyscale images (-5/+5 nT).

Geoelectric measurements were conducted in cooperation with Cornelius Meyer Prospection (CMP) and the Central Institute for Meteorology and Geodynamics (ZAMG). A total of three profiles à 50 and 40 m length with an electrode spacing of 0.5 m could be laid out in order to gain information about the internal structure of the rampart (Fig. 1). A 4PLight multi-electrode resistivity meter from Lippmann Geophysical Measuring Instruments (LGM) was used for Profile 1 and the ABEM Terrameter LS2 multi-channel device for Profiles 2 + 3. The processing of the ERT data (Profiles 2 + 3) consisted of the removal of measurements with negative transfer resistances and those associated with contact resistances larger than 15 kOhm and was performed with python packages developed at the ZAMG. The inversions were performed with the open source software ResIPy using a smoothness-constraint regularization. All inversions converged to a RMS misfit of approximately 1. The result of the measurements is shown as a vertical section, which depicts a lithological and structural model of the subsurface down to depths of about 6 m below ground level by classifying the resistivity distribution.

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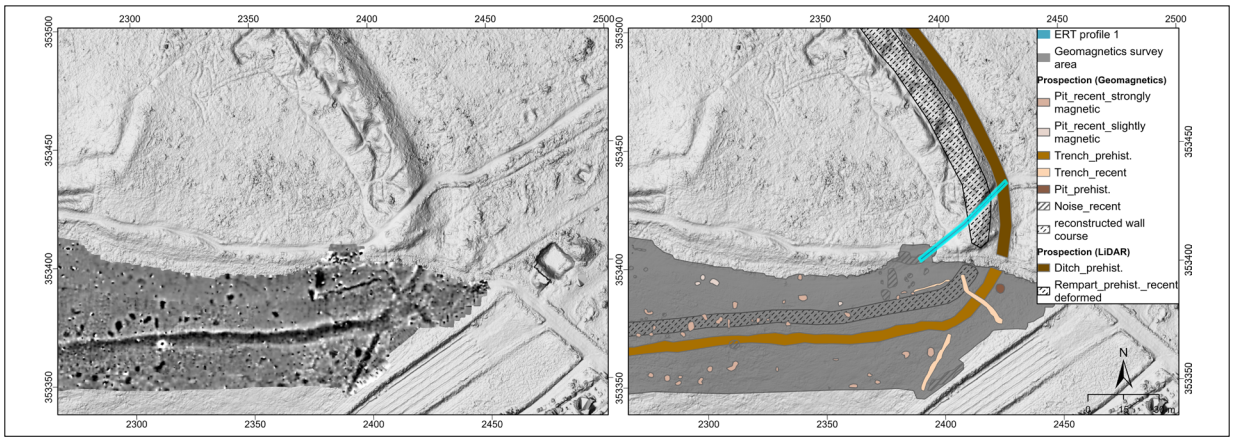

Fig. 2: Result of the magnetic measurements on the Gamshöhe (left) and archaeological interpretation (right) with background terrain model (© ÖAW-ÖAI/F. Reiner).

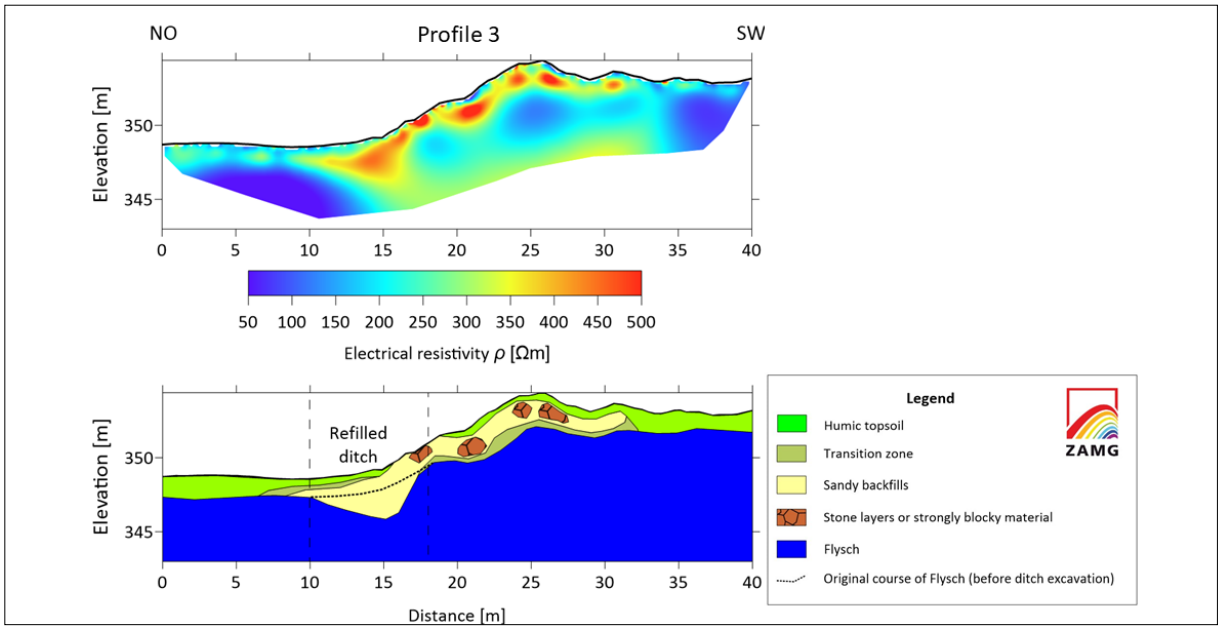

Fig. 3: Result of the 2D geoelectric inversion (top) and lithological and archaeological interpretation of the resistivity model (bottom) for Profile 3 north of the path towards Elisabethhöhe (© ZAMG/J. Gallistl).

The system used for the aerial survey consisted of the miniVUX-SYS mounted on the DJI Matrice 600 Pro, using the miniVUX-2UAV laser scanner and the APX-20 UAV IMU/GNNS.

Results of the survey

The course of a large ditch structure of about 250 m on the Gamshöhe was revealed by means of geomagnetics (Fig. 2). The greyscale image shows a massive ditch coming from the northeast and bending towards the west after about 30 m. The bend is only weakly visible and the ditch filling is slightly magnetic and inhomogeneous in the first 30 m. It is also interrupted after about 15 m by another small ditch. The ditch can be interpreted as possibly prehistoric due to its width of approx. 6 m and the irregular ditch edges. The further course of the ditch to the north can be traced in the LiDAR data for about 230 m. The prehistoric rampart is also clearly recognisable in the LiDAR data in the north-east. It can be assumed that the rampart in the meadow area is no longer present due to the slope and

the advanced erosion over time. However, the course of the rampart can be reconstructed on the basis of the ditch identified in the magnetometry survey in this area (Fig. 2).

In all three ERT profiles, areas with low resistivity values up to 100 Ωm can be associated with fissured sandstone and mudstone layers from the Flysch zone (Figure 3 presents an example of the results of the inversion and the interpretation of profile 3). The transition from Flysch to the areas of increased electrical resistivity is marked by a moderately electrically conductive zone. The areas with relatively high resistivities (> 200 Ωm) can presumably correspond to sandy backfills or fills of the presumed rampart. Within the wall zones with even higher resistivity values of more than 300 Ωm could be identified. These zones can be interpreted as stone layers or block material of the rampart construction. The stone layers are approx. 1 m thick and at a depth of 0.5 m below ground level.

Conclusion

The course of the rampart in the northeast could be perfectly shown in the LiDAR data. It is likely that the rampart continues southwards due to the clear ditch anomaly in the magnetics. The geoelectric results indicate that the rampart has massive stone constructions in its core, which suggests that it could indeed be of prehistoric date. An excavation cutting an accessible part of the rampart is planned to investigate the stratigraphy, explore potential phases of use and obtain datable material from the construction. The location of the actual settlement center is still unclear, which is why additional geophysical measurements are intended. Initial geomagnetic measurements on Elisabethhöhe revealed massive modifications of the plateau during the last wars, including trenches, military installations, and recent artefacts.

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Investigating the sedimentary fillings of Megalos Peristeres Cave, Rethymno, Crete, through GPR techniques

Apostolos Sarris [1*], **Thomas Strasser** [2*]

1 Department of History and Archaeology, Archaeological Research Unit, Digital Humanities GeoInformatics Lab, Sylvia Ioannou Chair on Digital Humanities, University of Cyprus, Cyprus
2 Department of Art and Art History, Providence College, Providence, United States of America
* Corresponding authors: E-mail: asarri01@ucy.ac.cy; tstrasse@providence.edu

Abstract
The study constitutes the first internal subsurface mapping of a cave environment in Crete. Mapping of the sedimentary deposits of Megalos Peristeres cave indicated the sequence of the fillings within the different chambers of the cave. Suggestions for the existence of anthropogenic residues have been made through the combined study of radargrams and depth slices.

Keywords
archaeological prospection; Crete; GPR; Megalos Peristeres cave; Rethymno; radargrams

Introduction

The mountainous terrain of the island of Crete contains a number of caves of different sizes, many of which contain valuable remains of past anthropogenic activity even from the Palaeolithic period as it has been suggested most recently by the Asphendou Cave rock carvings (Strasser et al. 2018). Due to their abrupt geomorphological settings none of them has been mapped through geophysical techniques until now. The cave of Megalos Peristeres, along the rocky northern coastline of Rethymno offered a great opportunity for such investigations aiming towards the definition of preserving strata that could be correlated to past human habitation containing both fossils and stone tools. Such kind of investigations have never been carried out before in the Cretan landscape, while only a few have been conducted worldwide (Weinstein-Evron et al. 2003; Quarto et al. 2007; Zhou et al. 2009; Lowe and Wallis 2020).

Materials and methods

The geophysical prospection survey was carried out on July 2021 with the collaboration of the Ephorate of Palaeoanthropology and Speleology of the Greek Ministry of Culture and Sports (Eleni Stravopodi, Crysanthi Kontaxi and Vassilis Giannopoulos). The detailed mapping of the main two chambers of the cave was accomplished through a Sensors&Software NOGGIN PLUS GPR unit carrying a 250 MHz antenna with a high resolution sampling (5 cm along parallel GPR transects 50 cm apart). The choice of the antenna was determined by the fact that the purpose of the survey was two-fold, namely to map the medium depth bedrock and to map the stratification of the sediment infill. Three grids (G1, G2 and G3) having a total area of about 283 square meters were covered (Fig. 1).

Results and discussion

Processing of the GPR data was carried out following the pipeline described by Sarris (2020). The transects that derived from GPR were processed using GFP Edit4 and EKKO Project 2 by Sensors & Software. The processes that were applied aimed to remove noise from the data and to enhance the signal's information that will lead to a better

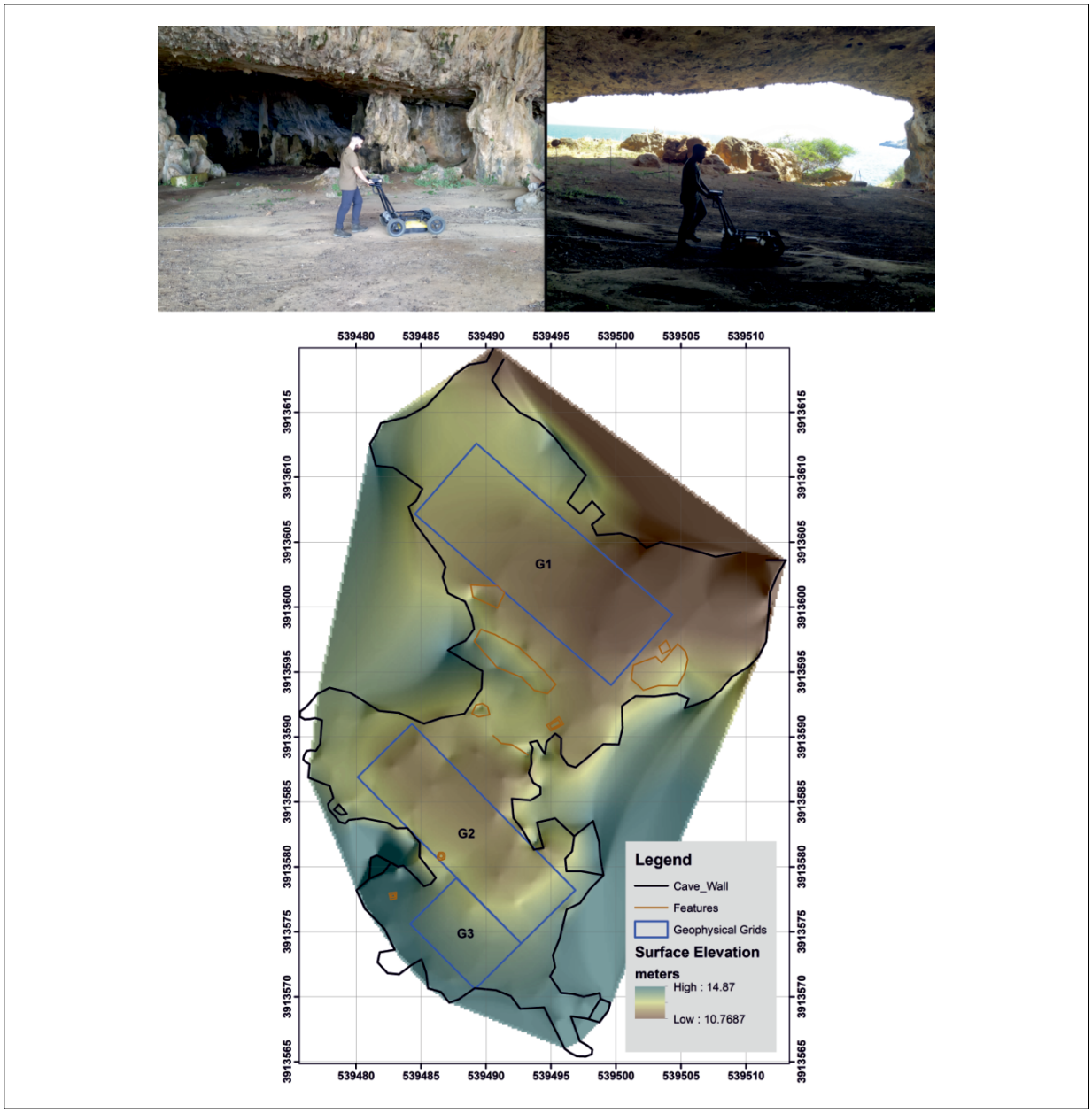

Fig. 1: Top: Details of the GPR surveying within the Megalos Peristeres cave. Bottom: Layout of the geophysical grids. G1 is located to the entrance of the cave, whereas G2 and G3 are located towards the interior chamber of it.

representation of the subsoil. Processing was divided into two stages: the first dealt with the application of correction and enhancement filters separately on every survey line, while the second stage involved the extraction of slices in accordance to depth and the creation of a subsurface 3D model.

The presentation of the data was made through 1) Radargrams (B-Scans), representing the reflectors along each transect, 2) Depth slices (C-scans), representing the amplitude of the reflectors with increasing depth from the surface and 3) in the case of Grids 2 and 3, 3D volumetric representations of the reflectors. The most important information resulting from the B-scans is related to the different stratigraphic layers and the deposits within the cave. The most representative depth slices and radargrams were rectified and fused in a GIS environment (ArcGIS).

In Grid 1, located close to the entrance and the north section of the cave, an upper layer has been recognized

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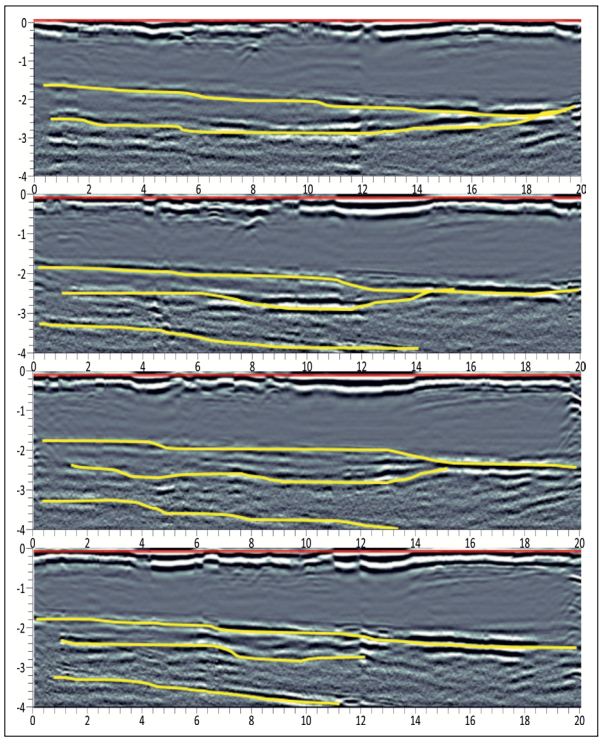

Fig. 2: Indicative radargrams showing the different subsurface strata from Grid 1. The yellow lines were drawn manually to indicate the direction of the underground strata.

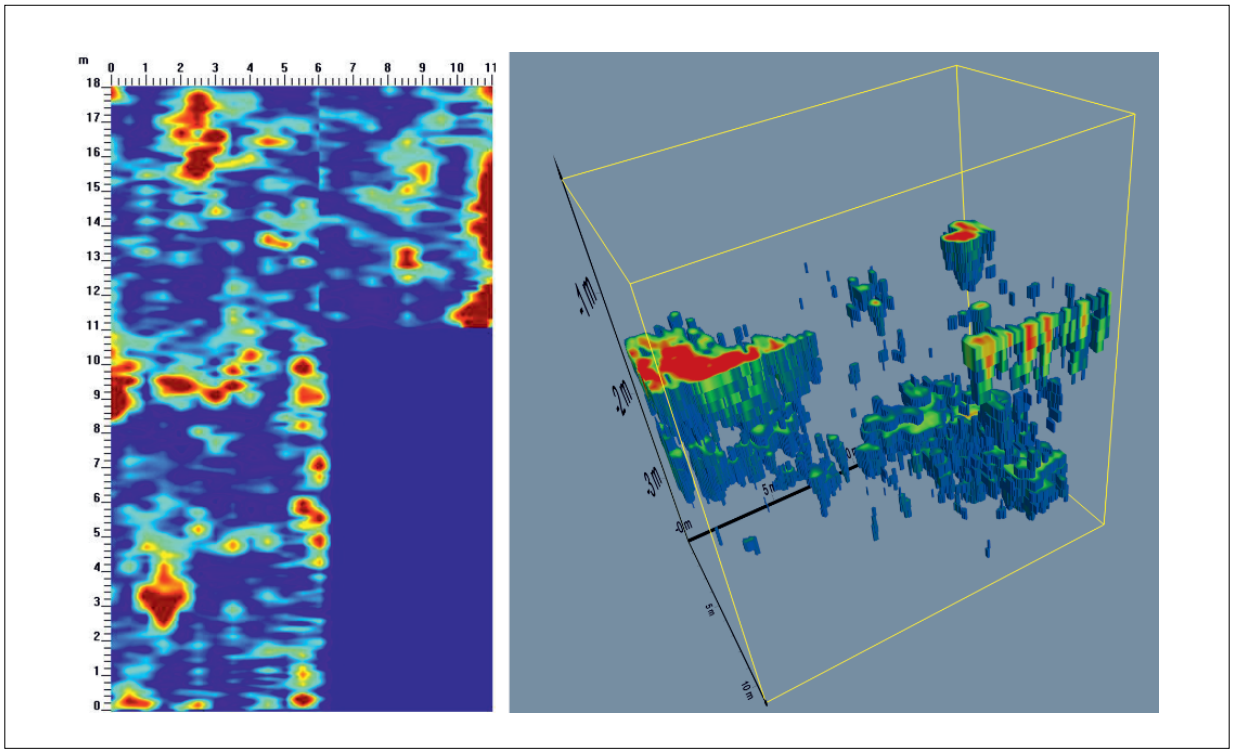

Fig. 3: Left: Depth slice of 90-100 cm from Grids 2 and 3, indicating some linear features that may correspond to past anthropogenic residues, most probably of the latest historical occupation of the cave. The most intensive reflectors may indicate the existence of stone foundations. Right: 3D surface render of the GPR signals from Grids 2 and 3. The 3D surface rendering was useful to indicate the differentiation of the underground strata below the different chambers.

having a small downward inclination from NW (~1.5-2 m below the surface) to SE (2-2.5 m below the surface) (Fig. 2). This layer is almost flat without any significant microtopographic variations. A second layer expands about 3.5-4 m below the surface, rising towards the NS and SE boundaries of Grid 1, reaching a depth of about 2.5-3 m below the surface. Both layers exhibit a rising trend towards the central section of the grid. The corresponding C-scans of Grid 1 indicated a cluster of strong reflectors (most probably related to rock outcrops) to appear at a depth of about 1.5 m from the NW section of the grid dropping down gradually to a depth of about 2.5-2.6 m toward the SE section of the grid (Depth slices of 150-160 cm to 260-270 cm). A large isolated reflector persists at the north central section of the grid.

The picture is changing as we move towards the interior chamber of the cave. The radargrams for Grids 2 and 3 indicate a well-shaped underground layer, that reaches a depth of about 2.5 m at the center of Grid 2. The layer starts at about 1 m below the surface towards the NW and goes up to a depth of about 1.8 m towards the SE. The particular layer starts dipping as we move to the south, reaching a depth of about 3 m towards the central SE part of Grid 2. The deep part of this layer continues towards the south in Grid 3 and then starts rising as we reach the south wall of the cave. This is also confirmed by the depth slices of 80-100 cm, which also indicate a few linear anomalies that may be related to anthropogenic structural remains (Fig. 3).

Conclusion

GPR measurements at the Megalos Peristeres cave managed to identify the sedimentary deposits of the cave that expand down to a depth of 4 m below the current surface of it. Within the entrance of the cave, recent deposits missing any significant features expand down to a depth of more than 1.5 m. Most of indications for anthropogenic residues are suggested towards the internal chambers of the cave. Future excavations are planned in 2024 to verify the results of the geophysical prospection.

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The contribution of geophysical and spectral imaging techniques in the archaeological investigations of Minoan Koumasa

Apostolos Sarris [1*], Kostas Hatzigiannakis [2], Diamantis Panagiotopoulos [3]

1 Department of History and Archaeology, Archaeological Research Unit, Digital Humanities GeoInformatics Lab, Sylvia Ioannou Chair on Digital Humanities, University of Cyprus, Cyprus
2 Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas (IESL-FORTH), Heraklion, Crete, Greece
3 Institute of Classical Archaeology, University of Heidelberg, Germany
* Corresponding author: E-mail: asarri01@ucy.ac.cy

Abstract
A manifold geophysical strategy has been carried out for mapping the Minoan cemetery and settlement of Koumasa, S. Crete. Multispectral imaging was used as a complementary method to investigate associations with the geophysical results. The GNVI proved the most effective in this task. Archaeological excavations have verified a number of features suggested by the remote sensing methods.

Keywords
Crete; geophysical prospection; GPR; magnetics; Minoan; spectral imaging

Introduction

Minoan Koumasa expands to the south region of the municipality of Herakleion, Crete and includes a major Pre- and Protopalatial cemetery consisting of three monumental tholos tombs, together with a Minoan sanctuary and settlement located on the hill of Korakies, which rises immediately to the south of the cemetery. The site has been initially excavated in the beginning of the 20th century and in 2012 fieldwork activities were resumed by the University of Heidelberg under the auspices of the Archaeological Society at Athens and in cooperation with the 23rd Ephorate of Prehistoric and Classical Antiquities. Excavation in the settlement so far revealed mostly Neopalatial structures, including a large building of particular significance. Available evidence nevertheless makes it clear that the Neopalatial buildings were erected upon older remains (Panagiotopoulos 2015).

Materials and methods

The magnetic gradiometry technique (Bartington G601 with 0.5 x 0.125 m sampling), the ground penetrating radar (GPR) (Sensors&Software NOGIN PLUS with 250 MHz antenna and 0.5 x 0.25 m sampling and the electrical resistance mapping (Geoscan Research RM85 with 0.5 x 0.5 m sampling) were all used in a complementary way for the prospection of a total area of 0.6 hectares around the cemetery, the sanctuary and the tholos tombs (Fig. 1).

Processing of the GPR data was carried out following the pipeline described by Sarris (2020). The transects derived from GPR were processed using GFP Edit4 and EKKO Project 2 by Sensors & Software. Processing of the magnetic and soil resistance data was carried out using the GPP software engine (Kalokerinos et al. 2004).

Based on the results of the geophysical mapping, an IRIS II custom made mobile Spectral Imaging Camera (350-1200 nm, 28 filters, 5 MPixels) was deployed in the context of the experimental monitoring of areas that could hinder shallow buried archaeological structures. In order

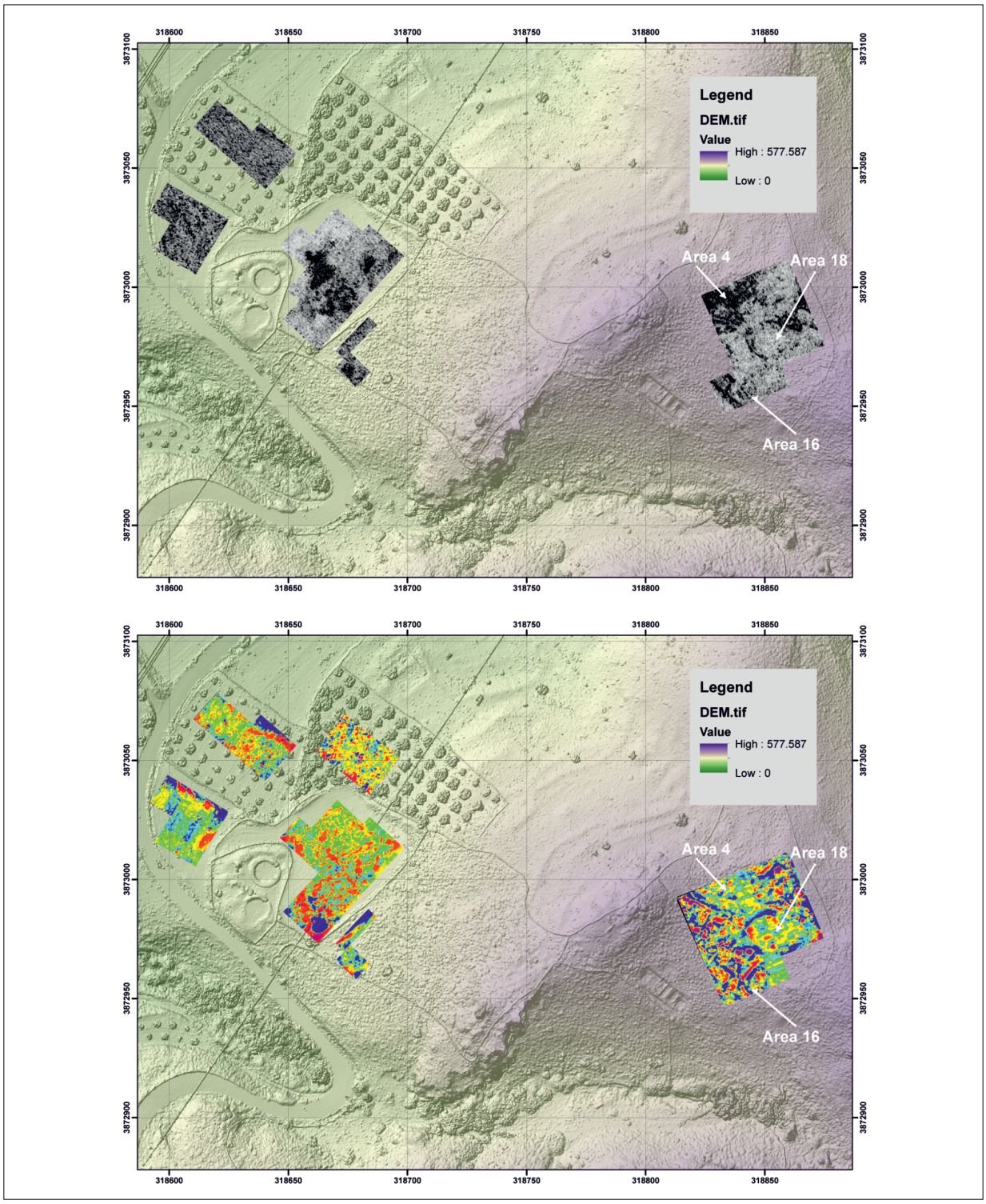

Fig. 1: Mosaics of the results of the GPR survey – depth slices for 0.8-1 m below the surface- (top) and geomagnetic survey (bottom) at the archaeological site of Koumasa. The dynamic range for the magnetic data is between -/+20 nT/m. The west section extends around the tholos tombs, whereas the east section is located on the top of the plateau where the Minoan sanctuary and settlement have been established. Areas 4, 16 and 18 represent the excavation sections in the area of the settlement. The DEM was created through a Terrestrial Laser Scanning carried out by the Institute of Geography of the University of Heidelberg. It covered an area of about 2x2 km and resulted to a raster resolution of about 0.2-0.5/1.0 m (onsite/offsite).

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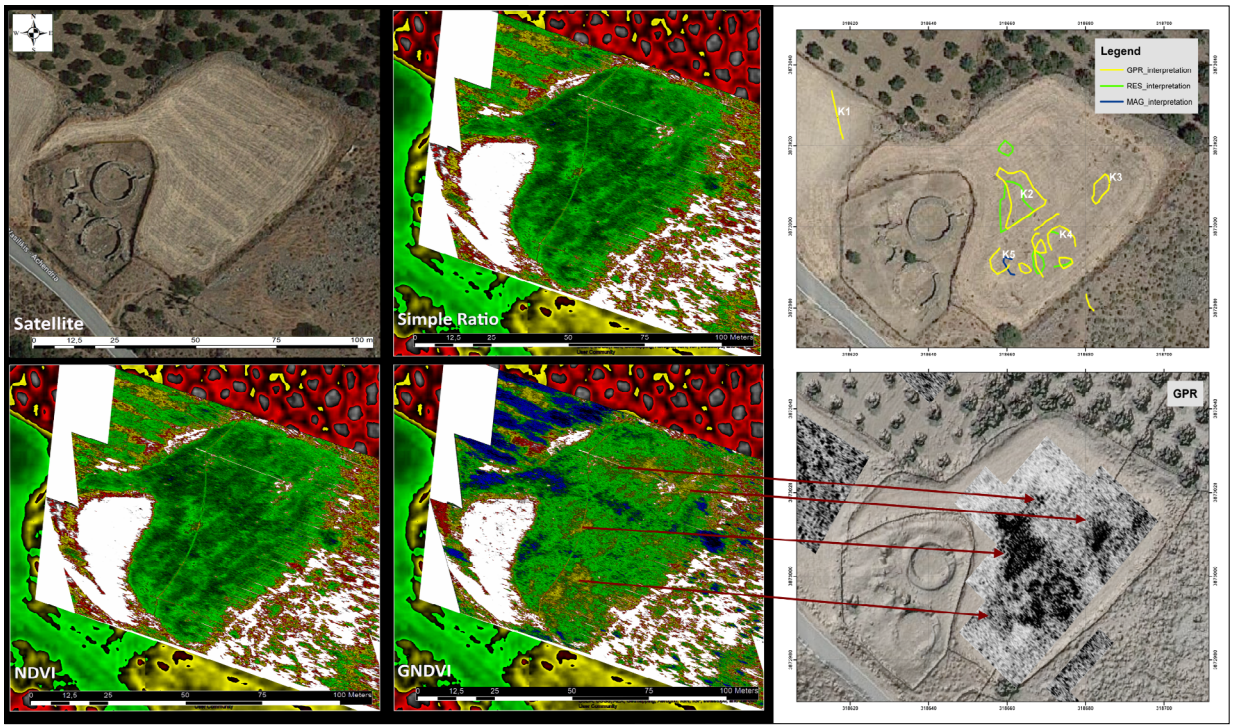

Fig. 2: Application of Imaging Spectroscopy for the detection of archeological remains at Koumasa. Top left: satellite imagery of the cemetery (Google, ©2023 CNES/Airbus, Maxar Technologies), top middle: Simple ratio, top right: results of the georadar survey, bottom left: NDVI, bottom middle: GNVI, bottom right: correlation between the GNVI and the results of the geophysical survey. The vegetation indices have a dynamic range between -/+1.

to certify the reliability of the measurements, laboratory controlled measurements on leaves of various plant species in different physical conditions, were carried out using a high spectral resolution UV-Vis-NIR spectrophotometer and a LMNT-II portable spot analysis LIBS and Diffuse Reflectance system (Avantes Avaspec-2048L-USB2, 200-1100 nm) (Hatzigiannakis et al. 2021).

Results and discussion

Focusing to the area of the cemetery, namely the west section of the site, most of the geophysical anomalies appear to the east of the two tholos tombs (Fig. 1). The particular features (dark colors in the GPR depth slices) may represent concentrations of building blocks which differentiate clearly from the rest of the background values.

The only GPR feature that was identified to the west of the tholos tombs was a linear diagonal anomaly that runs in an almost N-S direction. This feature defines a triangular zone of high reflectors that extend towards the east and it is most probably created by clearance of the rocks of the property and their pilling towards that section.

To the east of the tholos tombs, there are various areas manifested as high GPR reflectors (within 1-1.20 m below the surface) having high soil resistance values A couple of them have a relative circular outline, with one better defined (diameter of about 7 m). Due to their proximity to the tholos tombs, it is tempting to suggest that they belong to structures connected to the cemetery activities. As the field was cultivated with barley, the IRIS II was installed at the top of the plateau and used to capture spectral cubes during different seasons. A number of vegetation indices (VIs) were computed, including the Simple Ratio (SI), the Normalized Difference Vegetation Index (NDVI) and the Green Normalized Vegetation Index (GNDVI). The GNDVI was the most successful in relation to the suggested GPR anomalies (Fig. 2).

In the area of the settlement (Area 16), a number of structures that are aligned in a direction NW-SE, similar to the excavated complexes at the SW edge of the plateau, are obvious from the magnetic and GPR measurements. Taking into account the lower excavated building to the SW, we may suggest that the settlement was organized along terraces expanding at different iso-elevation levels. The subsequent excavations that were carried out in 2018 verified completely the finds of the geophysical survey and indica-



Fig. 3: Excavation results at the settlement area of Koumasa. Overview of the site and measurement areas (orthophoto: D. Panagiotopoulos).

ted a destruction layer (burning residues) dated in the Late Minoan I period (Fig. 3) (Panagiotopoulos 20220a).

At the center of the surveyed area (Area 18), both GPR and magnetic signals suggested a large (~17x19 m) oval shape structure, empty of internal divisions. The signature of this structure faints away towards the SE. Test excavation trenches of 2019 were able to verify part of the structural remains of the complex (Panagiotopoulos 2020b). In contrast, a couple of smaller compartments are exhibited as faint anomalies interrupting its perimeter, which may consist of a double wall.

Towards the west and northwest section of the plateau (Area 4), which is located to the east of the sanctuary, a high concentration of structural remains, can be considered as a continuation of the recently excavated structures to the south, which consist of carved flat building blocks (Panagiotopoulos 2020a). A double wall feature is obvious in both magnetic and GPR data and it may be associated to a corridor or road leading towards the sanctuary.

Conclusion

The geophysical survey at the Minoan settlement of Koumasa resulted some interesting features that are worth to be further investigated in the future.

Despite the relatively smooth terrain in the area of the cemetery, very few anomalies were identified in the particular region. On the other hand, the GPR was able to suggest a number of reflectors that can be associated either to badly preserved structural remains or to outcrops of the bedrock. In contrast, the results from the top of the plateau indicated a wealth of geophysical features that are related to the settlement. A penetration depth up to 2m was achieved with the GPR, whereas most cultural layers were identified within the upper layers up to depths of 0.8-1m below the surface. Both magnetic and GPR signals had a good correlation and the suggested features are associated to buildings and corridors/roads. In addition to the geophysical prospection, the ground based spectral imaging techniques proved to be really promising in relation to the mapping of the buried cultural remains.

Acknowledgments

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Buried, forgotten and rediscovered – prospecting the Roman *villae rusticae* in the area of Flachgau in Salzburg, Austria

Hannes Schiel [1*], Mario Wallner [1], Klaus Löcker [1], Tanja Trausmuth [1], Ralf Totschnig [1], Jakob Gallistl [1], Alois Hinterleitner [1], Ingrid Schlögel [1], Raimund Kastler [3], Astrid Stollnberger [2], Felix Lang [2]

1 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
2 Department of Classical and Early Aegean Studies, Paris Lodron University, Salzburg, Austria
3 Department of Archaeology, state archaeologist, Salzburg Museum, Salzburg, Austria
* Corresponding author: E-mail: hannes.schiel@geosphere.at

Abstract
At six different *villae rusticae* sites in the Salzburger Flachgau high resolution motorized and non motorized magnetic and radar data was gained. The sites are well preserved due to sustainable agricultural use.

Keywords
archaeological prospection; georadar; landscape; magnetics; Roman

Introduction

The Flachgau is a district of the Austrian county Salzburg that surrounds the city of Salzburg. One of its micro-regions is the Salzburger Seenland which is located only 15 kilometers north of the city of Salzburg. Due to the nearby lakes, the soft slopes of the Alpine foreland and the good Roman road network close to the Limes this region was a preferred area for Roman farm estates – the *villae rusticae* – which were the production centers for supplying the military camps and urban settlements along the Limes (Huber et al. 2022).

As part of the 2021 granted EU LEADER project in the rural Austrian region of the Salzburger Seenland six locations were selected (Fig. 1) where the existence of Roman *villae rusticae* were determined through finds and small excavations (Voithofer 1988). Until the funding of this project, no further information about the size and the state of the preservation of these sites was known. That is why the University Salzburg, in correspondence with the ZAMG – Zentralanstalt für Meteorologie und Geodynamik, now GeoSphere Austia, decided to use archaeologic-geophysical prospection to solve that mystery (Huber et al. 2022).

Methods

The archaeological prospection surveys were conducted with two magnetometer systems and two different GPR systems. A motorized 8-channel Fluxgate-type magnetometer array mounted on a custom built, non-magnetic cart equipped with eight Förster FEREX CON650 gradiometer probes, a 10-channel EasternAtlas AD converter and a toughbook for data acquisition using in-house developed data logging and navigation software was used in combination with RTK-GNSS for exact data positioning. The system was towed by an ATV Quad bike. This survey setup permits for a sampling resolution of 25 cm in cross-line and 10 cm in in-line direction at speeds of max. 20 km/h. For appropriate data positioning at this speed a RTK-GNSS with a 5 Hz NMEA string output rate was used and a PPS fed a time-stamp marker into the magnetic data. The data were recorded in XML format and visualized as coverage map in greyscale.

Additionally to the magnetic prospection GPR surveys were conducted at selected areas, using a 6-channel 500 MHz Sensors&Software SPIDAR and a custom build handheld 3-channel SmartCart from Sensors&Software equipped with three pulseEKKO PRO 500 MHz antenna pairs. The

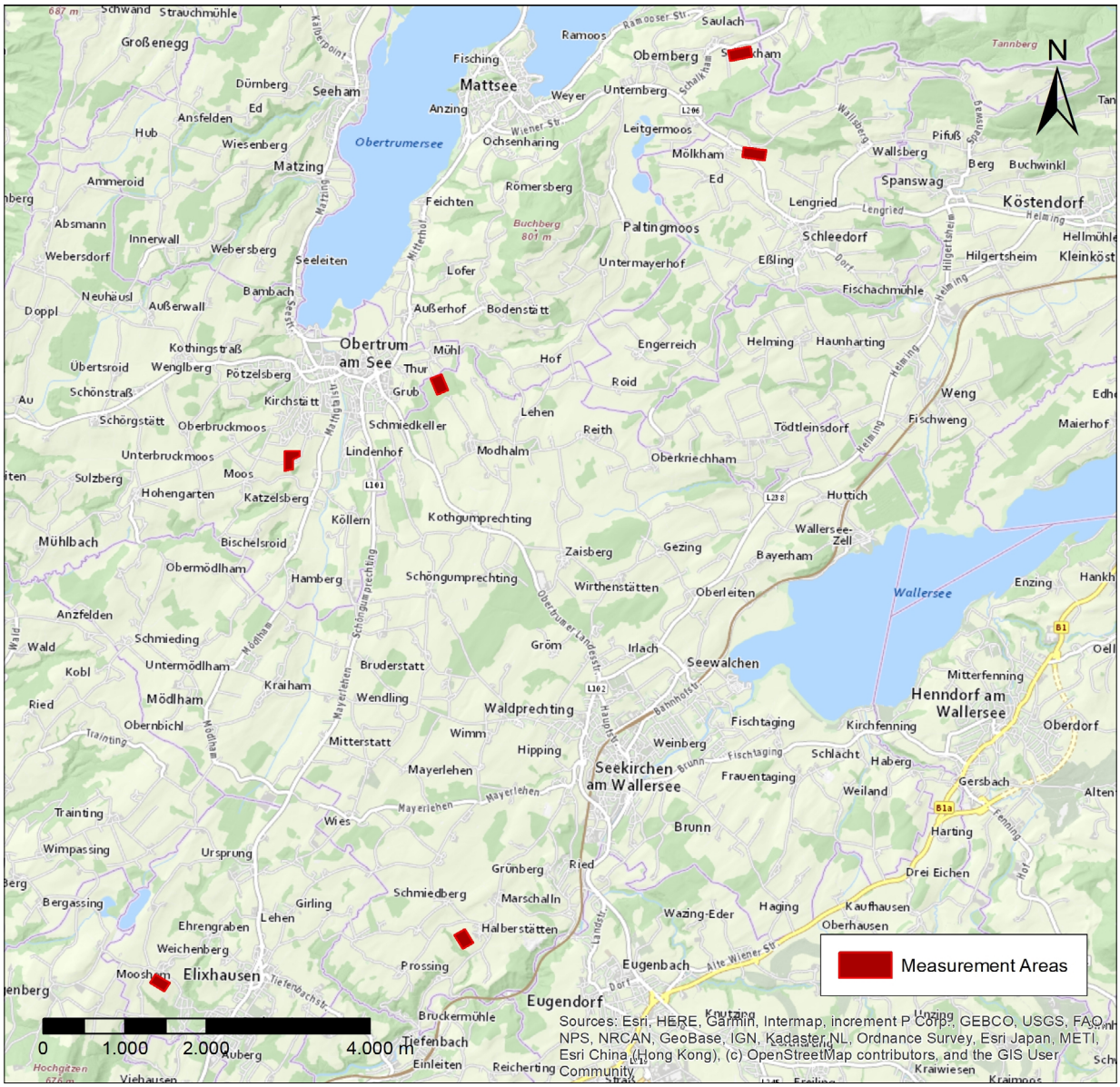

Fig. 1: Overview of the area and the archaeological sites that were prospected during the LEADER project (base map: © Geoland.at/2021).

SPIDAR system is towed by an ATV Quad bike. It consists of six radar antenna pairs arranged in two rows. Every receiver records the reflections of their behind transmitter antenna, resulting in a resolution of 25 by 8 centimeters at a speed of 5 km/h using a four-fold trace stacking factor. The SPIDAR system and the SmartCard are operated using the same RTK GNNS for positioning as the magnetometers (Trinks et al. 2018).

All data collected at the sites in Flachgau were processed and visualized with the software ApMag and ApRadar, an in-house development of ZAMG and its partners.

Results

The data were collected within two short campaigns around the 15th of November 2021 and around the 21st of March 2022. During the first campaign only the motorized magnetic surveys were conducted. The sites of Halberstätten, Mölkham (Fig. 2), Schalkham and Steinmauer showed plenty of thermoremanent structures, which can be affiliated to oven structures, hypocaust channels and brick debris as well as clusters of iron dipole anomalies. Using these results, the second campaign with the mo-



Fig. 2: Example for the magnetic surveys, the site of Mölkham magnetometry (top); interpretation of the magnetic data (bottom) (base map: © Geoland.at; 2021).



Fig. 3: Example for the radar surveys, the site of Mölkham radargram (top) depth 0.3 m to 1.0 m (background provided by INSPIRE BEV); interpretation of the radar data (bottom) combined with the magnetic data (background provided by INSPIRE BEV).

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torized multi-channel radar system SPIDAR was planned to get a more complete picture of the archaeological sites.

At the site of Moosham neither thermoremanent structures nor clustered iron anomalies of archaeologically relevant origin were detected, so a subsequent radar survey was called off.

During the second campaign in March, the sites of Halberstätten, Mölkham, Schalkham and Steinmauer were surveyed using a motorized 6-channel Sensors&Software SPIDAR system. Due to the already done magnetic survey, it was possible to focus on those parts of the investigated areas that showed the most promising anomalies regarding possible roman villas. The additional information gathered by the radar surveys shows partially well preserved walls and foundation structures deriving from roman villas and their outhouses at all four selected sites (Fig. 3).

With all these georeferenced data it was now possible to overlay both surveys and to combine the interpretations.

The site of Waldprechting was the only site that had to be done by hand and furthermore was not possible to be investigated with magnetics. Nevertheless, it was possible to detect a well-preserved Roman building within a wooded area.

Conclusion

In four of the six sites magnetic- and radar-prospections were carried out, in the two others only one method was used. It was possible to collect high-resolution data at all six sites. Five of the sites still contain more or less well-preserved remains of Roman *villae rusticae* and their outbuildings and facilities. Only at the site of Moosham the dataset shows no remains of a roman villa. It is highly possible that parts of the main buildings were overbuilt with modern structures. Due to these results, it is now possible to give the sites a better protection by listing them and to gain additional money to extend surveys on similar sites in this region.

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Large-scale motorised prospection along the "SuedLink" route in Lower Franconia

Ingrid Schlögel [1*], Jakob Gallistl [1], Alois Hinterleitner [1], Klaus Löcker [1], Hannes Schiel [1], Ralf Totschnig [1], Tanja Trausmuth [1], Mario Wallner [1], Janna Kordowski [2], Johannes Gillhaus [2], Martin Schaich [3]

1 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
2 Jacobs GmbH, Garching b. München, Germany
3 ArcTron 3D - Vermessungstechnik & Softwareentwicklung GmbH, Altenthann, Germany
* Corresponding author: E-mail: ingrid.schloegel@geosphere.at

Abstract
Large-scale archaeological prospection has proven itself as an essential tool in advance of a linear infrastructure project. The non-destructive survey is a basis for infrastructural planning and the protection of archaeological sites. More than 410 ha of high-resolution motorized geomagnetics were surveyed within six weeks. Such infrastructure projects can also be seen as an opportunity for archaeological research.

Keywords
archaeological prospection; infrastructural project; magnetometry; neolithic settlement; SuedLink

Introduction

In these times of energy transition, major infrastructure projects are a major focus of interest, also for policymakers. The public pressure to realize these projects as quickly as possible while still aiming for an environmentally friendly solution is therefore enormous. Linear infrastructure projects are quiet challenging, because they have a predefined starting- and endpoint, and a long corridor in between. This corridor must be subjected to existing structures like roads and villages, the terrain and geological conditions. In addition to all these immovable/stationary elements, there are zones that can also influence the route, for example: nature reserves or those contaminated by ordnance and, last but not least, archaeologically relevant sites. The planning of such infrastructure projects is therefore a particular challenge. Previous approaches for linear infrastructure projects are shown by Hulin et al. (2018) and Bonsall et al. (2014).

A 1000 m wide corridor for the possible "SuedLink" route was already defined in advance by the Federal Network Agency, the project operator TransnetBW (+NU) provided appropriate corridor alternatives and thus a corridor some 100 km long was created across Lower Franconia. Due to its enormous length, this corridor included some already known archaeological sites. The GeoSphere Austria (former ZAMG) was contracted by ArcTron 3D to carry out preliminary archaeological investigations for one of the largest construction projects in Lower Franconia (Germany).

Challenges

Due to the aforementioned time pressure for the execution of the infrastructural project called "SuedLink" and the enormous length of the corridor to be prospected, the magnetic survey could only be carried out by using motorized measuring systems. However, the survey was made even more difficult by several factors and thus perfectly demonstrates the true challenge of such large-scale projects:

- Due to the different agricultural cultivation of neighboring fields, not all areas could be surveyed in the same campaign/season of the year.
- The rapid crop rotation currently practiced by the modern farmer created an additional significantly shortened time window.



Fig. 1: Motorized measuring device on a cold winter morning. Weather is a serious factor in daily measurement performance. In winter, the days are shorter, but as shown on frozen ground optical navigation is easier.

- Extremely wet weather from late autumn to spring made it impossible to survey.
- The very long, but narrow corridor sometimes collided with existing agricultural field boundaries, creating strange and complicated survey fields.
- Citizens' initiatives against the construction project and spontaneous bans on entering the land led to further delays.

Methods

For the magnetic surveys, motorized measuring systems with eight fluxgate sensors were used (Fig. 1 and Fig. 2). The probes were mounted on a six-meter-long, custom-built measuring cart at a spacing of 0.25 m. The measuring accuracy of the FEREX CON650 was 0.1 nanotesla (nT). The speed of the towing vehicle was adjusted in such a way that a maximum measurement distance of 0.1 m could be maintained. The positioning of the measurement systems was carried out using RTK GNNS with an average accuracy of 2 cm.

The data from the fluxgate sensors were converted to greyscale images with different clip-off values using the ArcheoSoft software developed at ZAMG (now GeoSphere Austria) (Sandici 2013). In the course of processing, the measurement data were subjected to the following algorithms: subgrid and line shifts, displacements, spikes, noise. In this way an uncorrected image of the raw data was generated and also, using image enhancement methods, several optimized images that form the basis of the archaeological interpretation. It was shown that here a value between minus 2 nT and plus 3 nT gave the ideal contrast between geological background and archaeological structures for interpretation and analysis.

Results

Within nine weeks, split in several measurement campaigns, a total area of 410 ha could be surveyed by magnetometry. The surveys revealed for the first time the existing archaeological structures in a unique clarity and spatial resolution. Based on the archaeological interpretation and spatial analysis, the sites can be assigned to several time periods. These range from the Neolithic through the Bronze and Iron Ages to the Middle Ages. However, the majority of the settlement sites found can be assigned to the Neolithic

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Fig. 2: Motorized measuring device in summer. The long-lasting daylight in summer makes it possible to work slightly longer each day if necessary. However, after the crops are harvested, the fields are quickly cultivated on the surface, which in turn can make the survey somewhat more difficult.

period and generated an invaluable basis for the non-destructive exploration of these large-scale settlements.

Through the spatial analysis of the prospected areas, it is now possible to propose a corridor that ensures the greatest possible protection of the archaeological structures.

Figure 3 shows such an example for a major Neolithic settlement within the planned corridor. Here the planners are either forced to move to the western part, or to find an overground solution for the planned infrastructure.

Discussion

The SuedLink project impressively demonstrates the benefits that non-destructive exploration can provide in advance of such large-scale infrastructure projects. Through the detailed archaeological analysis of the survey data, the actual construction corridor can be planned with high precision. In this way, sensitive archaeological areas can be avoided and our cultural heritage will be protected for our descendants.

Although large-scale construction projects are always associated with the destruction of parts of our cultural heritage, nowadays - with good planning - great efforts are made for preliminary investigations. This is the opportunity that might be of great value for archaeology. Because of the modern possibilities of high-resolution non-destructive archaeological prospection - in the course of these preliminary investigations - unique data sets are generated, which survey entire settlement areas/landscapes and thus are able to increase our knowledge significantly.

The non-destructive explorations, which were carried out in the course of the infrastructure project, show a unique overview of the archaeological site. While the archaeological excavations in the course of the actual construction activities will give an even more detailed view into the site, which allows not only an exact dating but also statements about its use and function.

Conclusion

A well-prepared survey campaign and analysis, adapted to the situation on site, shows the potential of large-scale archaeological/geophysical prospection, on the one hand as a planning tool for large infrastructural projects and on the other hand as valuable information for the exploration and preservation of our Cultural Heritage.

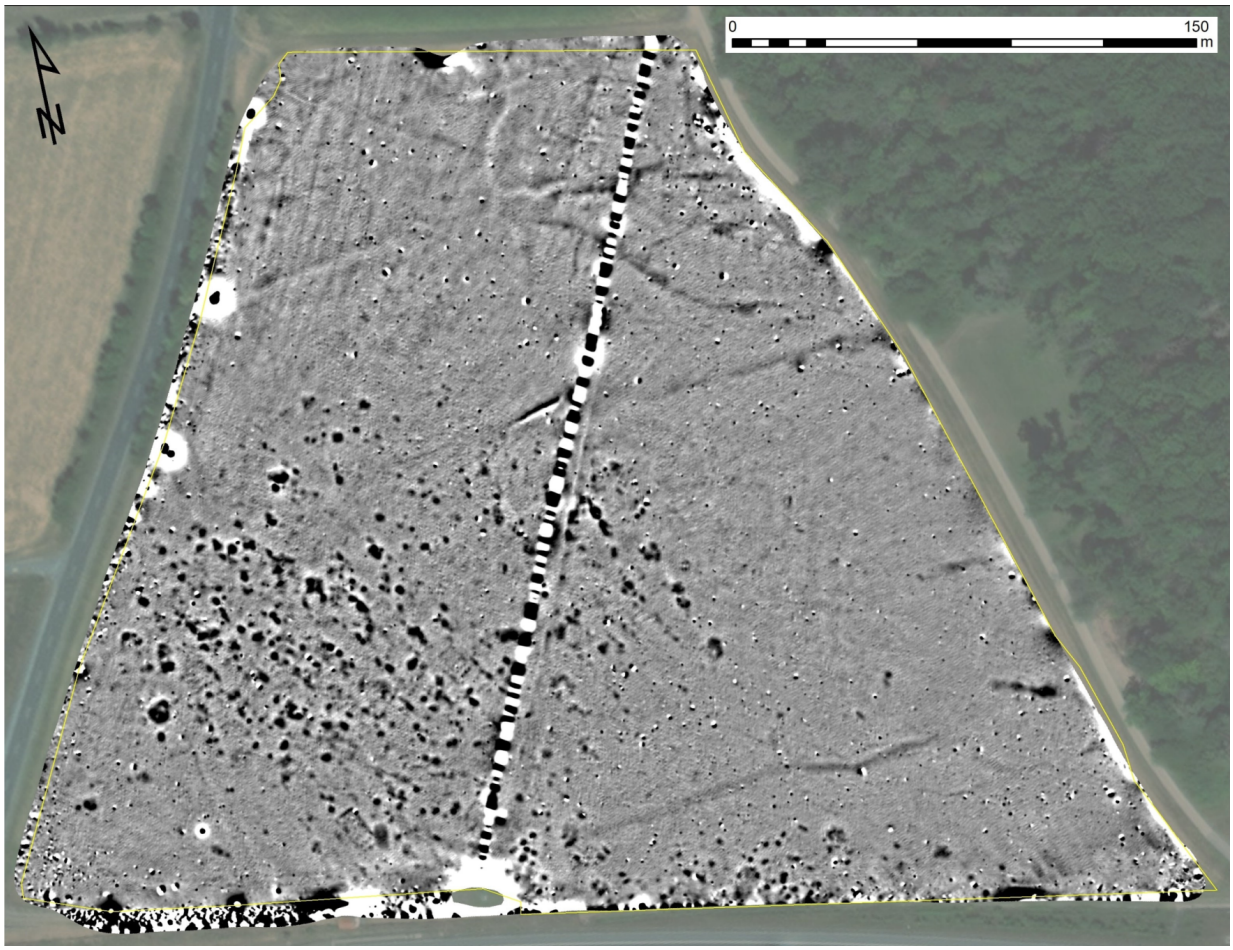

Fig 3: Magnetometry survey along the "SuedLink" corridor showing a major archaeological structure that forces the planning team to change the construction corridor. Clip off value -4nT/+6nT (base map: Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community, 2022).

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Understanding complexity: the case-study of al-Ḥīra, Iraq

Agnes Schneider [1,3*], Martin Gussone [1], Martina Müller-Wiener [2], Karsten Lambers [3], Burkart Ullrich [4], Rudolf Kniess [4], Sandra Kniess [4], Jochem Peter Dorrestein [4]

1 Technische Universität Berlin, Berlin, Germany
2 Museum für Islamische Kunst, Berlin, Germany
3 Leiden University, Netherlands
4 Eastern Atlas GmbH & Co. KG, Berlin, Germany
* Corresponding author: E-mail: a.schneider@arch.leidenuniv.nl

Abstract
The large-scale magnetometer prospection conducted in 2021 south of the al-Najaf International Airport, Iraq, reveals the complex settlement structure of the late Antique and early Islamic site of al-Ḥīra. The manual archaeo-geophysical interpretation resulted in 16 classes and the three most relevant archaeological classes will serve as a baseline for a (semi-) automated classification workflow.

Keywords
large-scale archaeological prospection; magnetometry; manual archaeogeophysical interpretation

Introduction

This paper presents the results of a large-scale magnetic prospection at the site of al-Ḥīra, Iraq. The fieldwork was part of the international project "The Late Antique and Early Islamic Hira – Urbanistic Transformation Processes of a Trans-regional Contact Zone" funded by DFG (grant nos. ES 286/9-1; MU 3169/2-1; SCHU 1562/10-1). The project is a collaboration between the Museum for Islamic Art Berlin (Dr. M. Müller-Wiener, DFG), the German Archaeological Institute (DAI) – Oriental Department (Prof. Dr. Dr. h.c. M. van Ess and Dr. I. Salman), the Technische Universität Berlin (Dr. M. Gussone), Eastern Atlas (B. Ullrich) and Leiden University (Dr. K. Lambers), as well as the SBAH (Iraqi State Board of Antiquities and Heritage) as local partner.

Materials and methods

The late Antique and early Islamic site of al-Ḥīra was founded in the 3rd century AD (Fig. 1, left). After flourishing in the 5th & 6th century, al- Ḥīra slowly lost its importance following the Muslim conquest (633 AD) but was continuously occupied at least until the 10th century. Following its demise, the site remained undisturbed by building activities until the 1970s. Since then, modern land use threatens the archaeological heritage of the site, the extent of which still has to be determined (Gussone et al. 2020; Müller-Wiener et al. 2019).

To address this, the "Hira Survey Project" (predecessor of the DFG project) reassessed between 2015 and 2018 previous archaeological research and conducted field surveys and prospections to understand the exact location, extent, chronology, and material culture of the settlement. In 2016 UAV (Stremke 2016) and magnetometer surveys were undertaken (HIRA2016/AoI1, Ullrich et al. 2016) in the area of a planned second runway of the al-Najaf International Airport. In 2018, the area south of the Airport was surveyed by UAV (Müller-Wiener et al. 2015; Müller-Wiener and Siegel 2018; Müller-Wiener et al. 2019; Stremke 2018).

Latter area is the focus of the DFG project. To understand and reconstruct the settlement history and chronology of al-Ḥīra carried out a magnetometer survey (HIRA2021/AoI2, Kniess et al. 2022). For both surveys (HIRA2016/

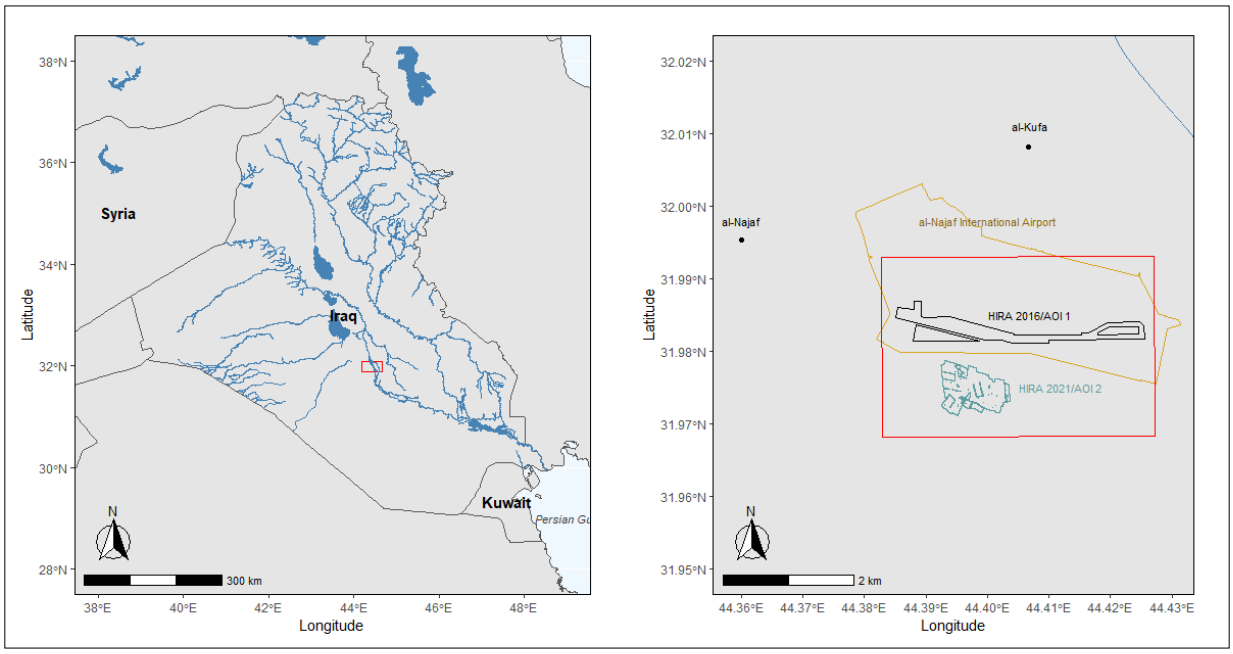

Fig. 1: Iraq and the location of the HIRA 2016/AoI1 and HIRA 2021/AoI2 surveys. © Agnes Schneider.

AOI1 and HIRA2021/AOI2, Fig. 1, right) the ultra-light LEA MAX System with ten Förster Fluxgate Gradiometer FEREX CON 650 probes with a vertical sensor separation of 0.65 m, 0.5 m profile distance and 0.1 m point distance was deployed. Two Forsberg ReAct GNSS receiver with an RTK accuracy of 0.02 m and an odometer were used for positioning. Large open and almost flat areas allowed the LEA MAX System to be towed by an ATV. Where needed, the LEA MAX System was adjusted to hand pulled mode. The data was interpolated by kriging with an image resolution of 0.15 m (Ullrich et al. 2016; Kniess et al. 2022; Ullrich et al. 2017).

Results

The 50 ha magnetometer survey conducted in 2021 (HIRA2021/AoI2, Kniess et al. 2022) is the continuation of the survey of 75 ha carried out in 2016 (HIRA 2016/AoI1, Ullrich et al. 2016). The manual interpretation of 40 ha of HIRA2016/AoI1 with 5298 identified anomalies delineating 9 classes was taken as baseline and extended to 16 archaeo-geophysical classes in the case of HIRA2021/AoI2.

The interpretation of the magnetometry is based on a primary distinction of the magnetic anomalies. On top level this distinction groups magnetic anomalies into either archaeologically relevant anomalies or anomalies of recent origin. Classes of anomalies, which might be of archaeological origin, have been included into the former, archaeologically relevant group (classes 1 to 8 and class 12), while anomalies, which are clearly of recent origin (classes 9 to 11 and 13 and 14), have been grouped into the latter, archaeologically not relevant group. On a secondary level, classes 5 and 7 were divided into subclasses (51, 52 and respectively 71 and 72), based on their archaeo-geophysical properties (Fig. 2).

In total 8317 individual archaeo-geophysical features were identified (Tab. 1). The identification was mainly undertaken on magnetic data with a dynamic range of ± 5 nT. 7074 anomalies were interpreted as archaeologically relevant, that is 85.05 % of all anomalies. 3225 slightly negative linear anomalies of class 3 (interpreted as in situ mud-brick walls) are accompanied by 2548 elongated negative linear or oval class 2 anomalies (interpreted as fillings) of more than 1 m diameter and complemented by 675 circular-oval positive anomalies up to 1 m in diameter of class 1 (interpreted as pits). These three classes form the incredibly dense settlement fabric of HIRA 2021/AoI2 and constitute 77.52 % of all anomalies (Kniess et al. 2022).

Discussion

The manual interpretation of HIRA2016/AoI1 using 9 classes was extended to 16 archaeo-geophysical classes, because

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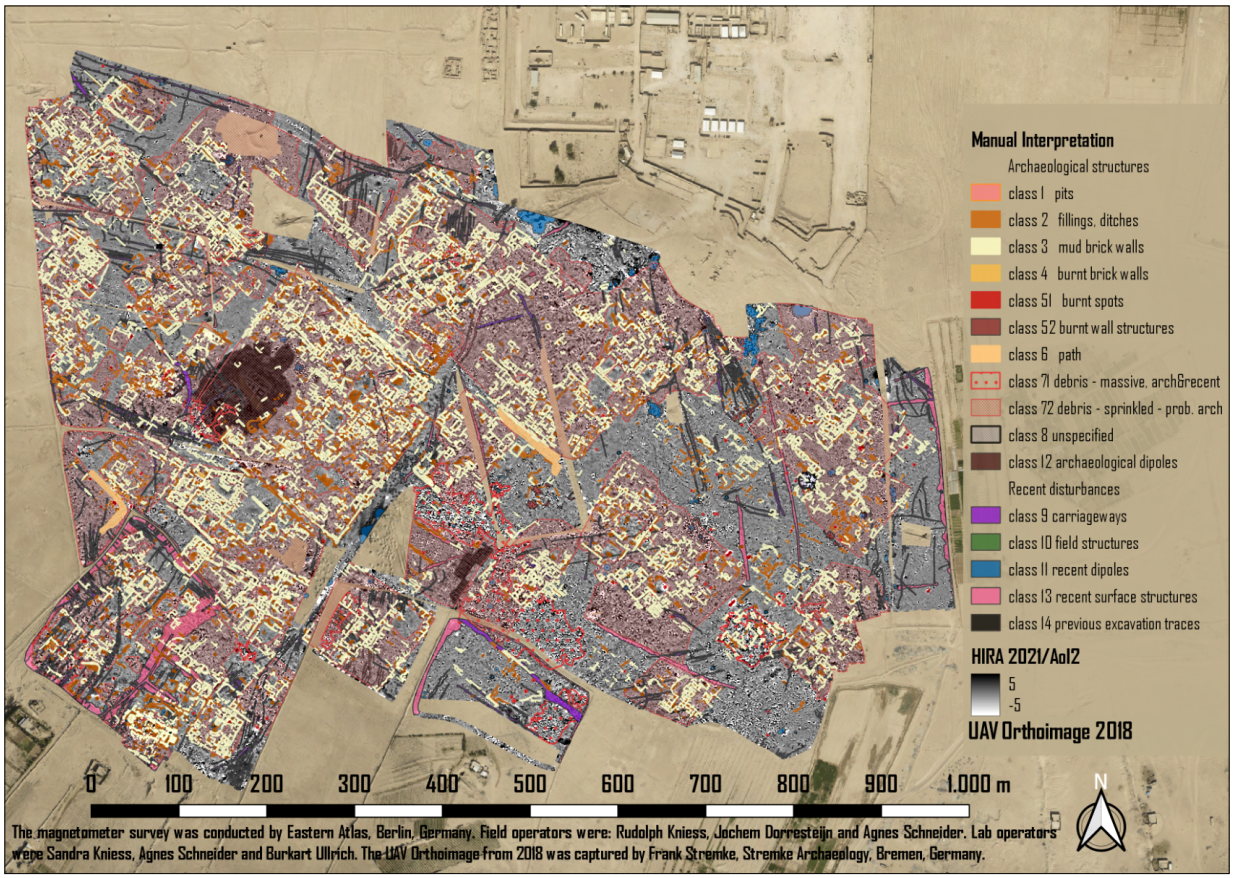

Fig. 2: Manual interpretation scheme of HIRA2021/AoI2 © Eastern Atlas.

Class	Colour	Anomaly Type	Amplitudes	Related Structures
Anomalies related to archaeological structures				
1		060 + < 1 m Ø	+3... +20 nT	Fillings of pits and post holes
2		linear/0 + > 1 m Ø	+3... +20 nT	Organically enriched fillings
3		linear -	-1... -10 nT	In situ unburnt mud brick walls & foundations
4		linear +	±1... ±10 nT	In situ burnt mud brick walls & foundations
51		+ high, dipole character	± 20.. ±400 nT	Burnt spots: furnaces, kilns, fireplaces, workshops
52		group of 51	±1... ±150 nT	Post hoc burnt wall structures
6		linear, moderate	± 1... ±10 nT	Roads, paths, streets
71		dipole character	- 10... ±10 nT	Debris of complete or partial buildings
72		<clear dipole character	- 5... ± 5 nT	Debris in/near buildings; under 5 nT
12		<clear dipoles	< ±35 nT	Dipoles, low amplitudes; archaeological origin?
Unspecified anomalies				
8		+/- dipole anomalies	-500... +500 nT	uncertain origin, archaeologically relevant
Anomalies of recent origin				
9		linear, often multiple	-4...+4 nT	recent carriageways
10		linear, at a distance	-5...+5 nT	recent field structures
11		dipole character	>±35 nT	recent iron objects above and below the surface
13		broad linear, connected	-15...+15 nT	diverse recent surface structures

Table 1: Manual interpretation scheme of HIRA2021/AoI2 © Eastern Atlas.

HIRA2021/AoI2 is the continuation of the same geomorphologic context. It is more compact and gives a glimpse of the real complexity of the settlement fabric. It was specifically chosen to identify as many classes as possible to understand the settlement structure, with a main focus on class 3 anomalies, which are the mainstay (and 38.77 % of all and 45.5 % of the archaeologically relevant anomalies) of the settlement structure of al-Ḥīra.

Conclusion

The manual archaeo-geophysical interpretation presented here serves as a starting point for the development of a Deep Learning approach for the automated analysis of the magnetometer data sets HIRA 2021/AoI12 and also of HIRA 2016/AoI1.

In the context of "The Late Antique and Early Islamic Hira – Urbanistic Transformation Processes of a Transregional Contact Zone" DFG project (grant nos. ES 286/9-1; MU 3169/2-1; SCHU 1562/10-1), the aim of the first author's PhD in the Digital Archaeology Group at Leiden University is to develop a reproducible and replicable workflow for the (semi)-automated classification of magnetometer data, considering the specific characteristics of the data type. This includes the reutilization of concepts, method, and code.

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Investigations at an Early Roman *vicus* in Moesia Inferior – the tale of the Beidaud site (Tulcea County, Romania)

Adrian Șerbănescu [1, 2*], Valentin Bottez [1], Cristian Roth [2]

1 Faculty of History, University of Bucharest, Bucharest, Romania
2 ArchaeoSciences Division, Research Institute of the University of Bucharest, Bucharest, Romania
* Corresponding author: E-mail: adrian.serbanescu@icub.unibuc.ro

Abstract
We did geophysical investigations in a provincial vicus in Moesia Inferior, Romania. Magnetics and GPR surveys were combined to detect the rural archaeology. With these methods, we could map the internal layout and buildings in a rural Roman settlement.

Keywords
geomagnetic prospection; landscape archaeology; Roman provinces; rural archaeology; settlement layout

Introduction

Modern province of Dobruja (South-East Romania today) is a region with rich historical background that starts in Neolithic and flourishes during the Greek and Roman periods. The catalyst behind this is the foundation of three Greek colonies during the 7th-6th century B.C. – Histria, Kallatis and Tomis, and more followed (Suceveanu and Barnea 1991). While research at these main urban sites has been going on for a century now, the study of the rural areas around them is just getting started.

This study focuses on the Early Roman *vicus* near Beidaud (Tulcea County, Romania), a settlement that appears with the changes that happen in the 2nd Century B.C. when, in the old hinterland around Histria, named *chora*, a new administrative unit appears - *regio Histriae* (Matei-Popescu 2013).

While the Roman influence in ancient Dobruja starts in the 1st century BC, the official annexation date is generally accepted as 69 A.D. (with the beginning of the Flavian dynasty), Vespasian making changes in the territorial layout of the provinces around the Balkans and Dobruja is included in Moesia Inferior. The first and main information about the *regio Histriae* is a document called `Horothesy of 25th of October 100`, when the governor Manius Laberius Maximus delimits the territory of the said *regio* by the courses of five rivers which today are yet to be identified (Olteanu and Amon 2008).

Methodology

Situated on the greenschists of the Casimcea Plateau, roughly 27 km in straight line from Histria, the site is West of the Archaic fortress near Beidaud modern village and West of the necropolis most likely associated with the *vicus*.

A total area of 6.25 hectares of magnetometry was covered using a Bartington Grad601-2 dual sensor with a resolution of 0.25x1 m during a campaign in April 2022 and Sensys Magneto DLM 98 cart with three sensors was used during the June 2022 campaign (Fig. 1).

A large number of anomalies related to stone dismantled from foundations of buildings were identified on the magnetic map and three complexes were chosen for further investigations using high resolution magnetometry and GPR (Fig. 2, result) – A Mala ProEx with a 500 MHz antenna was used.

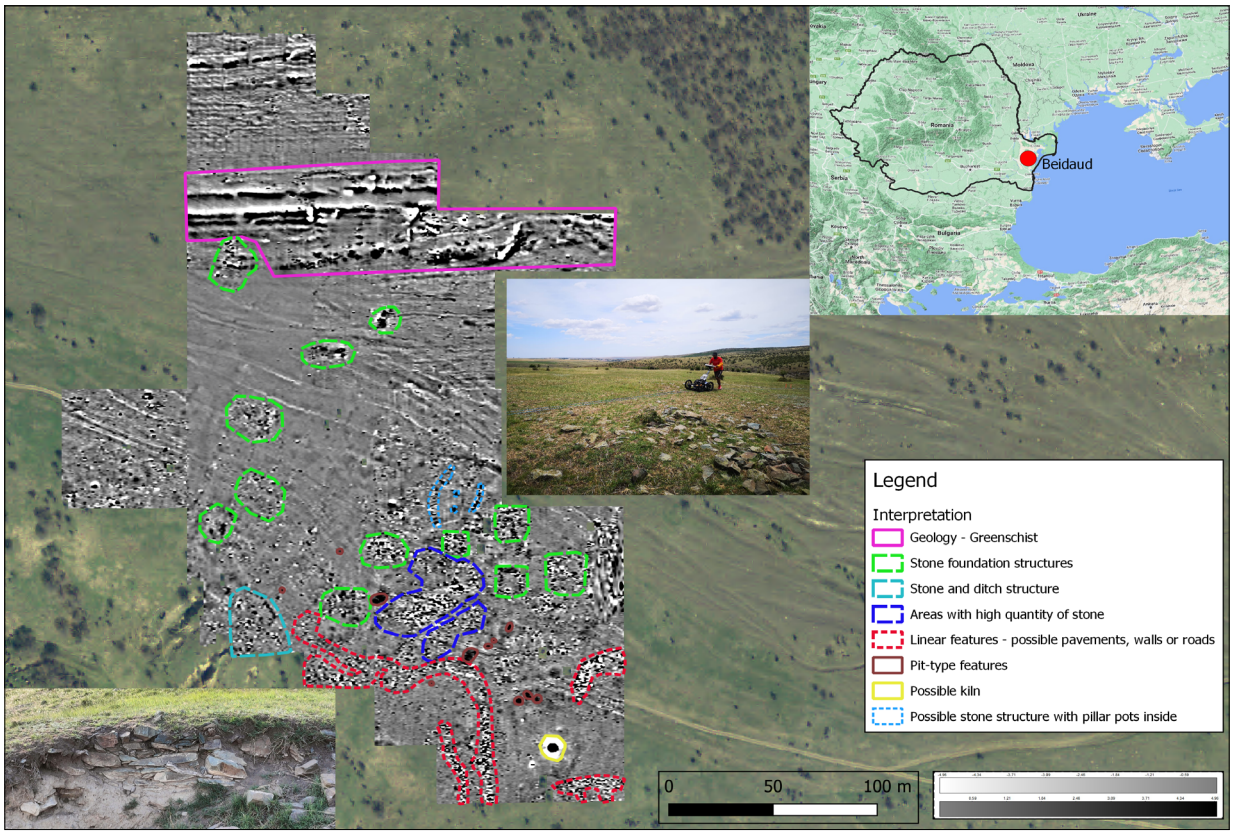

Fig. 1: The site of Beidaud (Map in top right corner: Google, Map data ©2023). Geomagnetic results and interpretation (base map: Bing maps - © 2023 Microsoft).

Results

In the magnetic map covering a large area of the settlement were located a number of interesting structures (Fig. 1, interpretation). The majority of anomalies were related to stone structures. They are either remains of buildings, or linear anomalies related to pathways or paved areas. On are the northern part of the map, the bedrock formed by greenschist alignments can be clearly seen as positive magnetic anomalies. Other possible types of structures have been identified including a round anomaly with strong positive/negative contrast and a radius of approximately 5 m. During the September 2022 excavation campaign and quarter of this anomaly was opened (the south-west part) with partial results pending and work there will be continued during the next campaign in 2023.

The three areas investigated using high resolution magnetometry (0.05x0.25 m) showed more detail of the structures and only in area 3 wall alignments were visible. GPR investigations with similar resolution were done over areas 1 and 3 and proved to be crucial to the investigation.

Discussion

While the survey covered roughly 6.25 ha, only the western limit has been found. To the North, the site might continue over the bedrock alignments, and the Eastern and Southern edges have yet to be determined. To the South there is a valley similar to small canyon and the remains of structures continue down the slope, so identifying it will prove to be challenging in areas where the slope becomes very steep.

It can be also determined that most buildings have stone foundation and most likely, as in other settlements in the region, the walls were made of wattle and daub or similar clay technology (Baumann 1983). Investigations using GPR in areas 1 and 3 showed great results.

In Area 1 the complete layout of a typical Roman building (Bâltâc 2010) can be seen in the -slices starting at -0.35 m up to -0.75 m (Fig. 2). A rectangular house with rooms on the sides and an interior courtyard can be observed, similar to other buildings excavated in the region (Baumann 1995).

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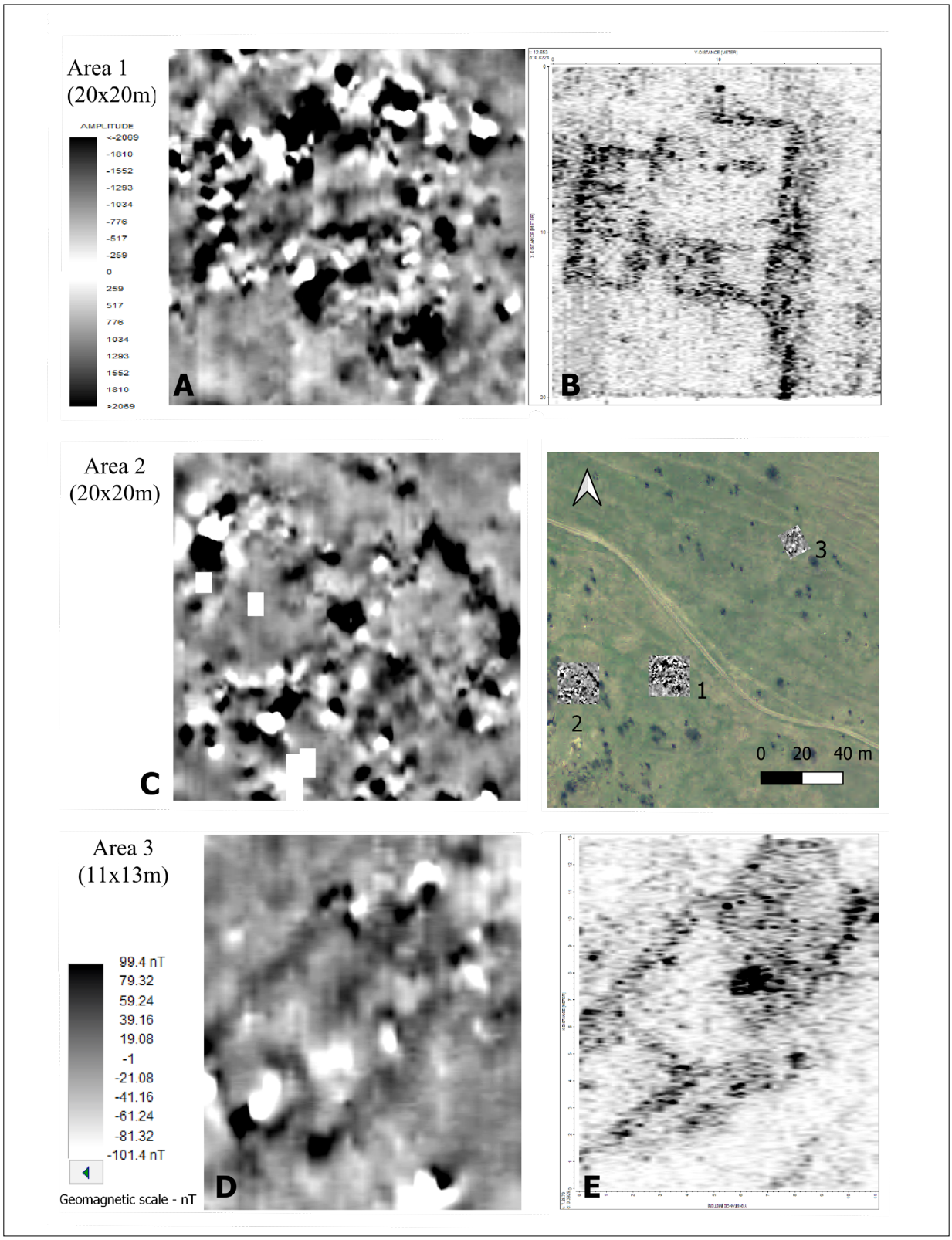

Fig. 2: High resolution areas 1, 2 and 3 and their position. Area 1 – A- geomagnetic results, B- GPR slice at – 0.80m; Area 2 – C- geomagnetic results; Area 3 – D – geomagnetic results, E- GPR slice at – 0.40m (base map: Bing maps - © 2023 Microsoft).

In Area 3, the layout of part of a building can be seen, oriented NE-SW, and this is probably part of a larger structure that can be seen in the magnetic map. In the middle of the structure a large anomaly can be related possibly to a fire installation, maybe a hypocaust.

What can be inferred from both GPR datasets is that both buildings have a layer of approximately 10-15 cm of rubble from -0.15 m to -0.30 m under which, the remains of the walls and other components of the buildings can be seen up to circa -0.95-1 m in the ground.

Conclusion

Investigations carried out so far at Beidaud *vicus* yielded remarcable results and show that further investigations are required to fully understand the context of this settlement in terms of its size, functions, internal layout etc. It is important to mention that the area where the site is situated is pasture and has been utilized this way for long time. There is no evidence of intense agricultural activity (ploughing especially) and the fact that intact walls can be seen in the GPR time-slices supports this hypothesis and is probably the main reason for the good conservation state of the structures.

Once the geophysical investigations will be completed, as we aim at fully delimiting the site using magnetometry and investigate more structures with GPR, we will have the first complete geophysical investigation of an Early Roman *vicus* in Roman Dobruja.

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Geophysical prospection of Iron Age coastal sites in Scandinavia known from metal detecting assemblages – new case studies from the PastCoast-project

Arne Anderson Stamnes [1*]

1 The NTNU University Museum, Dept. of Archaeology and Cultural History, The Norwegian University of Science and Technology, Trondheim, Norway.
* Corresponding author: E-mail: arne.stamnes@ntnu.no

Abstract
Geophysical surveying of sites known from metal detecting shows a varying spatial relationship between the finds material and the geophysical information. The survey results of two case studies indicate that coastal erosion has removed parts of the archaeological site at Langelands gaarde. The Austråt manor case study reveal a large number of archaeological features, and a strong spatial correlation between the geophysical observations and metal detecting objects.

Keywords
archaeological prospection; GPR; magnetometer; metal detecting; Scandinavia

Introduction

The PastCoast-project is a multidisciplinary project funded by the Norwegian Research Council, investigating coastal Iron Age sites known from metal detecting assemblages. Ultimately the project aims at studying changes and breakpoints in the utilization of prehistoric marine coastal environments, identifying possible causes for changes and creating an interpretive framework to identify possible human responses to changing environmental settings (Stamnes 2022). Along the shores of Scandinavia, a plethora of new and hitherto unknown sites has started to appear as a result of privately initiated amateur archaeology in the form of metal detecting. Such metal detecting assemblages identify some form of human presence and can provide new information regarding local and regional exploitation of land and settlement patterns. The metal detecting assemblages may result from a wide range of archaeological activity, such as coastal landing places, magnate farms, and possible commercial sites (Christiansen 2017). While metal detecting has a long tradition in Denmark (Dobat 2013), it is mainly within the last decade that it has really caught on in Norway. Here, knowledge of object assemblages has created new challenges in understanding the context of the finds and how best to protect potential archaeological sites (Fredriksen 2019). The depositional history of these objects might also vary, and it is important to investigate if the objects made their way into the ground as some form of redeposition, as direct evidence of past activity, or as an effect of post-depositional activities that might have shifted the objects in space (Henriksen 2016). Non-destructive techniques provide a large overview for prioritisation to optimise resources and minimise the impact of an archaeological excavations – ensuring maximum gain towards targeted research aims with a minimum of excavations. Therefore, there is an untapped potential to use large-scale geophysical surveys combined with small-scale excavation to understand sites known mainly from metal detecting assemblages. One of the main objectives of the PastCoast-project, is to survey a series of sites known mainly from metal detecting assemblages by large-scale high-resolution GPR and magnetometer-surveys, and firstly to investigate whether we can detect subsoil features at these sites, and interpret them from an archaeological perspective, and secondly to determine if there is a spatial relationship, both in a local

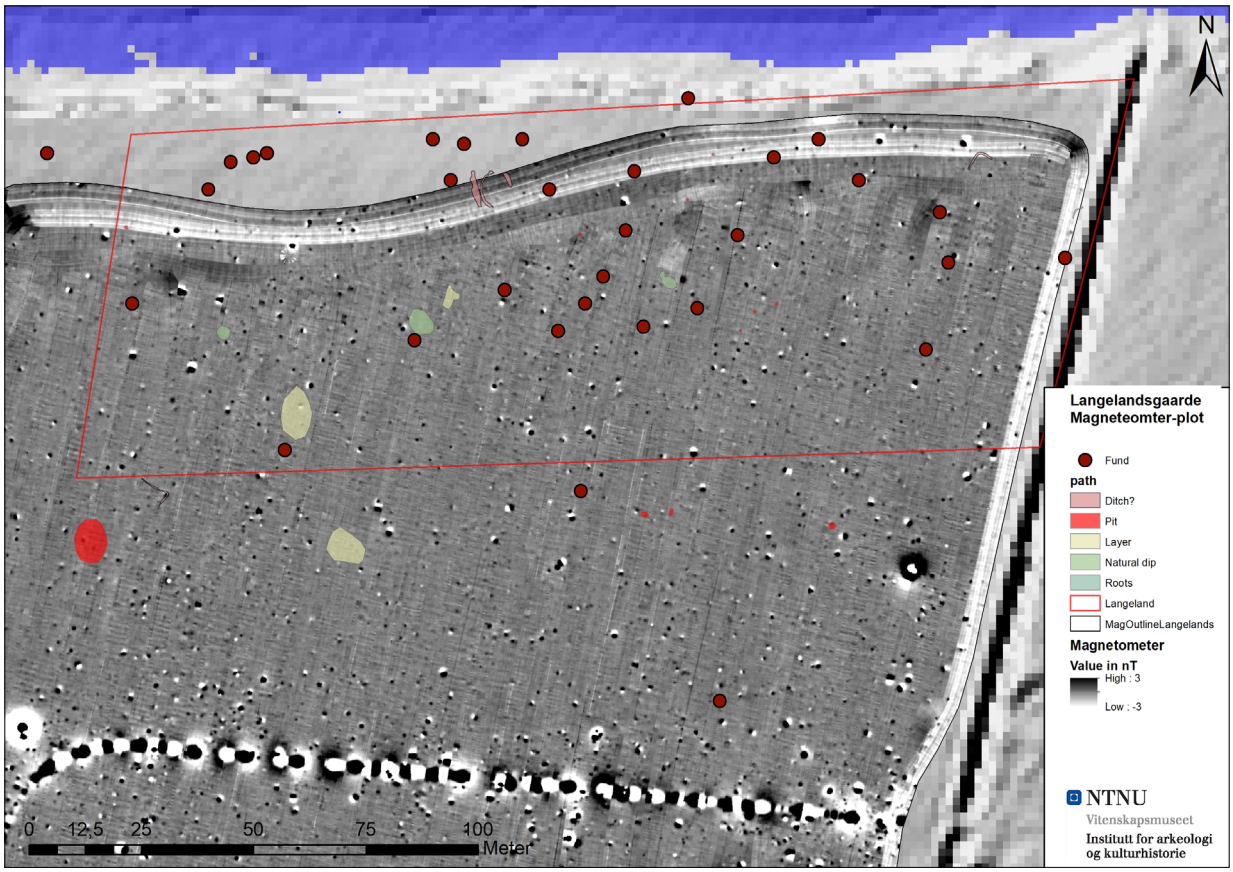

Fig. 1: Magnetometer plot, location of metal detecting objects and GPR interpretations from Langelands gaarde, Limfjord in Denmark.

and regional perspective, between the finds assemblages and subsoil features. This will help in the characterization of these sites, and improve our cultural historical understanding of their context and significance.

Materials and methods

The PastCoast-project aims at investigating at least six different sites in Denmark and Norway. Two sites, Langelands gaarde by Limfjorden in Denmark, and Austrått at Ørlandet in Mid-Norway, have until now been subjected to large-scale magnetometer and GPR surveys using the 3d-Radar Mark IV step-frequency GPR system with a ground-coupled antenna, and a sensys 16 channel magnetometer array. Two more sites will be surveyed in the Autumn of 2022 and winter of 2023. One of these will be the famous landing-site or coastal trading site of Lundeborg on Fynen in Denmark, closely linked to the Roman Iron Age magnate area of Gudme. While Langelands gaarde is mainly known through its find material, Austrått on the other hand was a large manor in high medieval times and the home of several nobles throughout history. A larger metal detection rally was conducted there in 2015.

Results

The Langelands gaarde site has revealed a wide range of objects from the early Iron Age, such as Roman denares, a golden berlok, gold clippings and several fibulae, all indicating some form of activity – potentially a landing- or trading site. Several of the finds have been found on the shorebed, and 10-15 m of the shore edge has been eroded away over the past decade. The geophysical survey revealed few, if any notable anomalies in the gradiometer data image (Fig. 1). The interpretation of the GPR data also revealed only a few geophysical observations within the area where the metal decetorist has found most of the objects. Subsequent trial trenching did not reveal any archaeological activity besides one pit and a ploughed-out layer containing charcoal and some animal bones.

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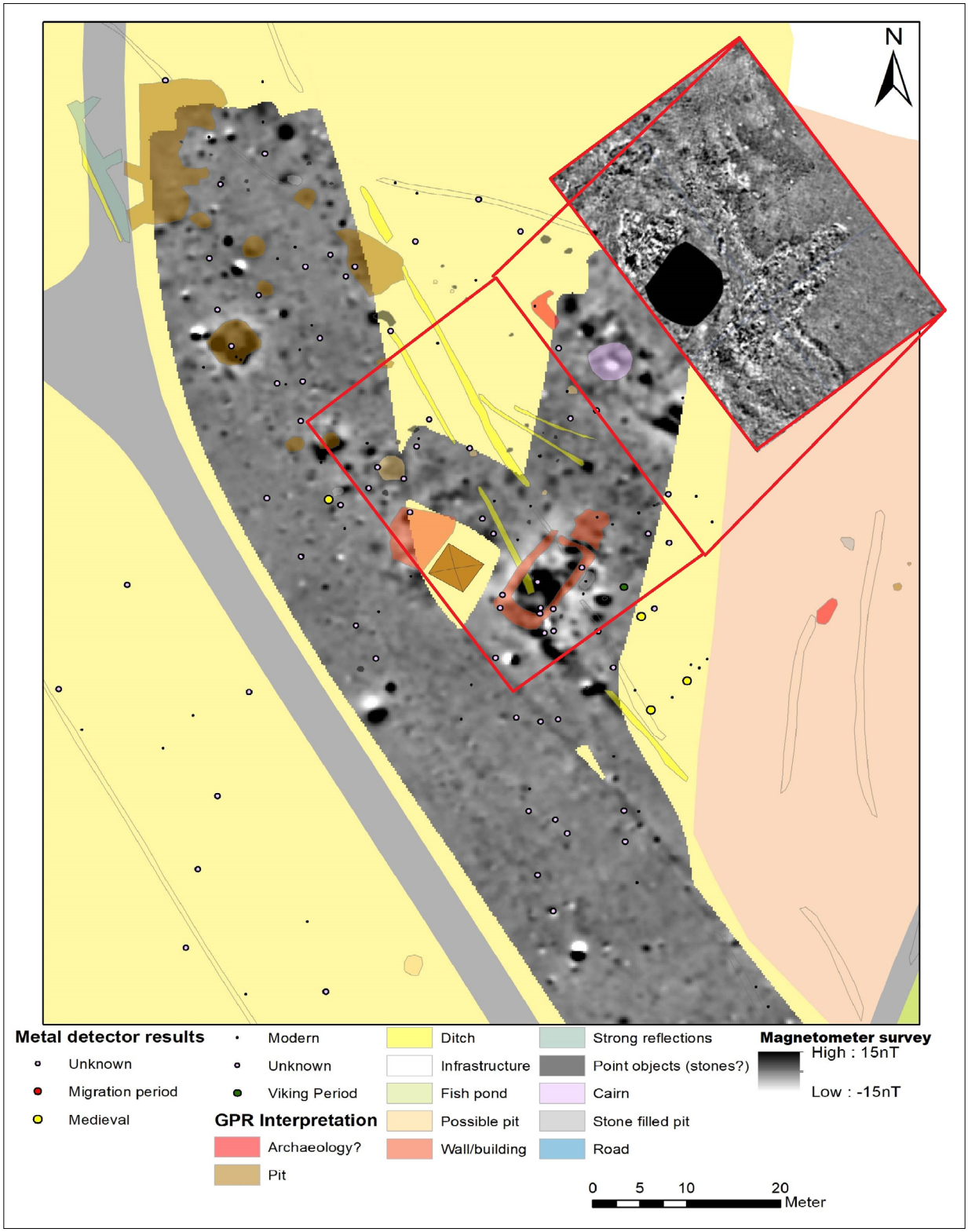

Fig. 2: Magnetometerplot, GPR interpretations and location of metal detecting objects from the central manor area of Austrått, Ørlandet Municipality, Norway. The red square shows an exctract of a GPR depth slice from the area around the possible tower building remains discovered.

The Austrått-site, on the other hand, revealed a plethora of observations related to the manor house and probably centuries of settlement history (Fig. 2). The GPR data from this site also showed a sequence of relict beach ridges and other palaeotopographical information. Archaeological interpretations of the GPR data from the area include four possible building remains, several larger pits – including the older fish-dam for the manor, a cairn and a ring-ditch within the manor garderns, and stone-filled pits (potentially cooking pits). One of the buildings is centrally placed within the area with the highest density of metal detecting finds, and is potentially the lost medieval "tower-house" mentioned in written sources.

Discussion and conclusion

The Langelands gaarde site revealed few notable indications of a spatial correlation between the metal detecting objects and the geophysical results or the trial trenching observations. The trenching to a large degree confirmed the lack of presence of archaeological features related to the metal detecting objects. This observation is interpreted such that most of the main area of activity has already been lost to coastal erosion, and that the metal objects still found are mainly the result of displacement activity, such as plowing or similar, which dispersed the objects over the area.

The Austrått dataset, on the other hand, revealed a large amount of archaeological activity, and a correlating trend between the location of metal objects and the archaeological interpretation of the GPR data. This dataset also revealed information on the garden archaeology on site, possible burial monuments, and settlement traces all relating to the manor and previous settlement history.

The two case studies show two different ways how geophysical data can provide new information on sites known from metal detecting assemblages. While at Langelangs gaarde there was a lack of spatial relationship, which might be interpreted as the result of coastal erosion, the situation was quite the opposite at Austrått. Here, a close spatial relationship between the two datasets has seemingly been found.

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War related impacts (WRI) in archaeological magnetometer data

Andreas Stele [1*], **Roland Linck** [1,2], **Jörg W. E. Fassbinder** [2], **Christoph A. Rass** [3]

1 Bavarian State Department for Monuments and Sites (BLfD), Archaeological Prospection, Munich, Germany
2 Ludwig-Maximilians-Universität München (LMU), Department of Earth and Environmental Sciences, Geophysics, Munich, Germany
3 University of Osnabrueck, Department of Modern History, Institute for Migration Research and Intercultural Studies (IMIS), Osnabrück, Germany
* Corresponding author: E-mail: Andreas.Stele@blfd.bayern.de

Abstract
The relevance of archaeological prospection in conflict landscape research is briefly outlined. Several examples of WRI in magnetometer data are presented and systematized. For a prediction of filled bomb craters in magnetometer data, respective characteristics are worked out.

Keywords
conflict landscapes; geophysical data interpretation; magnetic prospection; war related impacts

Introduction

Intense shelling, bombardment, and trench warfare, key features of modern warfare, leave a sustained material impact on landscapes. The two World Wars of the 20th century have thus created many landscapes, which often figure prominently in historical narratives and cultures of memory. In fact, modern war leaves massively disturbed, polluted soil landscapes and altered geomorphology. Moreover, the wars of the 20th century often left destructive influences on (older) archaeological features across Europe. Furthermore, wars change landscapes in our present that will soon be history. The impact of modern war thus deserves to be studied with appropriate, and often interdisciplinary, methods. Archaeological prospection plays an important role in this process (Stele et al. 2021).

Regarding archaeological prospecting, impacts such as covered and filled explosive weapon impact craters (EWIC) and unexploded ordnance (UXO) are particularly relevant near the former military or war-related infrastructure. Figure 1 shows how they can be detected quite frequently and unexpectedly during geophysical surveys of older archaeological sites.

EWIC and UXO are often accompanied by other WRI and structures, such as aircraft crash sites or massive fortification earthworks (Fig. 2). Based on geophysical data alone, such findings can be quite difficult to attribute. Magnetometer prospecting can provide useful interpretive approaches, but additional data, such as historical aerial photographs, testimonies, and other historical documents, are often necessary for a reliable assessment of WRI anomalies. Therefore, we aim to improve the understanding of WRI anomalies in magnetometer data. For this purpose, we try to work out some characteristic properties of magnetic anomalies caused by such impacts based on several examples.

Approach

Data of handheld carried total field magnetometer Scintrex SM4G-Special, and fluxgate gradiometer Bartington Grad601 are presented in this extended abstract, but data from other magnetometer types are also used for the study. The WRI anomalies were verified using historical

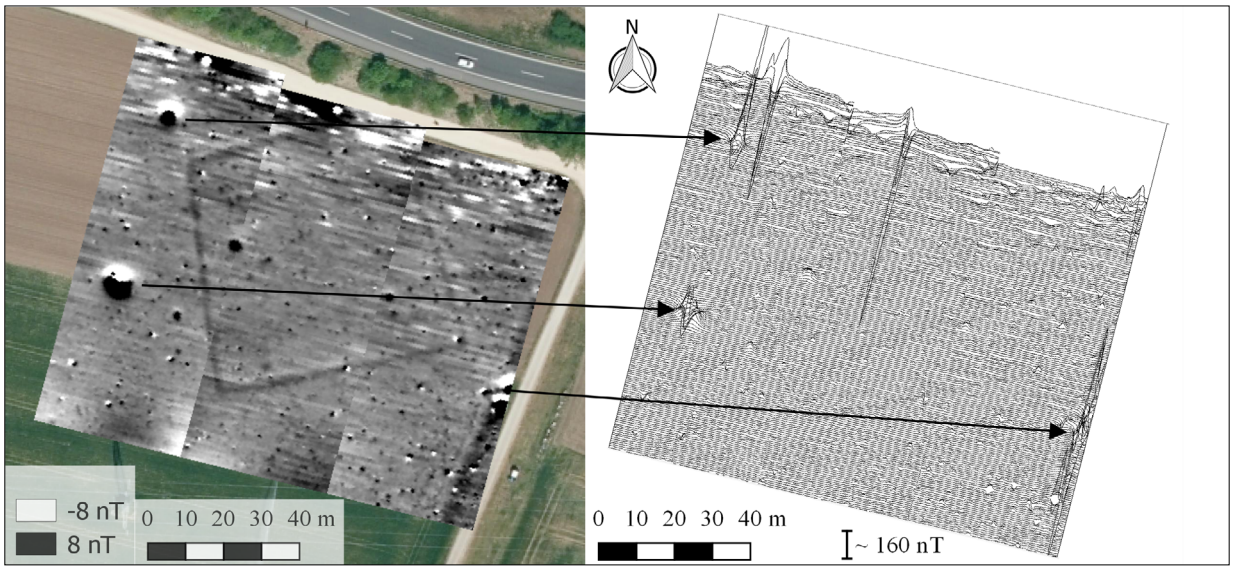

Fig. 1: Feldmoching in the north of Munich (southern Germany). The caesium magnetometer data (left as a shade plot and right as a trace plot) show a Latène square enclosure near the MAN factories, which were bombed by the Allies during the Second World War. Anomalies caused by bomb impacts (WRI-2) are marked with arrows (aerial photograph: ©2022 Bayerische Vermessungsverwaltung).

aerial photographs. This verification and comparing the magnetometer data are carried out using QGIS.

The examples took place in landscapes subject to different intensities of war-related effects during the Second World War. Based on these examples, we first classify the WRI simplistically into three groups:

- WRI-1: Impact craters due to artillery rounds of ~50 kg in average;
- WRI-2: Impact craters created by bombs or rounds of ~250 kg in average;
- WRI-3: Impact craters/features attributable to heavy bombs/missiles over 1000 kg impact weight.

Results

The anomalies in Figure 2 corresponding to craters from artillery shelling in historical aerial photographs occur mainly as positive anomalies with maximum intensities of ~10-20 nT/m. Many of these WRI-1 appear to be contaminated with dipolar, ferrous fragments (shrapnel?). Furthermore, the comparison of areas experiencing different intensities of shelling in Figure 2 shows that the magnetograms in intensively shelled areas appear noisier than in moderately shelled areas. In the presented example, the *Wehrmacht* position trenches are expressed as positive anomalies with an intensity of about 15 nT/m.

The WRI-2 anomalies can have a complex and partly different habitus depending on the magnetometer type. They vary widely in size and show very different intensities (range: from ±30 nT up to >> ±1000 nT). On the other hand, a repeating scheme can be observed mainly for this group: no matter how intense the anomalies are, they show an exact north-south alignment with the negative part of the anomaly in the north in all our measurements (e.g. Fig. 1).

With regard to the orientation and intensity of the anomalies in the magnetic field, a similar scheme can be observed for some WRI-3 anomalies (Fig. 3). However, the size and structure of the anomalies vary particularly strongly in this group. In the example with V-2 rocket impacts presented in Figure 3, a strong dependence of the WRI-3 anomalies on the lithology and soil texture can be derived.

Discussion

It is important to note that the post-impact backfill can contain remnants of the impact (e.g. UXO) and/or objects that have nothing to do with the impact, such as (post-war) iron debris or settlement waste. We can see an increased WRI-1 influence in the form of irregularly distributed shrapnel and the resulting noise in the magnetograms (Fig. 2). If we look at the individual crater anomalies, they are often hardly distinguishable from features that could also be addressed as older (settlement) pits.

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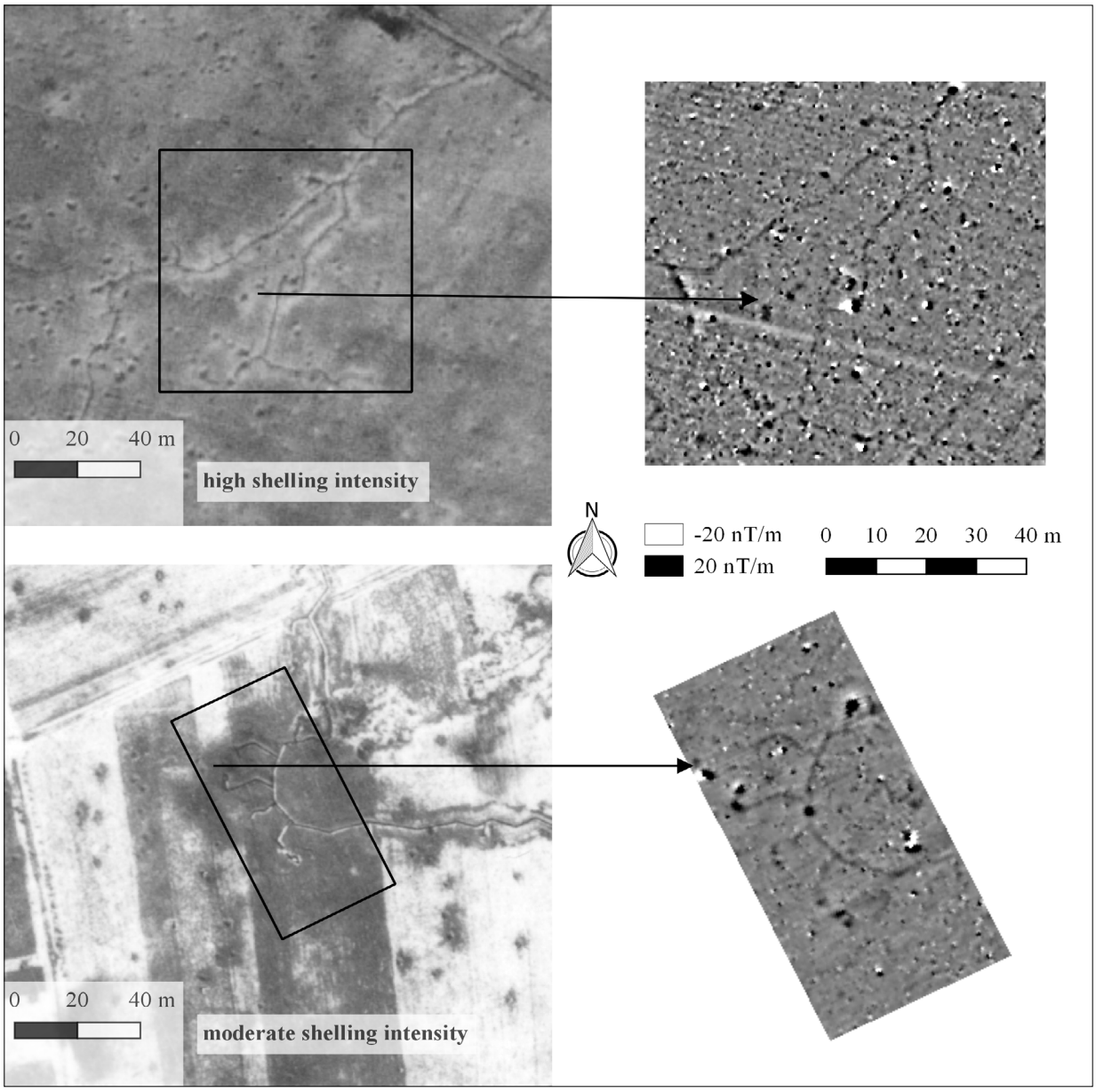

Fig. 2: Areas with artillery shelling of varying intensity in the Hürtgenwald (western Germany) on the left (National Collection of Aerial Photography (NCAP), Scotland). The gradiometer data on the right were acquired for investigating the state of preservation of the *Wehrmacht* position trenches.

For bombs and some rocket impacts, characteristics can be worked out that allow a reliable assumption as a WRI-2 or 3 impact. Anomalies of such impacts are aligned precisely north-south, with a negative part in the north. The intensity of the anomalies depends primarily on what remains in the crater after the explosion. Several scenarios are possible: if only the heated soil material remains, we see thermoremanent behavior that rarely goes above anomaly intensities of ±50 nT; if we observe anomaly intensities above ±150 nT and more, we must expect shock-remanent munition remnants; at anomaly intensities well above ±1000 nT, the presence of UXO is very likely (Stele et al. 2022). However, this repeating scheme does not seem to apply to all WRI-3 impacts (see e.g. Yalding in Fig. 3).

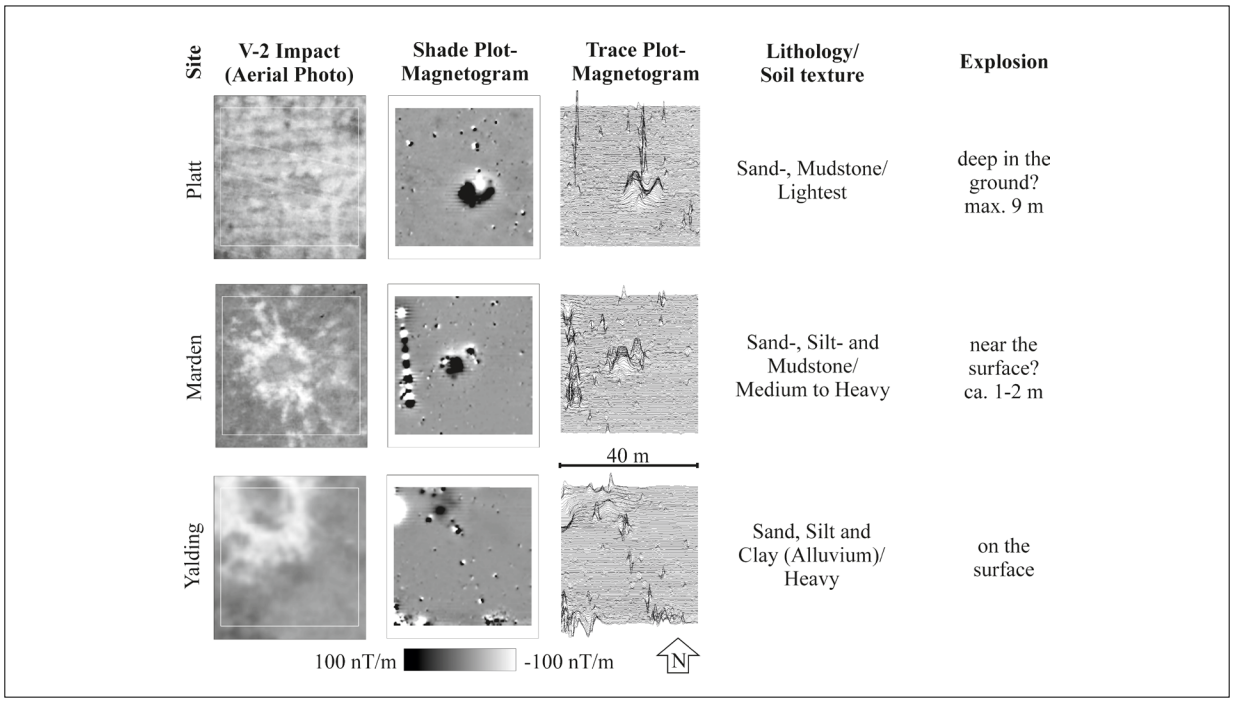

Fig. 3: Three sites with V-2 rocket impacts in the Medway catchment area (Kent, GB). In addition to the dependence on the soil texture, the depth of the explosion can also be deduced from the shape of the crater and the WRI-3 magnetic anomaly (sources: Google, ©2023 Kent County Council (historical aerial photographs); United Kingdom Soil Observatory).

Conclusion

To research WRI-cases, it is always advisable to use historical aerial photographs to interpret geophysical measurements. Multitemporal aerial reconnaissance images are often available for bombarded infrastructure objects. If no historical aerial photographs are available, it is possible to explore the suspected areas for patterns of impact craters using the historical imagery of Google Earth Pro.

Due to their typical north-south orientation with the negative part of the magnetic anomaly in the north, craters of the WRI-2 group are relatively easy to recognize in the magnetograms. More difficult to determine are influences of the WRI-1 and 3 groups. However, there are often different historical sources available for areas with such impacts.

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19th century excavations, research program, geophysical survey and archaeological investigation: converge, complete and reinterpret

Leïla Tickner[1*], Karine Jardel[1], Armin Schmidt[2], Roger Sala[3]

1 Service Archéologie, Conseil Départemental du Calvados, Caen, France
2 Dr Armin Schmidt - GeodataWIZ, Remagen, Germany
3 SOT Prospecció Arqueològica, Spain
* Corresponding author: E-mail: leila.tickner@calvados.fr

Abstract
We used GPR to delineate a building excavated in the 19th century. Data from old excavations and geophysical surveys are incorporated in the methodology applied to developer-led archaeology in France. The case study exemplifies the benefits of a cross-disciplinary approach as to allow a better interpretation of archaeological data.

Keywords
developer-led archaeology; ground penetrating radar; Roman baths; trial trenches; 19th century excavations

Introduction

Under the current village of Vieux (Calvados, Normandy, France) lies buried the Gallo-Roman city *Aregenua*. The latter has been subject of considerable excavations since the sixteenth century. The last decades have been particularly rich in ancient discoveries thanks to the archaeological investigations carried out by the *Conseil Départemental du Calvados* with various research excavations including the *forum* of the city. These data were supplemented by those from developer-led archaeology (or rescue archaeology), thus gradually filling in some of the remaining gaps. Although the overall urban fabric is known, much of the site remains to be explored. To do this, the use of geophysical prospecting as a non-invasive tool appeared to be perfectly adapted to the type of research conducted in Vieux.

Thus, in 2017 a ground penetrating radar (GPR) survey was undertaken on a private plot of land where, in the 19th century, excavations had indicated the presence of a monumental building. At the time of the survey, no excavations or subsequent investigations were planned in this area. However, a development project (building extensions and trenches for utility pipes) was applied for in 2021 and hence an archaeological investigation was required.

The 19th century excavations

The "Manoir de la Pallu" is a building of the early seventeenth century located in the heart of the current village of Vieux. Several archaeological investigations have taken place within the grounds of the manor.

In 1841, excavations were carried out by the *Société des Antiquaires de Normandie* in the garden of the manor. Three walls were unearthed to form a building with dimensions of 12.66 m x 10.66 m x 5 m, with a preserved elevation of 2.66 m. The hypothesis favored was that of a bathhouse, similar to the one excavated in the seventeenth century (Gervais 1841). Other historians and archaeologists considered it to be the *forum* of the ancient city (Pilet 1983).

The discovery and excavation of the forum made this latter proposal obsolete and the building excavated in 1841 was hence still awaiting identification.

Materials and methods

Three geophysical survey grids were placed in the site of the "Manoir de la Pallu" (GP-5.1, GP-5.2 and GP-5.3) with

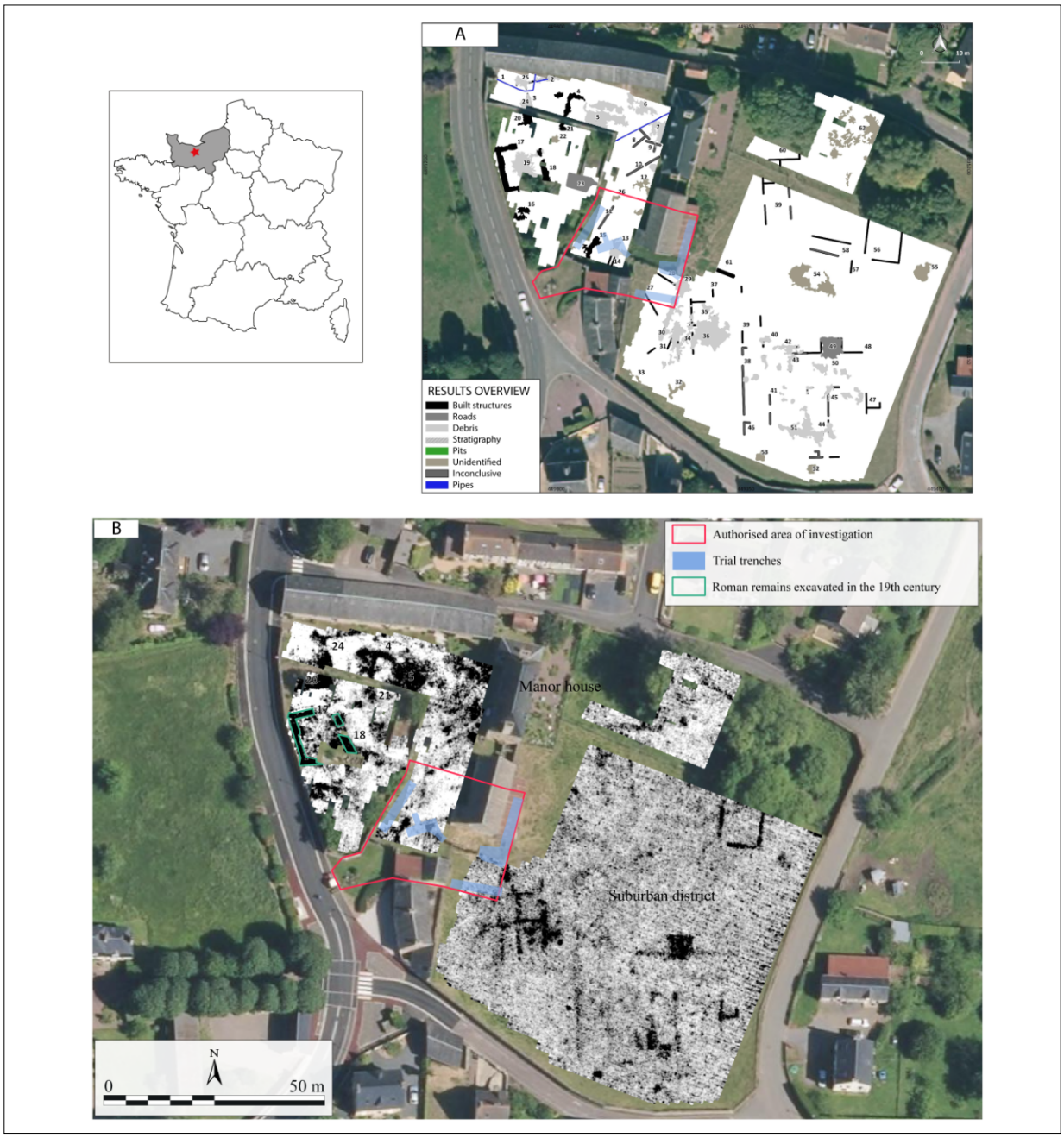

Fig. 1: a) Overview of the results of the GPR survey (SOT Prospecció Arqueològica) (base map: ©IGN 2012 (CD14)), b) Slice 19 (depth between 1.05 m and 1.17 m) of the survey in the manor grounds (base map: ©IGN 2020 (CD14)).

a total area of 6116 m². The GPR survey was carried out with an IDS custom system based in the Fast-Wave GPR module, using a stack of 5, 600 MHz independent antennae. The data had a spatial resolution of 0.02 m x 0.20 m (parallel profiles of 0.20 m separation and readings every 0.02 m) over the entire extension explored. Following their acquisition, the data were filtered and then integrated into a three-dimensional block using the "GPR-Slice" software. This block allowed the creation of a sequence of 24 depth slices of reflectivity of 0.12 m thickness for depths between 0 and 1.46 m. The depth estimations were based on a reference velocity of 0.1m/ns. This appeared to be too optimistic considering the archaeological results.

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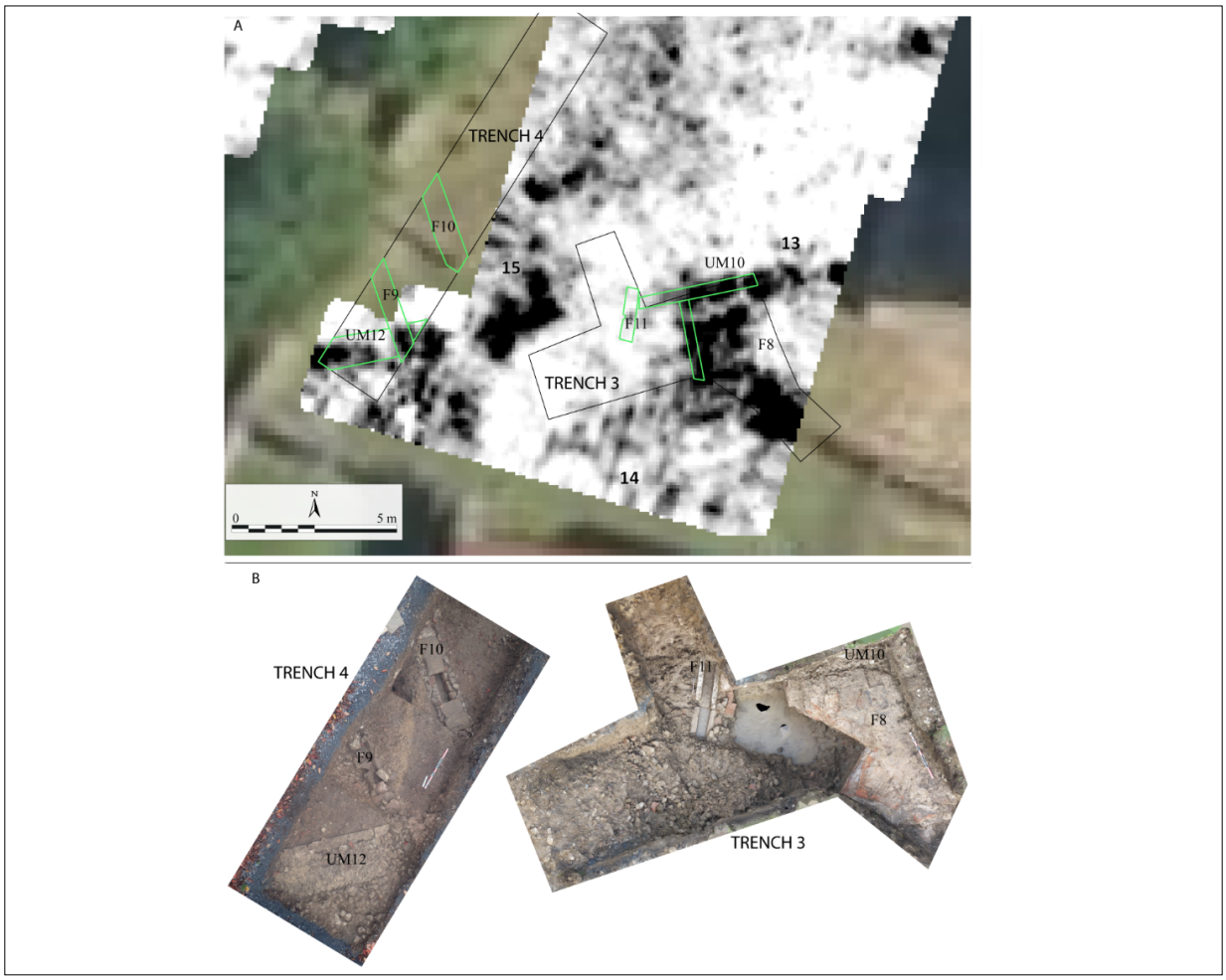

Fig. 2: Detail of the results in the southern part of the manor's courtyard, trenches 3 and 4. a) Slice 15 (depth between 0.82 m and 0.95 m) of the survey superimposed with the outlines of the excavated structures (base map: ©IGN 2020 (CD14)). b) Digital orthophotographies (© Pierre Rohée) of the excavated trenches 3 and 4.

Results

The geophysical survey

The data collected show a rectangular building whose dimensions are very close to those given by the antiquarians: 0.25 cm below the current level and at a minimum depth of 1.50 m. Another anomaly (group 20-24 – Fig. 1) emerges north of this building. This anomaly has a reflectivity similar to that of the monumental building and seems to follow the same orientation. It is not difficult to imagine that it belongs to the same complex or, at least, that they are contemporary. A third built structure (group 4-5-21 – Fig. 1), has a different orientation from the groups already described but aligns with the buildings of the "Manoir de la Pallu". It is thus suggested that these elements are contemporary with the latter. The field to the east of the manor also shows many radar responses that delineated remains following the ancient urban fabric, hence suggesting a peripheral or suburban district of the ancient capital.

In the courtyard of the manor, below the garden, several diffuse anomalies are indicated without forming a coherent whole (Fig. 1 group 13-14, anomalies 15, 11, 26).

Trial trenching in 2021

The objective of archaeological trial trenches is to excavate shallow trenches in order to assess the archaeological potential and prepare a possible full excavation. In the case of the manor, the antiquarians' data and the geophysical survey made it possible to estimate the density of the remains. The trenches were thus positioned according to these data and with regard to the planned construction, part of which was unfortunately outside the already sur-

veyed area. Four trenches revealed many built remains as well as a graveled surface (road or courtyard).

Discussion: data comparison

The only excavated structures that appear clearly in the GPR data are the wall UM10 and the platform F8 in trench 3 (anomaly 13, seen between 0.82 m and 1.50 m deep on the GPR data – Fig. 2). These anomalies are clear and contrasting, with outlines and orientation identical to the portions of structures unearthed. On the other hand, the depths of appearance of these built elements do not correspond with the depths of the geophysical slices. The platform F8 and the wall UM10 were found directly under the topsoil layer, about 0.55 m thick, while they appear around 0.80 m deep in the radar data, showing an overestimation of the velocity of GPR pulses. On the other hand, its thickness of at least 1 m indicated by the survey was confirmed.

This trench also made it possible to observe the interruption of UM 10 on its western limit, forming an opening. Slice 15 indicates a void at this location over a length of 3.4 m, overlooking a new anomaly (anomaly 15 – Fig. 2) which draws an angle whose southern wall shares the same axis as UM10. This anomaly could therefore be the continuity of UM12 observed in trench 4. This void corresponds to the passage of the F11 aqueduct (- 1.20 m) whose continuity is observed beyond trench 3 (group 14 – Fig. 2), confirming its extension to the south.

The wall UM12 does not appear clearly in the geophysical data although it lies only 0.15 m below the current ground level. Indeed, its signal is quite diffuse and its outline can only be guessed thanks to its excavation, unlike group 15. South of the latter, the low reflectivity could indicate occupation/abandonment surfaces related to UM12.

Some built structures identified in the geophysical survey were not excavated in the trenches, anomalies 27 and 30 in particular (Fig. 1). On the other hand, the aqueduct F10 does not appear in the GPR data while having been uncovered in trench 4 (Fig. 2).

Conclusion

The comparison of excavation and geophysical data makes it possible to affirm the presence of an important complex (UM10, F8, F11, UM12 and groups 15 and diffuse signal south of UM12), which is extending southwards. This complex lies in the same orientation as the building excavated in 1841, indicating that they may be contemporary. The remains found during the investigation - several aqueducts, a platform built in waterproof Roman cement (a possible bath chamber) - , compared with the data from the 19th century excavation indicate that this is a large thermal building (1450 m²), which quite certainly includes groups 17-18-19, 15-14-13 and 20-24-25 of the radar data.

In the technical side of the GPR survey, the case shows two interesting issues to be noted: the estimation of GPR velocity in urban and sub-urban environments could be difficult, as soils are too variable in composition and therefore susceptible to important imprecisions when using a general estimation.

A second issue is the lack of shallow structures or horizontal features in the time-slice sequences. This shows the importance of time-slice parameters and metrics (previous data-processing, lapse of time/depth, magnitude, real data resolution). The interesting case of wall UM12, despite laying only at 0.15 m depth, was not clearly defined in the time-slices sequence used on the report. It would be probably visible using slightly different parameters in the time-slice creation.

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Bridges to the past – the Roman settlement of Emmersdorf/Rosegg, Austria

Ralf Totschnig[1*], Jakob Gallistl[1], Alois Hinterleitner[1], Klaus Löcker[1], Hannes Schiel[1], Ingrid Schlögel[1], Mario Wallner[1], Tanja Trausmuth[1], Christian Gugl[2]

1 Near Surface Geophysics, GeoSphere Austia, Vienna, Austria
2 Department of Classical Studies, Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria
* Corresponding author: E-mail: ralf.totschnig@geoshere.at

Abstract
A large-area archaeological prospection of a roman bridgehead settlement using aerial photography, magnetics and GPR was conducted. The roman bridgehead settlement of Emmerdorf/Rosegg is one of the best preserved Roman settlements in Austria.

Keywords
ground penetrating radar; large-area survey; magnetics; multi-method; Roman rural settlement

Introduction

Rosegg in Carinthia has for a long time been known for its early Iron Age graveyard near Frög, but since 2003 new finds illustrate the importance of the area also for late Iron Age and Roman times. Multiple Roman funerary monuments were found during excavation works north of the river Drava along with a building inscription and a piece of an altar (Piccotini 2010). Several poles driven in the riverbed of the Drava and a single iron pile shoe indicated a former wooden bridge in this area, where a ford has been used since prehistoric times.

In 2015, the archaeological park "Keltenwelt Frög-Rosegg" got possession of a collection of small finds from the area around the site of the stone monuments (Drotleff 2019). The collection comprised some 1500 late Celtic and Roman coins, five Carolingian coins and about 75 late Iron Age and Roman iron, bronze, and lead pieces. The follow-up excavation by the provincial museum of Carinthia in 2017 (Gleirscher 2017; Gleirscher 2018) showed the remains of two pile bridges next to each other and more iron pile shoes. Dendrochronological analyses of the wooden finds by Innsbruck University indicated that the bridges have been constructed successively and date to the late 2nd and the middle of the 3rd centuries AD (Gleirscher et al. 2020). It seems that in the area of the ford and both bridges sacrificial acts took place, which can be traced through the coins found dating to the 2nd and 1st century, although there are still finds from the 3rd and 4th centuries (Schachinger 2020).

During a geophysical prospection commissioned by the Austrian Federal Monuments Office in 2020 to investigate the area of the late Iron Age and Roman finds, remains of a large Roman bridgehead settlement were found in Emmersdorf, north of the Drava. Since the measurement did not cover the entire settlement area, additional measurements were carried out in 2021 and 2022 to find further settlement remains on both banks of the Drava and to try to map the total extent of the settlement.

Materials and methods

The magnetic survey of about 15 ha was carried out using a motorized measurement system with eight FEREX CON650 probes in a line of 25 cm (Fig. 1). An area of more than 8 ha of GPR data was surveyed using a Sensors & Software SPIDAR multichannel system with six 500 MHz antenna pairs with a line spacing of 25 cm (Fig. 2). The geophysical data have been processed using the APSoft



Fig. 1: Magnetic data image of the Roman settlement of Emmersdorf/Rosegg (background data provided by INSPIRE BEV).

software package by ZAMG (Trinks et al. 2018) and the resulting images and data integrated into ArcGIS Pro for further interpretative mapping.

The Roman settlement

The magnetic data image (Fig. 1) shows multiple strong anomalies and altogether the picture of a large-area rural settlement with buildings, roads, pits, ditches, and large areas with debris. Some of the buildings show clear signs of hypocausts, Roman floor heatings. Other areas, especially in the north of the Drava, seem to contain the remains of workshops. The settlement covers an area of at least eight hectares in the north and one hectare in the south of the Drava. To the north, the vicus seems to be confined by a road leading east-west. This road has connections to roads leading into the settlement and further on to the bridges over the Drava. South of the river the settlement appears to be less widespread, possibly containing only a few buildings along the road leading south from the river (Fig. 3).

The GPR data of course show a much clearer picture of the vicus (Fig. 2). The northern part of the settlement holds numerous stone and brick buildings, where the western part could have the character of public buildings together with private houses. The central part shows workshops and storage buildings, whereas the eastern part seems to be dedicated to ritual activities and might also contain a graveyard. The southern part of the settlement shows only few buildings, a large house, and a single storage building, marked by numerous stone pillars, possibly belonging to a villa complex (Fig. 3).

Conclusion

During the non-destructive archaeological investigations, the extensive remains of a Roman settlement were discovered on the fields between Emmersdorf and St. Lambrecht in the north and east of the modern cemetery in Rosegg south of the Drava with the help of magnetic and ground penetrating radar prospection. From the data images, conclusions can be drawn about the size and structure of the Roman settlement of the 1st to 4th centuries AD. Apart from the Roman cities of Virunum (Zollfeld) and Teurnia (St. Peter in Holz/Upper Carinthia), this is the most com-

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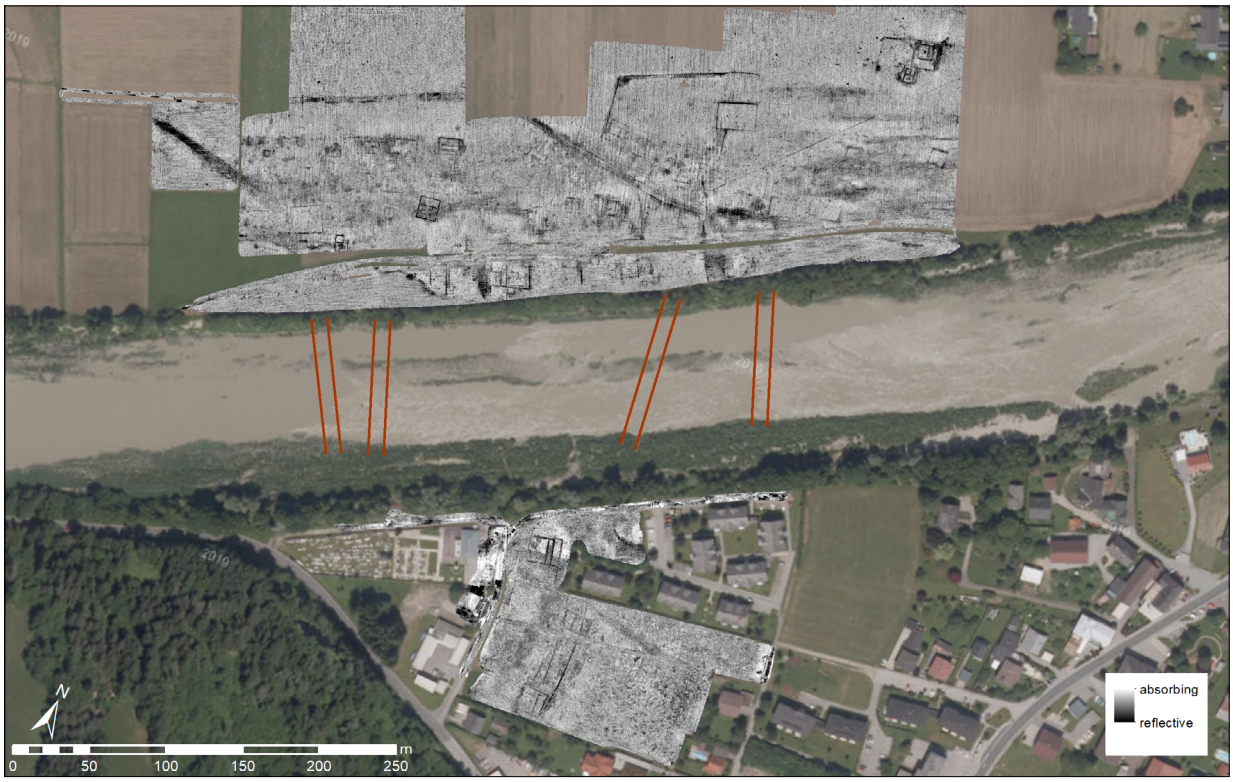

Fig. 2: GPR depth slice (0.3 to 1.0 m depth) of the Roman settlement of Emmersdorf/Rosegg (background data provided by INSPIRE BEV).



Fig. 3: Archaeological interpretative map of the Roman settlement of Emmersdorf/Rosegg (background data provided by INSPIRE BEV).

plete ground plan of an ancient settlement in today's Carinthia. In the present data images, several streets as well as numerous buildings and graves can be recognized. A very good preservation of the Roman building structures in the ground can be assumed, due to the thick covering of the remains of the Roman walls. The building remains on both banks of the Drava are clearly connected to the Roman wooden bridges examined in 2017. The discovery of this village-like settlement in Emmersdorf and Rosegg puts a whole new complexion on the Roman finds, marble fragments of tombs and sanctuaries, coins, and metal finds that have repeatedly come to light in the riverbed of the Drava.

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Non-invasive research of the deserted enclosed medieval villages in South Moravia (Czech Republic)

Michal Vágner [1*]

1 Department of Archaeology and Museology, Masaryk University, Brno, Czech Republic
* Corresponding author: E-mail: vagner@phil.muni.cz

Abstract
The combination of non-invasive methods and written historical and map sources brought a lot of new information about the phenomena of enclosed medieval villages in the region of South Moravia. The research revealed how the village's ground plan looked like, how it evolved, what the possible function of the village's ditch enclosure was, what it may have looked like, or how and from where this type of settlement got into this region. The magnetic survey also indicated from what materials the individual village houses could have been built. The research also resulted in new information on the transformation of the settlement network in the investigated region in the Middle Ages.

Keywords
deserted medieval villages; enclosed areas; geophysical survey; remote sensing; settlement structure

Introduction

Thanks to aerial photography carried out in the South Moravian Region (southeastern part of the Czech Republic) at the beginning of the 1990s, a few medieval villages were discovered that were, in the past, enclosed by several meters wide ditch (Bálek and Unger 1996). In recent times, the same type of enclosure in other deserted medieval villages has been identified by remote sensing as well as analysing historical maps (Vágner et al. 2020). A total of 35 settlement units (originally villages, some of which later evolved into towns) were identified within the investigated area, which exhibited some form of the external enclosure during the Middle Ages (Fig. 1).

In 2021, the previous research was extended and summarised in the author's doctoral thesis (Vágner 2021). The work aimed to extend our knowledge regarding the overall internal layout of the deserted villages, on the form and character of the individual components – rural houses, ditches, sacral buildings or feudal residences. Another task was to answer questions about where and how this type of site could have reached the region of southern Moravia.

Materials and methods

In order to elucidate the presented questions, non-destructive archaeological methods were used – primarily geophysical prospecting accompanied by remote sensing and the study of historical maps and written sources. The magnetic prospection was carried out at nine selected sites and covered a total area of 98.25 ha. Where it was necessary from the point of view of solving specific questions, other geophysical methods were also used – ground penetrating radar (GPR) and electrical resistivity tomography. In particular, the magnetometry survey allowed for an effective investigation of the large settlement area; the targeted GPR survey provided different points of view on selected features identified by the first method. Aside from GPR, electrical resistivity tomography was also used to estimate the depth of the ditches.

Results

The most frequently represented ground plan type in the set of investigated localities was the communication village (lined around a road or a watercourse) or the village common type with a regular or planned geometrical/stan-

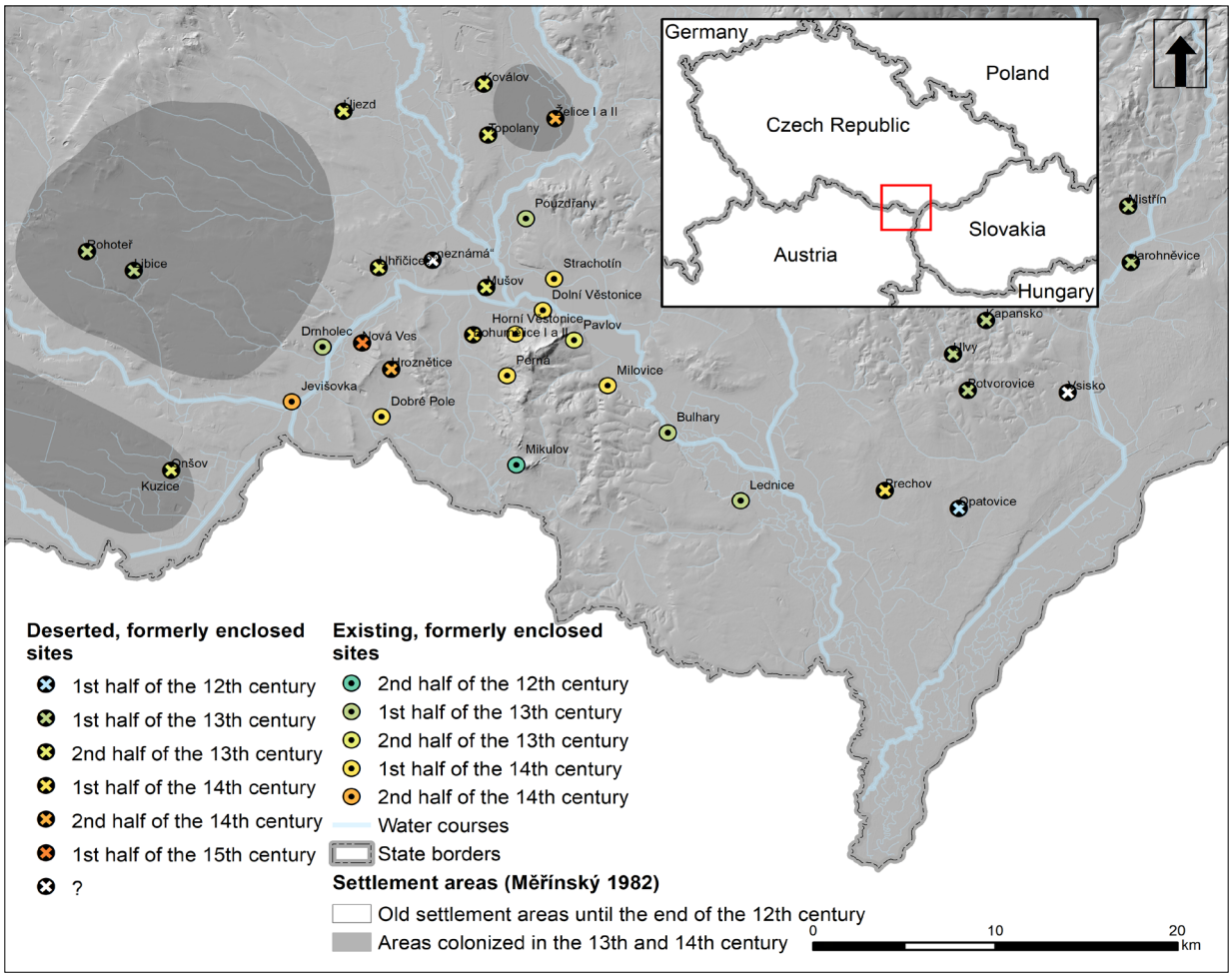

Fig. 1: Deserted and existing, formerly enclosed settlements (villages, towns, cities) in the South Moravia Region (base map: ČÚZK; DIBAVOD).

dardised ground plan. This type of appearance is probably a matter of the second half of the 13th century and corresponds to the first mentions from written sources of the individual investigated sites. At the two locations investigated, two almost identical, side-by-side fenced areas were captured, which can be explained by the relocation of villages to new areas. This phenomenon was then best documented and described for the case of the deserted medieval village "Bohumělice" (Fig. 2).

In the vast majority of cases, the identified settlement features tended to cluster in strips oriented perpendicular to the central element of the village – a communication area or a watercourse. Based on their concentration, shape, size and orientation, it was possible to determine the hypothetical locations of individual homesteads in most of the investigated locations. Stone was not used to a greater extent to construct residential and other buildings. It can be assumed that the prevalent construction techniques for individual houses had been based on using clay, wood or a combination of both. The stone was used only for the construction of functionally distinguished buildings – churches or feudal seats. The primary function of the outer enclosure was a legal function. The external enclosure clearly defined its scope concerning property rights when the village was founded or rebuilt. The question of the genesis of this type of settlement is closely related to the legal function of enclosed villages, i.e. how (and with whom) the walled villages could reach the territory of South Moravia. Based on the gathered information and parallels from abroad – especially from Germany and Lower Austria (Vágner 2021; Biermann and Mangelsdorf 2005; Civis 2015; Filzwieser 2018; Kühtreiber 2015; Scharrer-Liska 2007), the origin of these locations can be linked to the spread of German law in the followed territory.

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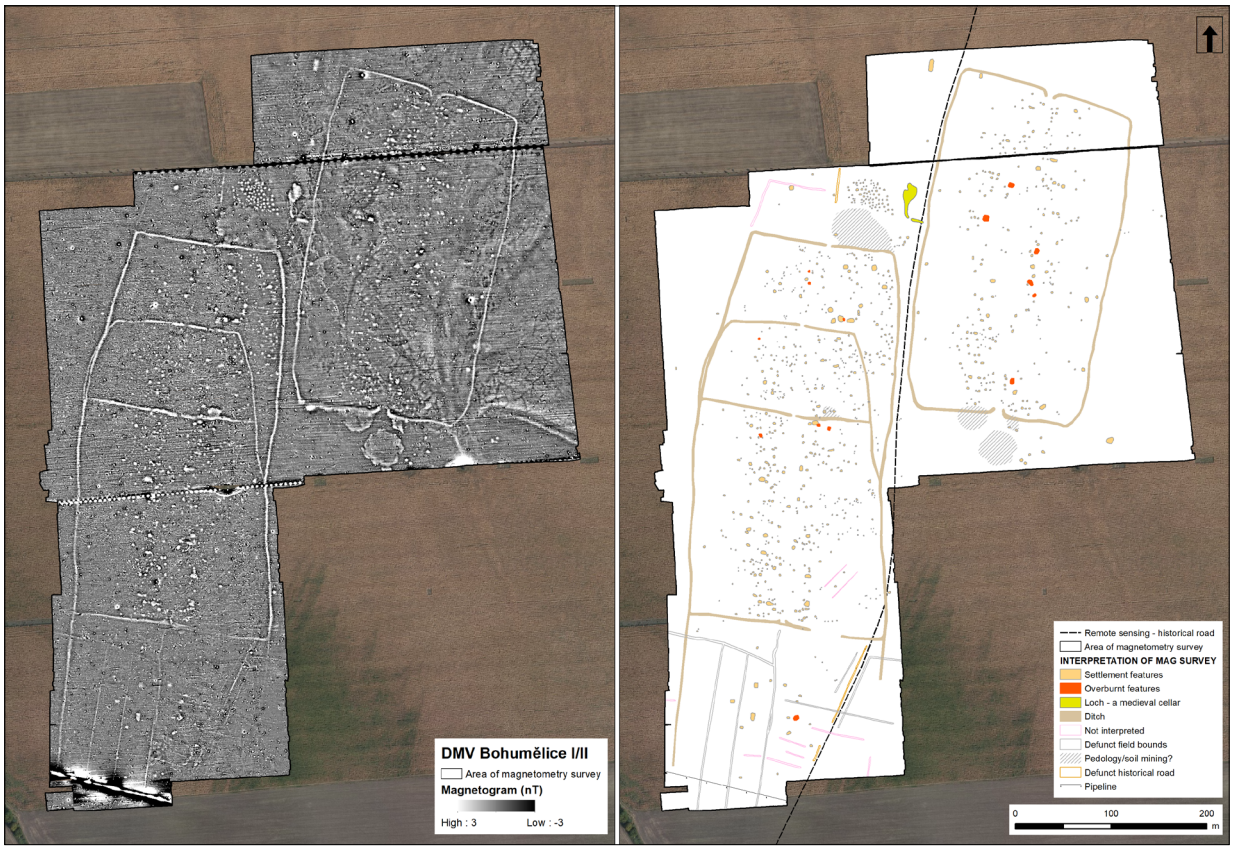

Fig. 2: Results of magnetic prospection on the deserted medieval village Bohumělice. The original establishment of the village most likely reflects the more westerly enclosed area ‹Bohumělice II›. Based on ceramic fragments, it can be dated to the second half of the 13th century/14th century. The younger complex ‹Bohumělice I› can be dated to between the second half of the 14th century and the turn of the 14th and 15th centuries (base map: ČÚZK).

Discussion and conclusion

The combination of remote sensing and geophysical methods, as well as field walking and studying of historical sources, showed that a large amount of information about deserted medieval villages can be quickly and efficiently obtained in the flat and long-term agriculturally cultivated landscape of South Moravia. According to the obtained information and analogies, it can be assumed that the fenced village settlements are related to colonisation processes, the beginnings of which are generally placed at the turn of the 12th and 13th centuries. Several parties were involved in the transformation of the settlement network in the area of South Moravia. In addition to land-lord activities, which at that time consisted rather than in the establishment of village settlements in the founding of new towns, in this respect, one can think about secular power in the form of lower nobility, as well as ecclesiastical authority. In the first case, the family of the Sirotci, followed by the Schenks and the Lichtensteins, is the most likely. The second category most likely included monasteries.

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Test with ImpulseRadar Raptor GPR array at Gisacum (Vieil-Évreux, France), and comparison with MALÅ MIRA

Lieven Verdonck [1*], **Michel Dabas** [1]

1 Archéologie et Philologie d'Orient et d'Occident (AOrOc), UMR 8546, École Normale Supérieure, Paris, France
* Corresponding author: E-mail: lieven.verdonck@ens.psl.eu

Abstract
The ImpulseRadar Raptor-45 GPR array was tested. The instrument achieves a high signal-to-noise ratio, also at high survey speed. Lifting the sensors off the ground introduced multiple reflections. 3-D migration can enhance these multiples in profiles and time-slices. Fast data acquisition by lifting the sensors should be balanced against data quality.

Keywords
air-launched vs. ground-coupled; groundpenetrating radar; multi-antenna array; multiple reflections; 3-D migration

Introduction

On 7 September 2022, a test was carried out with an ImpulseRadar Raptor-45 groundpenetrating radar (GPR) array instrument at the Gallo-Roman sanctuary of Gisacum, near Évreux, Normandy, France (Guyard 2005). The test was conducted over the western *fanum*, where electrical resistance, magnetometry and GPR surveys have previously taken place (Dabas 2009; Novo et al. 2012). A hitherto unpublished survey with a MALÅ MIRA GPR array, carried out in August 2012, provided suitable data for comparison.

Instruments, data acquisition and processing

The ImpulseRadar Raptor-45 was deployed in two configurations (Tab. 1) by René Ruault (Georeva, France). The first one consisted of 18 channels (10 transmitters and 9 receivers with centre frequency 450 MHz), and was mounted behind a small van, 5–10 cm above the surface. This allowed fast data collection: an area of 1.3 ha was covered in 1 hour and 40 minutes. A manually pushed, ground-coupled, 8 channel ImpulseRadar array was used to survey an adjacent area. The results were compared with data collected in 2012 by Mike Langton (Guideline Geo, Sweden) with a ground-coupled MALÅ MIRA towed by an ATV, consisting of 8 channels with frequency 400 MHz.

For all three surveys, cross-line spacing was 0.08 m. An estimation of the dielectric permittivity by means of migration velocity analysis resulted in a slightly higher value for the 2012 MIRA survey (Tab. 1). The moisture content, and its possible influence on conductivity and attenuation, can therefore be assumed to be somewhat higher for the 2012 data, complicating exact comparison with the 2022 ImpulseRadar survey. All data were processed using the same workflow, including dewow (1-D high-pass filter which from each temporal sample in the trace subtracts the mean of a window of 20 samples (4 ns) centred around the sample to be corrected), time zero alignment, gain, band-pass filtering, background removal and 3-D phase-shift migration.

Results and discussion

Due to the high data acquisition rate, enabling the stacking of multiple traces also at high survey speed, the ImpulseRadar data show little random noise (Fig. 1a) and a somewhat larger penetration depth (≈ 1.8 m) than the

Instrument	No. of channels	Frequency (MHz)	Inline spacing (m)	Crossline spacing (m)	Deployment	Area (ha)	Duration (min)	average wave velocity (m/ns)	average relative dielectric permittivity
Impulse Radar Raptor	18	450	0.03	0.08	lifted off the ground	1.29	100	0.1107	7.3
Impulse Radar Raptor	8	450	0.05	0.08	ground-coupled	0.06	30	0.1145	6.9
MALÅ MIRA	8	400	0.08	0.08	ground-coupled	0.62	200	0.1021	8.6

Table 1: Data acquisition parameters.

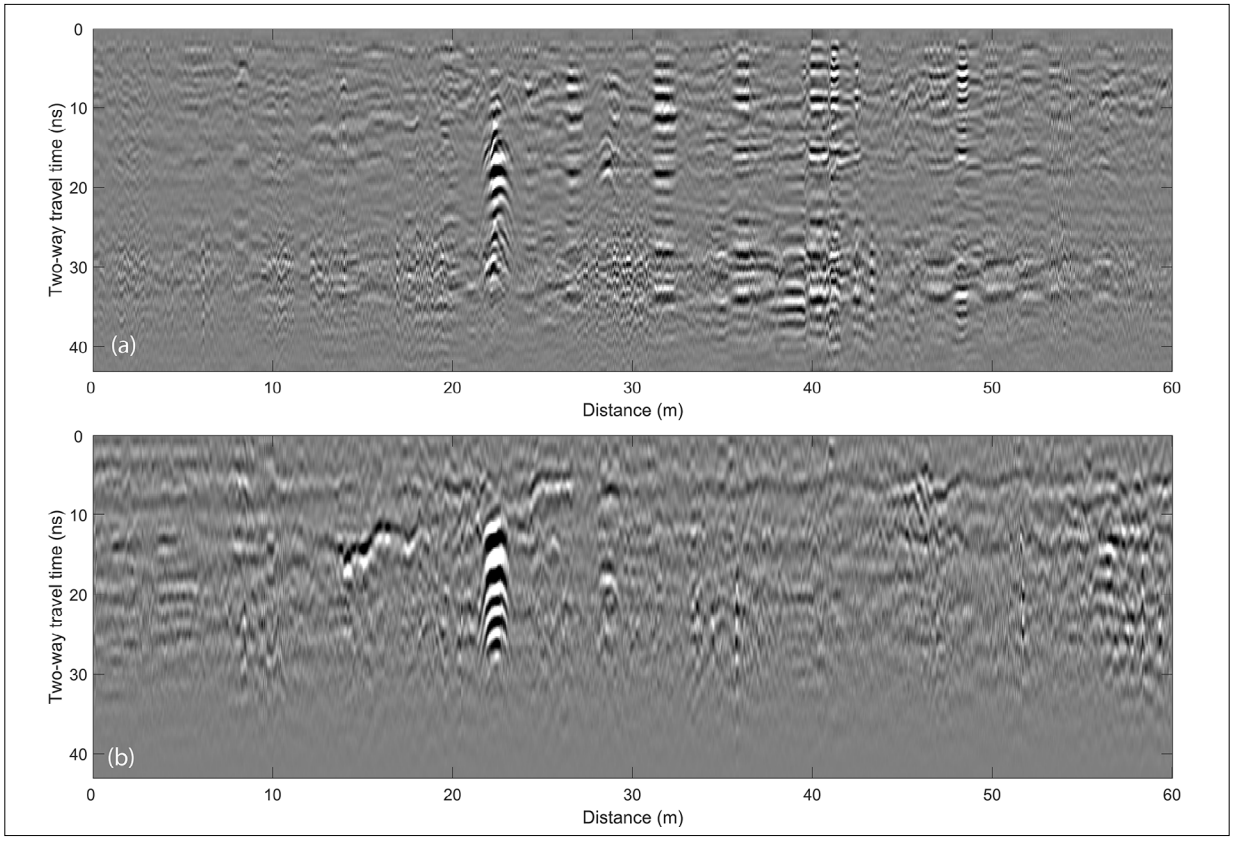

Fig. 1: a) Profile collected with the vehicle-mounted ImpulseRadar Raptor-45, after background removal, showing a wall reflection at 22 m, and remnants of multiples. b) Same profile, collected with the MALÅ MIRA.

MALÅ (~1.5 m, although the slightly wetter soil conditions may also play a role here). In the profiles collected with the ImpulseRadar, repetitive horizontal reflections are visible, because the waves were reflected back and forth between the slightly elevated antennae and the surface. Also after background removal (subtraction of the average of the complete profile from each trace) numerous anomalies remain, since the multiple reflections are not perfectly horizontal, but follow the uneven surface (Sala and Linford 2012). In the profiles collected with the ground-coupled MALÅ instrument, these are much less apparent (Fig. 1b).

In the time-slices, these multiples form noise stripes with higher amplitudes where shallow furrows run in N–S direction (Fig. 2a). In Figure 2 c), these are visualized in

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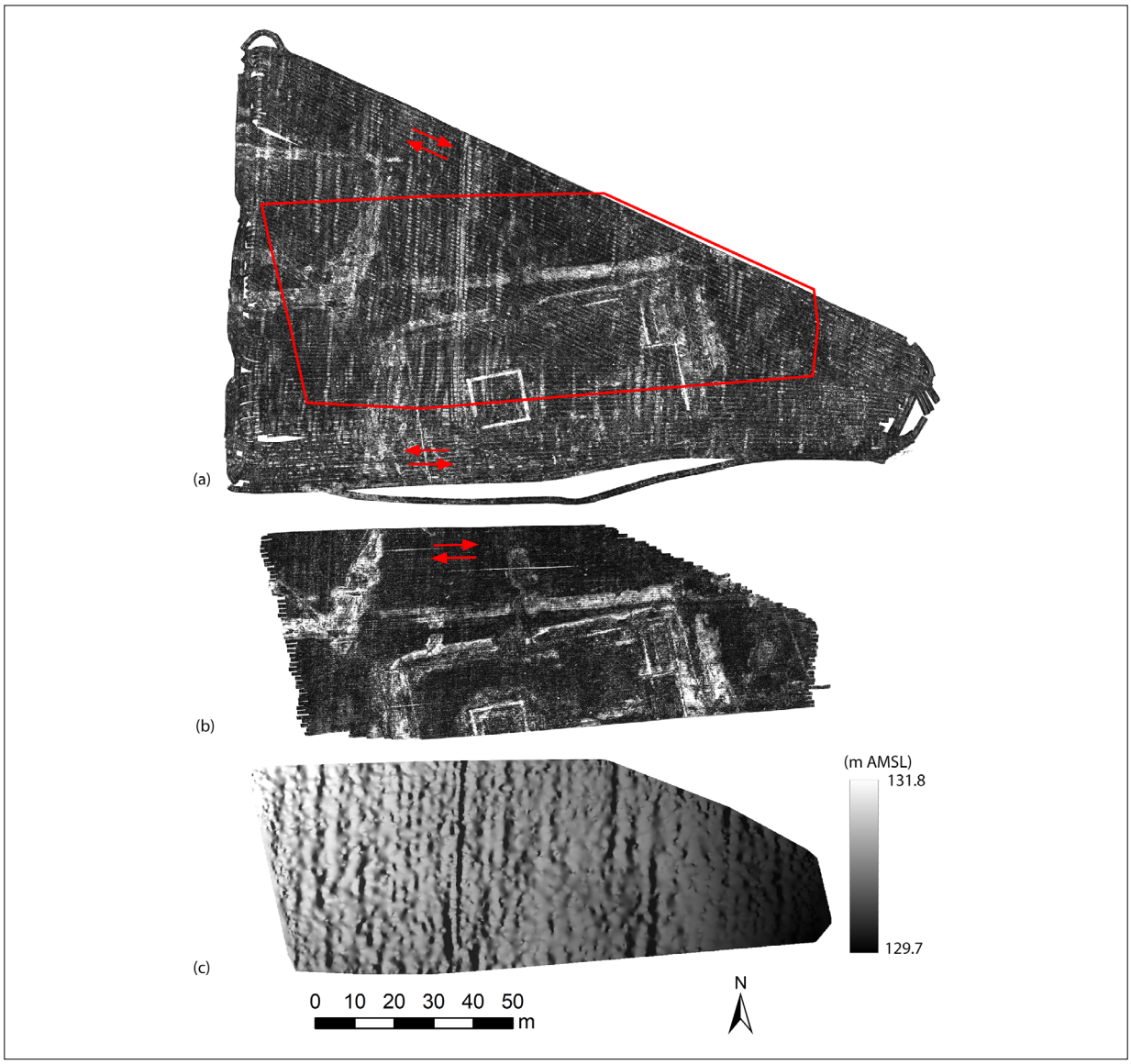

Fig. 2: a) – b) Time-slices at 7–8 ns, after background removal, based on data collected a) with the vehicle-mounted ImpulseRadar and b) with the MALÅ MIRA. The perimeter of the slice in b) is indicated in red in a). The arrows indicate the direction of the transects. c) Hillshade representation of the digital elevation model based on RTK GNSS measurements acquired simultaneously with the MALÅ MIRA survey.

a hillshade representation of the digital elevation model. When compared to the MALÅ data (Fig. 2b), the noise hampers the interpretation of the archaeological structures, mainly in the shallower slices. By contrast, in the data collected with the manually pushed, ground-coupled ImpulseRadar the noise patterns visible in the vehicle-mounted dataset are absent. Data quality seems affected even if the elevation of the antennae is very small (hence this deployment cannot be called 'air-launched': Diamanti and Annan 2017).

The noise found in the vehicle-mounted ImpulseRadar data can complicate 3-D migration, which improves horizontal resolution (Fig. 3a – d compares unmigrated, 2-D and 3-D migrated data). Migration cannot handle multiple reflections, which in crossline direction often appear as separate anomalies, because of the different response of the individual channels in the array (Fig. 3e). Whereas migration focuses the energy of diffraction hyperbolae, it expands multiples (Fig. 3f), so that destriping algorithms (Verdonck et al. 2013) can become less effective. For exam-

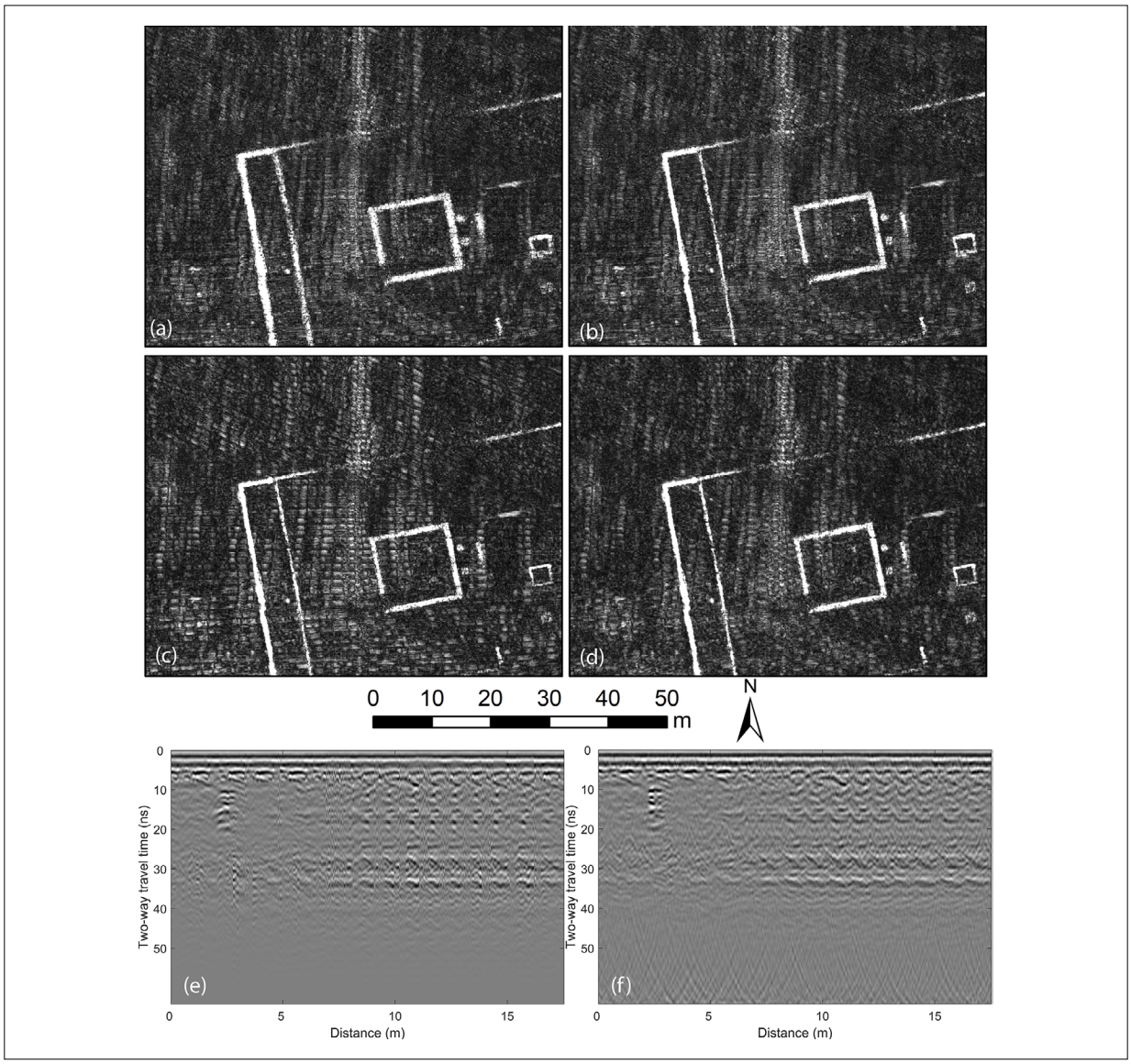

Fig. 3: Time-slices at 17–18 ns, showing results obtained with the vehicle-mounted ImpulseRadar, a) before migration. b) After 2-D migration. c) After 3-D migration. d) After 3-D migration and application of a destriping algorithm using a short window in the direction of the transects. e) Cross-line profile showing a buried wall (at 2.5 m) and multiple reflections, before migration. f) After 3-D migration.

ple, non-migrated and 2-D migrated data (Fig. 3a – b) were adequately destriped by balancing the channels in the array (using the median of the complete transects). However, this method proved insufficient when applied to the 3-D migrated data (Fig. 3c). A better result was obtained by using a short window in the direction of the transects. For each measurement in the window, the closest neighbours in cross-line direction were selected (not necessarily belonging to the same swath), and of these measurement series, the median was equalized (Fig. 3d).

Conclusion

Tests with an ImpulseRadar Raptor-45 array produced data with little random noise. In the vehicle-mounted configuration, with the array slightly elevated above the surface, multiple reflections originating from the air-ground transition are visible, also after background removal. The effect of these multiples can be enhanced by 3-D migration. Therefore faster data acquisition by lifting the sensors off the ground should be balanced carefully against data quality.

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Non-invasive depth estimation of Delos quarries

Quentin Vitale [1,2*], **Cécile Finco** [3], **Jean-Charles Moretti** [4]

1 Éveha International, Ivry-sur-Seine, France
2 Université de Lyon, CNRS, Archeorient, UMR 5133, Maison de l'Orient et de la Méditerranée, Lyon, France
3 Université de Rouen, CNRS, M2C, UMR 6143, Rouen, France
4 CNRS, IRAA, Maison de l'Orient et de la Méditerranée, Lyon, France
* Corresponding author: E-mail: quentin.vitale@eveha.fr

Abstract
A lightweight geophysical survey method was used to estimate quarry filling layer thickness based on EMI and DCP data.

Keywords
archaeological prospection; Delos; dynamic cone penetrometer; EMI; quarry thickness estimation

Introduction

The island of Delos is an important archaeological site in Greece, despite it being one of the smallest islands in the Cyclades. Mythologically, it is said to be the birthplace of Apollo and Artemis and enjoyed high religious prestige and aura. Its famous sanctuary, combined with its port and its importance in trade in the Hellenistic era, led to the development of the island and its urban expansion. As a result, from the third millennium BC until the sixth century AD, hundreds of public and private buildings were erected in Delos, constructed using both local and imported materials from the surrounding islands or mainland Greece. In 2018, the multidisciplinary research project GAD (Geology and Architecture at Delos) was launched and aims to study all the stages in the use of stone in the monuments of Delos, from its extraction in a quarry to its implementation. It is led by J.-Ch. Moretti and funded by the French National Research Agency. Estimating the total volume of rock extracted on the island is a key part of this research project and the main objective of the work presented in this paper.

Twenty open pit quarries which exploited gneiss and granite have been identified in the northern part of the island. These quarries are now partly filled with a mixture of blocks of rocks and fine sediments of an undetermined thickness. The determination of this thickness is crucial for the estimation of the total volume of extracted rock. Estimating the thickness through direct digging was not possible within the framework of the project. During spring 2022, geophysical and geotechnical methods have therefore been used in this initial investigative study of the quarries on the northern part of the island. This project took place in the framework of the work of the French School at Athens, in partnership with the Ephorate of Antiquities of Cyclades.

The underlying hypothesis for this paper is that there are significant mechanical and electrical contrasts between the filling layer of the quarries and the geological substratum. As it is at least partly composed of fine and salty sediments, the filling layer is expected to be more conductive and less compact than the bedrock. The objectives were (1) to confirm the existence of this contrast and propose a simple and easy-to-implement methodology that could then be applied to all the quarries and (2) to get a first estimation of the filling layer thickness on a few sample quarries.

As this was an initial study, light acquisition equipment was used to perform electrical soundings (ES), frequency-domain electromagnetic induction (EMI) measurements and dynamic cone penetrometer (DCP) soundings.

Materials and methods

The lightweight dynamic cone penetrometer used in this study (the PANDA® by Sol Solutions, Fig. 1) characterizes the mechanical resistance of the ground by driving a rod



Fig. 1: Implementation of DCP sounding (top left), EMI mapping (top right) and example of quarry configuration (bottom) in Delos.

into the ground. The simultaneous measurement of the variable strike energy and the penetration depth of the rod after each blow allows us to calculate the ground resistance at the rod tip and to discriminate ground layers based on their mechanical properties. Due to the limited number of rod segments available, the maximum depth the DCP could reach was approximately 2.25 m. The rod can only pass through relatively soft media and would not penetrate the substratum. A stoppage is however not a definitive indication that the rod reached the bottom of the quarry as it could have encountered a block of rock. Nevertheless, these soundings give an important indication of the minimum thickness of the filling layer as the substratum cannot be above the penetration limit of the rod.

Electrical soundings were performed using a versatile and lightweight resistivity meter (the 4point light 10W by Lippmann Geophysikalischen Messgeräten) to provide a 1-D model of the ground electrical resistivity with depth. A simple Wenner configuration was used and the electrode spacing was limited to a maximum of 15 m due to the available cable length.

As EMI is also sensitive to the electrical properties of the ground and is able to map soil conductivity with different depths of investigation, it was used in order to map the filling layer when possible and also as a complementary dataset to the ES. EMI soundings were attempted where mapping was not possible, using measurement at three different heights above the ground. Although the filling layer thickness has yet to be determined, it could

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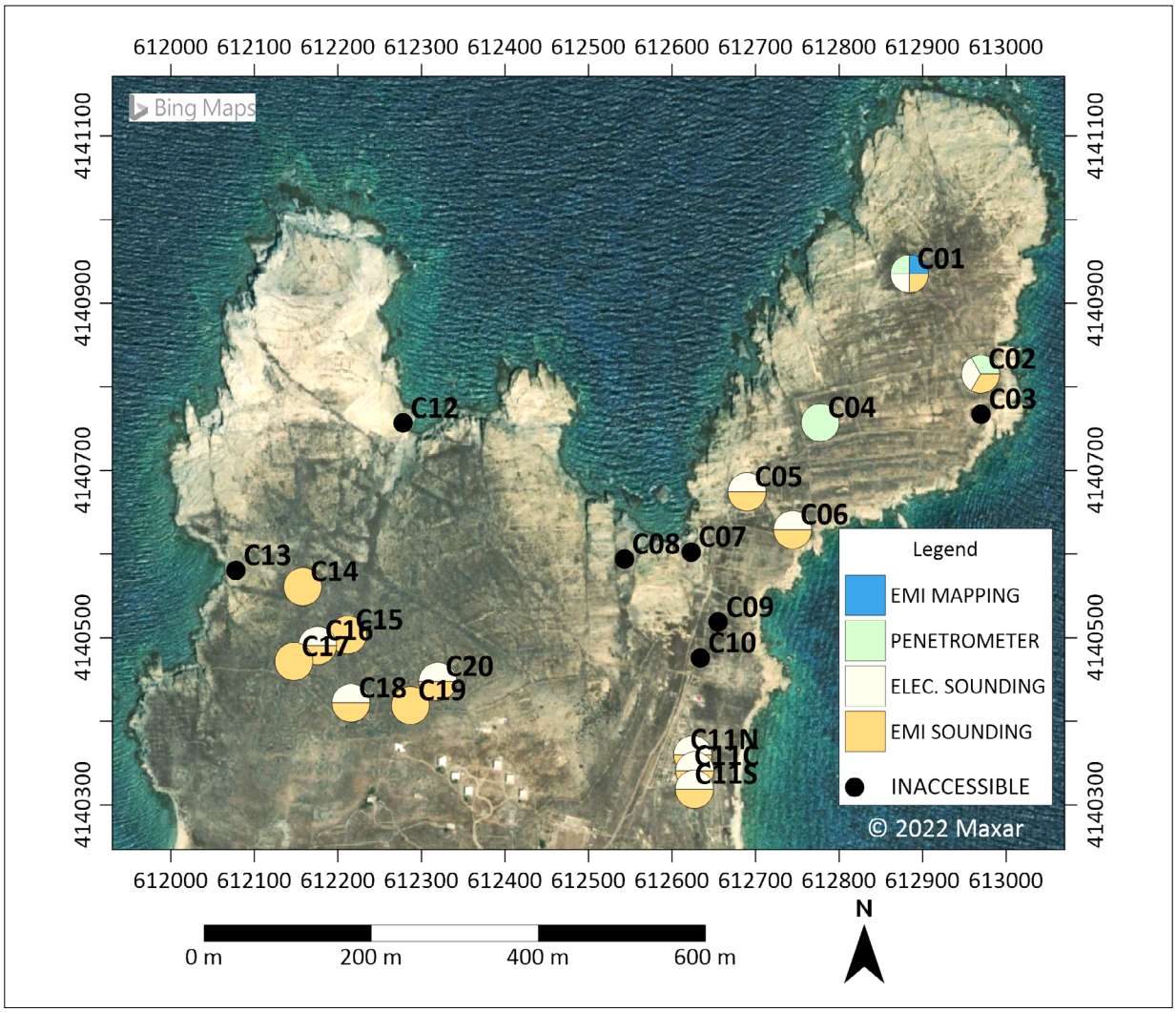

Fig. 2: Implemented methods on each quarry of the north of Delos.

potentially be several meters thick. A CMD-Explorer (by GF Instruments, Fig. 1) was therefore used as it offers at least three different penetration depths ranging from one to approximately six meters.

As the quarries' configuration and geometry are very different, it was not possible to implement all geophysical methods in all of them. Some were filled with water, blocks of rocks or vegetation and were therefore inaccessible. In order to have a general overview of the northern part of the island, ES and EMI soundings were acquired in all of the accessible quarries. In addition, quarry C01 was chosen as a test area for more detailed research because of its favourable geometry (Fig. 2). We were able to use all the available methods for soundings (ES, EMI, DCP) and establish a full EMI map for this quarry.

Results and discussion

The ES acquired on the different quarries all showed a very conductive filling layer (from 35 Ωm to less than 10 Ωm), confirming the existence of contrasting electrical properties. However, because this layer is so conductive, the estimation of its thickness would require a long electrode array as well as an important injection power. Because of the limited extension of most quarries, the resistive underlying substratum could not be reached, and the thickness of the filling layer was not estimated using this method.

The attempted EMI soundings did not prove to be satisfactory: only the middle height measurement (~1 m) seems to be sufficiently reliable to be inverted. Including

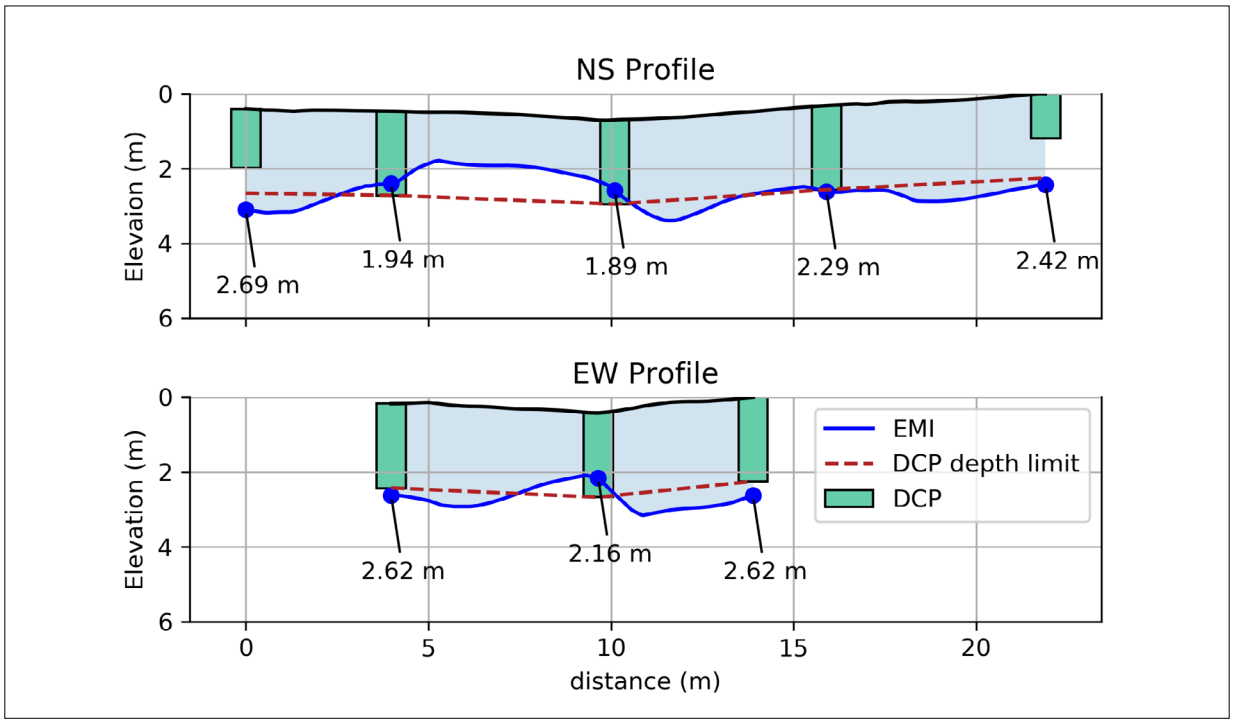

Fig. 3: Comparison of DCP and EMI results on the north-south and east-west profiles of the quarry C01 of Delos.

the other heights only resulted in a less reliable estimation of the sub-soil thickness. The EMI soundings were therefore disregarded. However, the EMI mapping in both HCP and VCP configurations (Rejiba et al. 2018), as implemented in quarry C01, resulted in a very promising thickness estimation.

On C01 (Fig. 2), two perpendicular ES were acquired in the quarry's center. DCP and EMI soundings were acquired along two profiles oriented north-south and east-west and a full EMI map of the quarry was established. The DCP located in the center of the quarry all reached the limit of 2.25 m (Fig. 3), indicating a minimum depth of the quarry. The profiles extracted from the EMI inverted map show comparable results with a maximum estimated thickness close to 2.80 m.

Conclusion

Up to four lightweight geophysical methods were implemented on the north of the island of Delos to try to estimate the quarries' filling layer thickness. Due to the variety of quarry configurations, it was only possible to implement all the geophysical investigation techniques we intended to use on one of the quarries. Electrical and electromagnetic soundings turned out to be mainly unsuitable for the site but confirmed the existence of contrasting electrical properties between the filling layer and the substratum.

The DCP soundings showed convincing results, although the depth of investigation had to be limited to 2.25 m. They provided a minimum thickness of the filling layer in the quarries.

EMI mapping led to thickness estimates broadly in agreement with the DCP results, although this thickness appears to be underestimated at the center of the quarry.

For future investigations, the use of additional rod segments and of a mechanical rod extractor would make it possible to remove the rods more easily from the ground and therefore to exceed the limit of 2.25 m of rod penetration set for this study. Furthermore, at the widest electrodes spacing, the signal-to-noise ratio was often poor and the use of a more powerful resistivity meter would make it possible to implement ERT profiles crossing the quarries with a better chance of reaching the substratum. Finally, other methods, not tested during this first study because they were too heavy to transport and implement, could be considered for future acquisitions in selected quarries, such as the seismic method as it is sensitive to mechanical contrasts.

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The more, the merrier? A multi-methodological survey at the Roman town of Carnuntum

Mario Wallner[1*], Christian Gugl[2], Alois Hinterleitner[1], Jakob Gallistl[1], Klaus Löcker[1], Ingrid Schlögel[1], Franziska Reiner[2], Adrian Flores-Orozco[3], Clemens Moser[3], Jürgen Zeitlhofer[4]

1 Department of Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
2 ÖAI - Austrian Archaeological Institute, ÖAW - Austrian Academy of Sciences, Vienna, Austria
3 Department of Geodesy and Geoinformation, Technical University of Vienna, Vienna, Austria
4 Armaments and Defence Technology Agency, Austrian Armed Forces, Federal Ministry of Defence, Austria
* Corresponding author: E-mail: mario.wallner@geosphere.at

Abstract
We have newly discovered the garrison of the governor's guard, the castra singularium, in the Roman Town of Carnuntum. For a more detailed research we decided to apply a multi-method research approach on this important archaeological site. The analysis of the different geophysical prospection methods was carried out prior to an archaeological excavation. By excavating a small area, the interpretations of the non-destructive methods could be evaluated.

Keywords
Carnuntum; evaluation excavation; multi-method survey; Roman archaeology

Introduction

The Roman site of Carnuntum was once a flourishing center on the frontiers of the Roman Empire. Through a large-scale archaeological prospection project, this huge area could be investigated and analyzed in great detail using nondestructive prospection methods (Wallner et al. 2021). One of the main discoveries of the project was observed in the military settlement, where it was possible to identify a military camp, interpreted as the garrison of the governor's guard. Through the archaeological analysis of the immediate surroundings, the Roman fort was determined to be embedded in a large administrative complex related to the seat of the Roman governor at Carnuntum (Gugl et al. 2021).

The garrison of the governor's guard in Carnuntum

In the area between the governor's palace (A) and the military training ground (C) a massive enclosing wall of a large building complex (B) was visible in the archaeological prospection datasets (Fig. 1).

Thanks to the unique situation in Carnuntum, the vast administrative center of a Roman province was not overbuilt by modern structures. This results in an incredible field of activity for the non-destructive investigation of this archaeological site (Fig. 2). We will summarize our efforts made so far and will compare the results of the different applied methods.

Materials and methods

As early as the 1960s, it was possible to derive the first images of the Roman settlement of Carnuntum from aerial photographs. However, it was not until the large-scale geophysical prospections in the 2010s that the entire urban landscape could be explored in detail. Here, mainly motorized magnetics and ground penetrating radar systems were used. However, at the area presented here, additional methods were applied to generate a comparative data set, which should reveal the potential of each individual method (see Fig. 3). All systems were operated with an

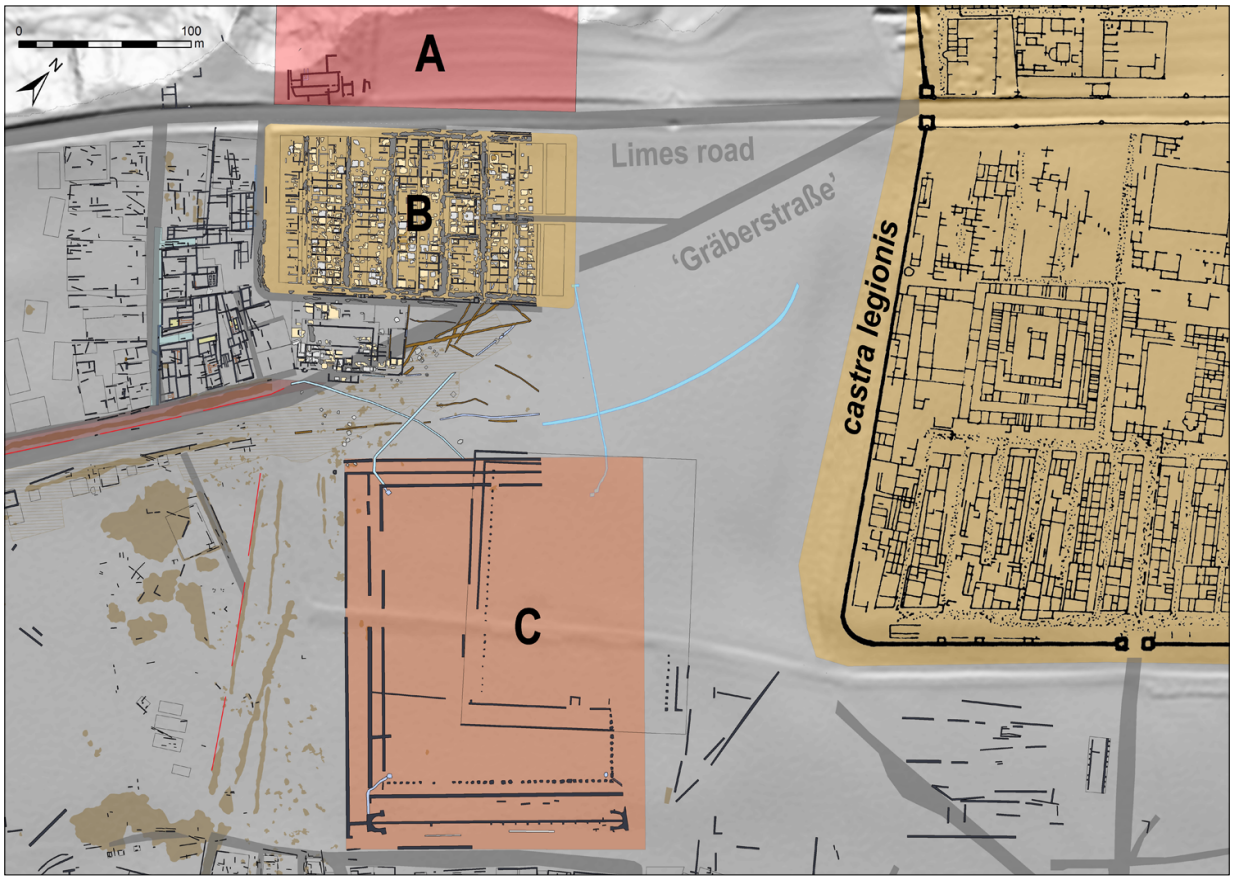

Fig. 1: Current archaeological interpretation of the area southwest of the legionary fortress representing the administrative district of Carnuntum consisting of A = governor's palace (*praetorium*), B = garrison of the governor's guard (*castra singularium*) and the C = military training ground (*campus*).

RTK-GNSS to ensure the accurate georeferencing of the measurements.

Aerial photographs

The development of vegetation marks depends on many factors and therefore the buried remains underneath the surface are not always visible. Unfortunately, the area discussed here did not show clear vegetation mark over many years. Only the extremely dry springs and summers of recent years revealed clearly recognizable structures.

Ground penetrating radar (GPR)

The motorized GPR survey using a Malå 16-channel 400 MHz MIRA system was carried out two times, but with perpendicular surveying directions. The diagonally staggered arrangement of the antennas achieves a measurement resolution of 8 × 4 cm. The dataset was processed using the ZAMG in-house ApRadar software.

Magnetometry

A motorized magnetic survey was conducted using 8 Foerster FEREX CON650 gradiometer probes with a line spacing of 25 cm on a six-meter long custom-built survey cart. The speed of the survey vehicle was adapted not to extend the inline spacing to more than 10 cm. The dataset was processed using the ZAMG in-house ApMag software, resulting in georeferenced grayscale images with a resolution of 10 cm² per pixel.

Electric Resistivity Tomography (ERT)

Measurements were collected with the DAS-M instrument (MPT-IRIS instruments) using 96 stainless electrodes distributed along 8 parallel lines and 12 electrodes in each line, with a separation of 1.5 m between electrodes. To achieve a real 3D configuration, current injections were performed in odd lines with voltage dipoles located in the even lines, and subsequent collections after reversing these. Data were processed using normal-reciprocal analysis (Flores

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Fig. 2: The Garrison of the Governor's Guard (a) aerial photo overlayed with GPR visualization (depth slice 80–200 cm) (orthophoto: M. Wallner), (b) archaeological interpretation of GPR dataset.



Fig. 3: The applied methods: (a) GPR - 16-channel 400 MHz MIRA, (b) Magnetometry – Fluxgate probes, (c) EMI – CMD Explorer, (d) EMI – DUALEM-21HS, (e) EMI - EMD2, (f) ERT – DAS-M, (g) percussive core drilling, (h) stratigraphic excavation.

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Orozco et al. 2012) and ResIPyfor the inversion. A resolution of 30 cm was achieved in the 3D imaging results.

Electromagnetic Induction (EMI)

Lateral changes in subsurface electrical conductivity were mapped using four different instruments: the CMD Explorer and CMD Mini-Explorer (by GF Instruments), the DUALEM-21HS and EMD2 (by Sensys), thus providing apparent conductivity information for a large variety of coil separations and coil orientations.

Targeted percussive core drilling

By targeted percussive core drilling, it is possible to gain a microinvasive insight into the stratigraphic nature of the site. Hereby a metal cylinder, driven into the ground, is used to recover a continuous and, as far as possible, undisturbed sequence of layers of sediments.

Stratigraphical excavation

One of the most challenging areas for the archaeological interpretation of the surveyed area was chosen for an evaluation excavation. The excavated area (10 m x 15 m) is located in the administrative building (*principia*) of the military camp. The excavation was carried out following the stratigraphic method and documented as digital surfaces generated by photogrammetry.

Results

The potential of large-scale, non-invasive prospection methods has been widely recognized in archaeology in recent years. Our study reveals the possibility to extend the details in the investigation when combining high resolution GPR and 3D-ERT. Additionally, EMI maps confirm the structures defined with ERT and increase the resolution, and facilitate quick mapping. The extensive investigation of Roman Carnuntum by the combined application of a wide variety of survey methods resulting in detailed information on its ancient infrastructure.

Through the detailed investigation, by means of various archaeological prospection methods (aerial photography, GPR, magnetometry, ERT, EMI, stratigraphical excavation), it is now possible to gain far-reaching conclusions about the administrative center of a Roman province.

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The Roman burgus of Trebur/Astheim in FDEMI multi-system data

Dennis Wilken [1*], Elena Appel [2], Peter Fischer [2], Lea Obrocki [2], Timo Willershäuser [2], Sarah Bäumler [1], Thomas Becker [3], Andreas Vött [2]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Institute of Geography, Johannes Gutenberg University, Mainz, Germany
3 Hessian State Office for Monuments and Sites, Archaeological Unit (HessenARCHÄOLOGIE), Field office Darmstadt, Darmstadt, Germany
* Corresponding author: E-mail: dennis.wilken@ifg.uni-kiel.de

Abstract
We present a rare multi-system FDEMI survey at a Roman burgus in Hesse (Germany). The dataset shows the benefits of EMI/ERT system combination for investigating archaeology and embedding paleolandscape.

Keywords
archaeological prospection; ERT; FDEMI; Hesse; Roman castle

Introduction

During the 1st century AD the Romans performed several river alterations in the vicinity of the River Rhine in Hesse. These planned water ways were of great strategic and economic importance and were protected by small forts, the so-called burgi (Heising 2012). In this work, we investigate such a fortress near the town of Trebur-Astheim. Its construction is dated to AD 364/375 (Heising 2012). The fortress belonged to the Rhine Limes of late Antiquity and controlled the supply of two bodies of water on the right bank of the River Rhine (Heising 2012). Due to the exposed position, such systems could only be supplied from the riverside. The fortification walls were usually open to the river, providing a protected harbor in which the ships could be safely landed. This combined function – fortress and sheltered pier – corresponds to the ground plans of most of these structures on the rivers Rhine and Danube (Heising 2012).

Earlier earth resistance mapping performed by Posselt and Zickgraf in 1999/2000 using the RM15 device revealed a first floor plan of the fortress. A tower-like core (burgus) stood in the center of the fortress. Slightly less massive wing walls were attached to its narrow sides. From here, the wing walls led into the river and shielded a 45 m wide section of the bank as a harbor basin (see Fig. 1a). A shallow ditch surrounded the entire building at about 20 m distance (Heising 2012).

Excavations in 2003 showed that all Roman remains were completely missing because of stone robbery (Heising 2012). The Roman surface may have been about 80 cm higher than today. The only layers from the Roman period were found in the filling of the enclosing ditch, which was designed as a flat, trough-shaped ditch with stepped walls (Fig. 1b). Nothing was left of the original fortress, although foundation ditches reflect the former structure quite well.

In this work we investigate how those kinds of features can be investigated with frequency domain electromagnetic induction (FDEMI) data. This has three reasons. First, magnetic gradiometry often shows a low contrast of Roman remains to the sandy background sediment of the region, so another fast mapping method is needed for archaeological heritage purposes in Hesse. Second, we know of a contrast in conductivity, and third, when using different coil separations in different EMI devices, we pose the question, whether it is possible to access both, fluvial landscape and archaeological remains.

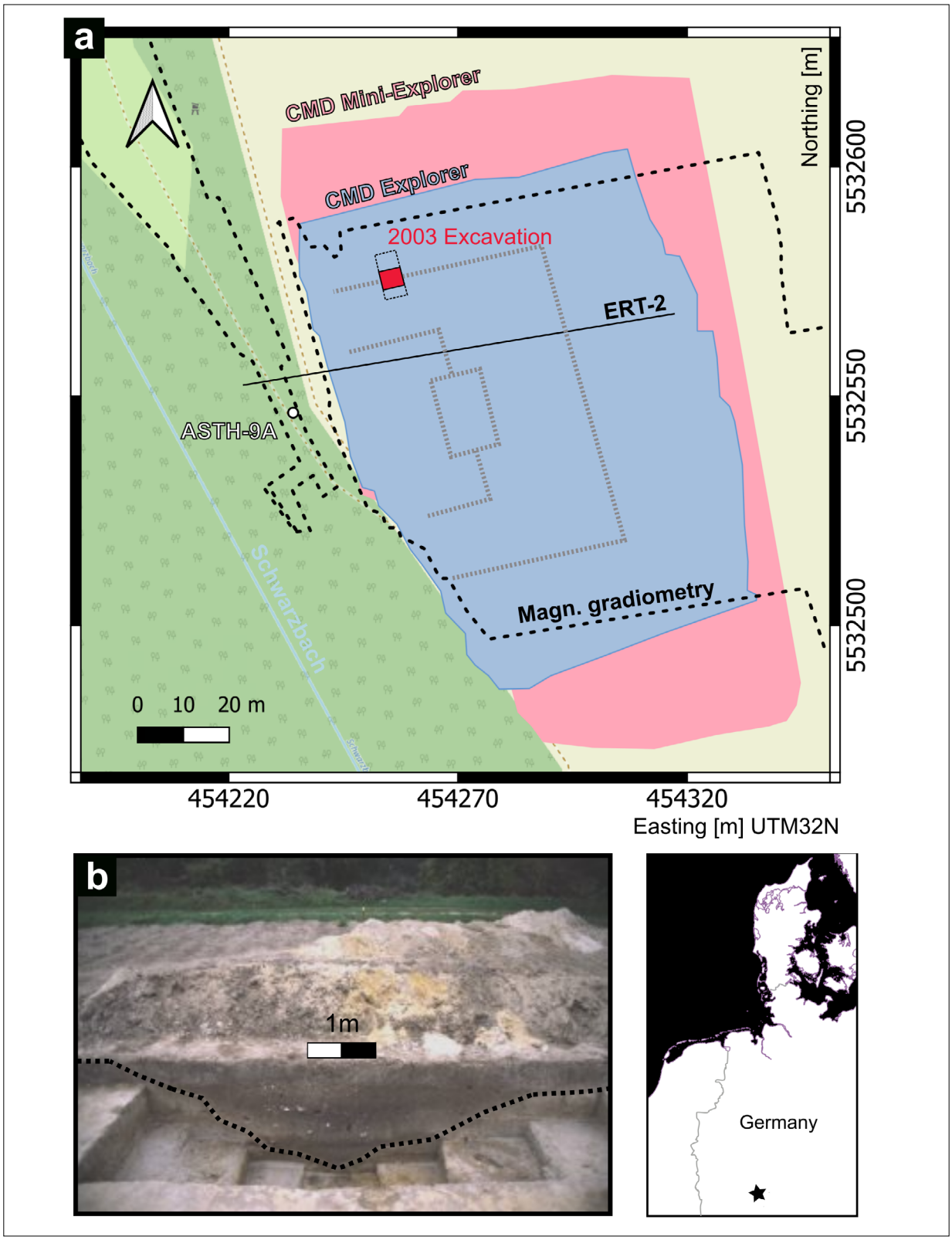

Fig. 1: a) Map of the investigation site and outlines of the different measurement areas, profile and core. The gray dashed line indicates the foundation ditches of the fortress as derived by ERM. b) Profile of a test pit crossing outer ditch (after Heising 2003).

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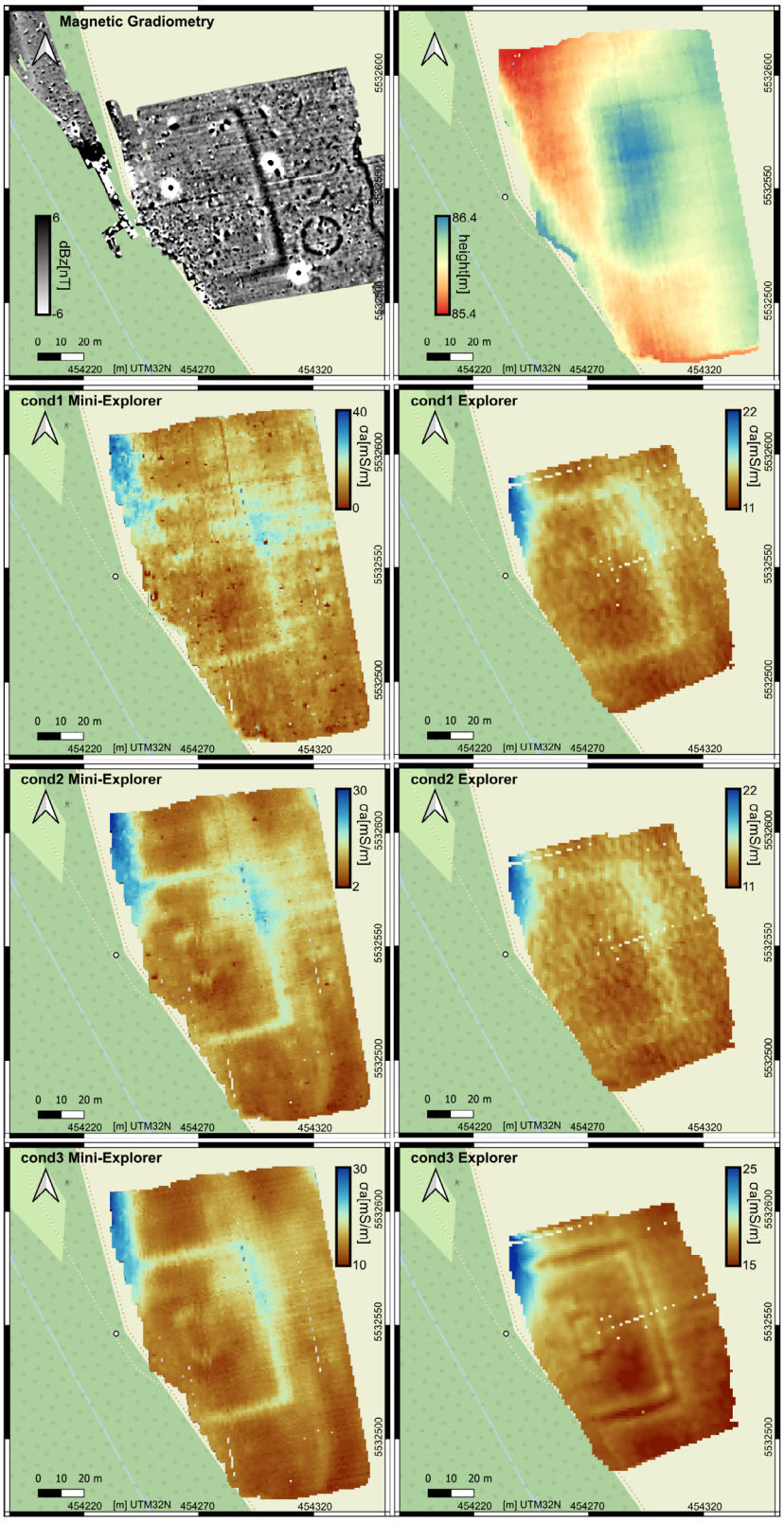

Fig. 2: Top row: magnetic map and topographic map of the site. Second to fourth row: apparent conductivities of the three coil separations of both EMI devices (left: CMD Mini-Explorer, right: CMD Explorer).

Materials and methods

In March 2022, we investigated the fortress with three different methods (see areas in Fig. 1a). Magnetic gradiometry was performed using an array of six Foerster fluxgate gradiometers with a horizontal sensors pacing of 0.5 m and a sampling frequency of 20 Hz. FDEMI data were collected using both the CMD Mini-Explorer (CMDME) and CMD Explorer (CMDE) by GF Instruments. The devices consist of one transmitter and three receiver coils. The planes of the coils were oriented horizontally (horizontal coplanar, HCP). The distance between the transmitter and receivers were 0.32, 0.71, and 1.18 m and 1.48, 2.82, and 4.49 m. Processing of EMI data included coordinate offset correction and inline spatial bandpass filtering to remove walking noise. A drift correction was not necessary for conductivity/quadrature data. Finally, all the data were interpolated using 2D linear interpolation. Positioning was achieved by RTK (Real Time Kinematic) DGNSS (Stonex S9i).

Beyond EMI mapping, we performed 1D conductivity inversions on two example profiles. For comparison and interpretation we added an example Electrical resistivity tomography (ERT) profile and core data (profile ERT-2 and core ASTH-9A, Fig. 1a). The ERT was recorded using a Syscal Switch 48+ with 48 electrodes of 2 m distance. Measurements were done in Wenner-Schlumberger configuration. The subsequent inversion was done using the RES2DINV software. The regarded sediment core was a closed vibracore of 4 m length in total that was later investigated and described in the laboratory.

Results

Figure 2 shows the results of the geophysical measurements. In Figure 2 (top row) the magnetic gradiometry map is shown in the 6 nT range, showing the surrounding ditch of the fortress as well as three round anomalies that can be addressed as medieval burial mounds (Heising 2003). The second, third and fourth row of Figure 2 show the apparent conductivity maps of the three different EMI coil separations for both devices (left: CMDME, right: CMDE). All maps show the surrounding ditch, whereas the castle itself is only visible in the Mini-Explorer data and strikingly in the largest coil distance of the Explorer data. Beyond the burgus, all maps show long wavelength changes probably indicating the background geology.

Discussion

Figure 3 summarizes the observed features and effects of the data sets and is the basis for the following discussion and interpretation. Figure 3a shows an example profile of inverted CMDE data in comparison to the ERT-2 profile and the facies description of core 9A. The comparison supports the idea that this kind of data contributes as well to landscape reconstruction, as it images the transition to the lower Terrace sands (dotted lines), but also maps the large-scale archaeological features, meaning surrounding ditch and castle (as indicated by the black dashed lines). The result is comparable to the ERT tomogram down to a depth of 6.5 m. Figure 3b again shows the apparent conductivity map of the largest coil distance of the CMDE. Figure 3c shows the inversion result for both example profiles in both devices. In Profile 1 we added the sensitivity curves for all coil distances after McNeill (1980) (white lines). The sensitivity curves explain for example, the high noise level of the maps of shortest coil distance, which is the influence of the high conductive plow layer, where the first coil distance of CMDME has its maximum. In contrast, this layer is not resolved by the CMDE. The maximum of the first coil distance of the CMDE is in the air, because the instrument was carried at 1 m aboveground. The second maximum reaches the surface level, so both are probably influenced by the rough plow layer. The largest coil distance of CMDE however has its maximum coincidentally at the depth of the archaeological remains (see black dashed line; which is the outline of the ditch after the excavation profile.), which explains why the shallow archaeology is imaged so well in the CMDE data. In CMDME data the ditch already is at the lower part of the depth range. A joint inversion of both data sets would be obvious. However it would need a proper regularization and discretization because of the different value ranges in the topsoil, and the hardly overlapping depth sensitivity. A combined dataset however offers the possibility to investigate archaeological structures such as the Roman burgus of Astheim together with the surrounding landscape even in 3D in reasonable time and thus offers a feasible method for Roman heritage investigation in Hesse.

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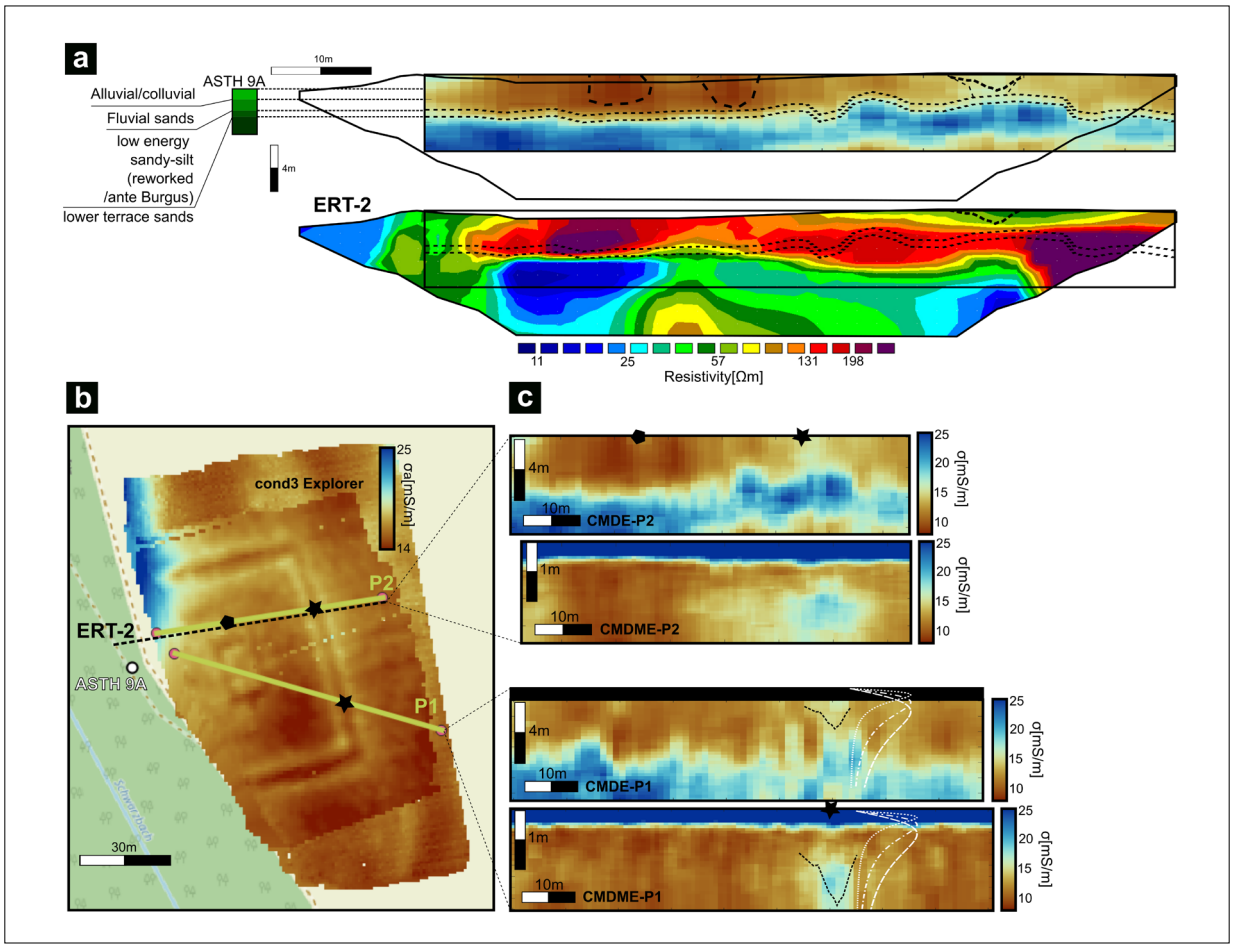

Fig. 3: a) Facies in core 9A in comparison to CMDE inverted profile 2 and inverted ERT-2. Black dotted lines show the lower terrace sand and reworked ante Burgus layer. Dashed line on the right shows the excavation based ditch bottom. b) Overview map showing CMDE largest coil distance and the position of all profiles and the core. c) Two inverted example EMI profiles together with depth sensitivity curves (white lines) and ditch outline based on the excavation.

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Hunte 1 reloaded – combining ground penetrating radar, electrical resistivity tomography, corings and excavations at the Neolithic domestic site Hunte 1, Germany

Tina Wunderlich [1,2*], **Jan Piet Brozio** [2,3], **Ingo Feeser** [2,3], **Marion Heumüller** [4], **Clemens Mohr** [1,5]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Collaborative Research Center 1266, Kiel University, Kiel, Germany
3 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
4 Lower Saxony State Service for Cultural Heritage
5 Cluster of Excellence ROOTS, Kiel University, Kiel, Germany
* Corresponding author: E-mail: tina.wunderlich@ifg.uni-kiel.de

Abstract
With the help of geophysics an old excavation plan from the 1930ies and 1940ies could be relocalized. The interface between peat and sand can be traced over the whole area by GPR. Diffraction hyperbola in GPR data as well as excavation revealed piles and timbers. The Neolithic domestic site was much larger in extent and more complex than known before our research.

Keywords
archaeological prospection; corings; electrical resistivity tomography; ground penetrating radar; Neolithic domestic site

Introduction

The Hunte 1 site north of Lake Duemmer is one of the most important Neolithic archaeological sites in the North European Plain. This is mainly based on the excellent preservation conditions in the wetlands of the Duemmer Geest lowlands on the southern border of the Northwest German Lowlands in Lower Saxony, Germany.

Excavations conducted between 1938 and 1940 (Brozio and Heumüller 2022; Kossian 2007; Reinerth 1939) uncovered 24 building structures at the Hunte 1 site (Fig. 1a). These had been preserved in the form of piles, remains of wooden floor, clay lenses and fireplaces. Dendrochronological examinations of individual timbers from the buildings made it possible to date parts of the settlement to around 2820 BC. The 120 m × 75 m large settlement was surrounded by an oval-shaped palisade consisting mainly of alder stems, having been constructed, extended and maintained between 2837 BC and 2744 BC.

The aims of the combined fieldwork that was carried out in August 2022 as part of the Collaborative Research Centre 1266 "Scales of Transformation" using geophysical methods, corings and excavations were

1. to relocalize the excavation areas from the 1930s and 40s,
2. to verify the dimensions of the known settlement and to detect still possibly unknown areas of settlement activity, and
3. to investigate the geomorphology of the area in for a better understanding of the dynamics of landscape changes and their influence on the settlement.

The locations of geophysical measurements, corings and excavations have been marked in Fig. 1b.

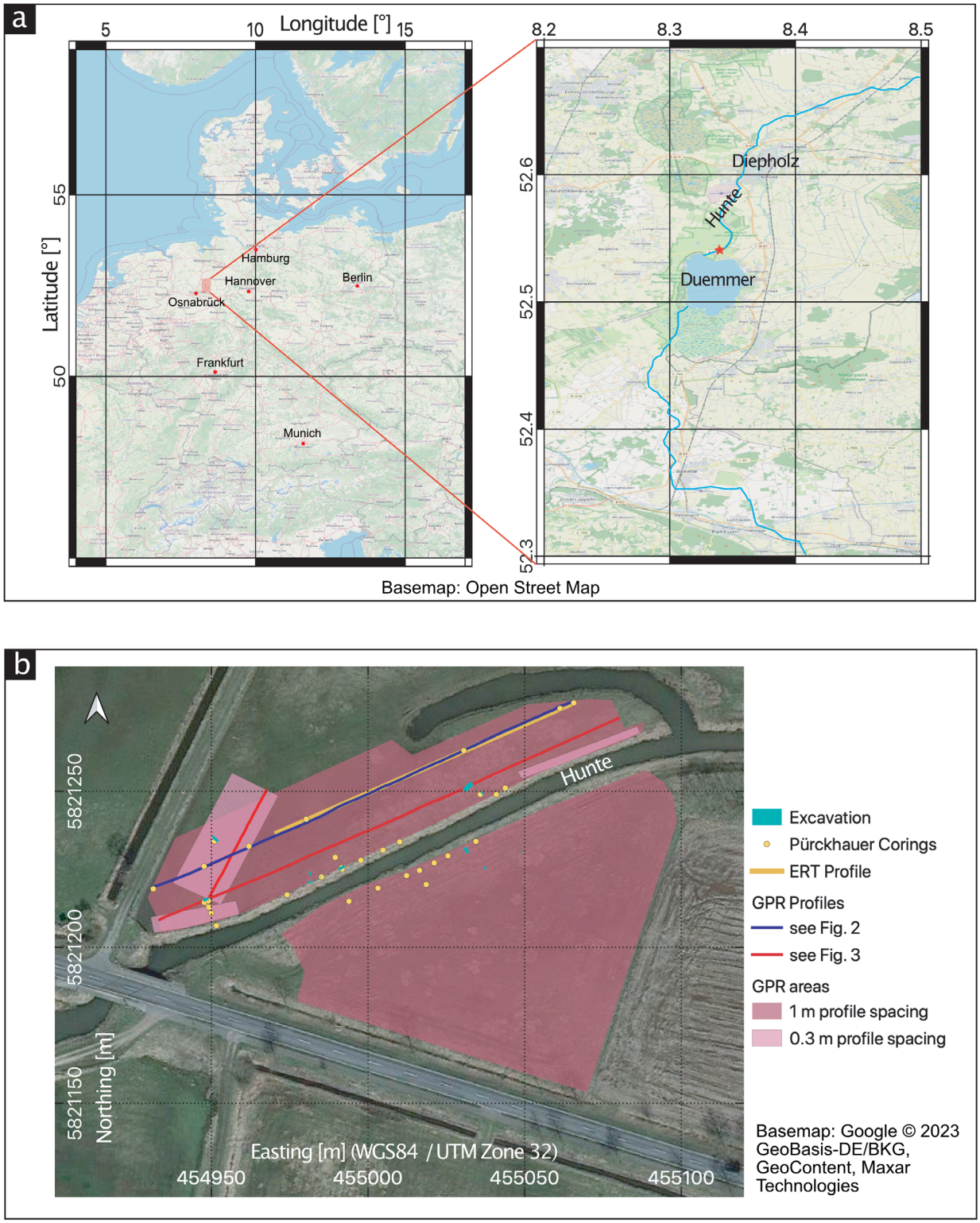

Fig. 1: Overview of the location of the Duemmer area in Germany (a) and the Hunte 1 site north of Lake Duemmer (b). b) Also shows the placement of the measurement areas, profiles, corings and excavations.

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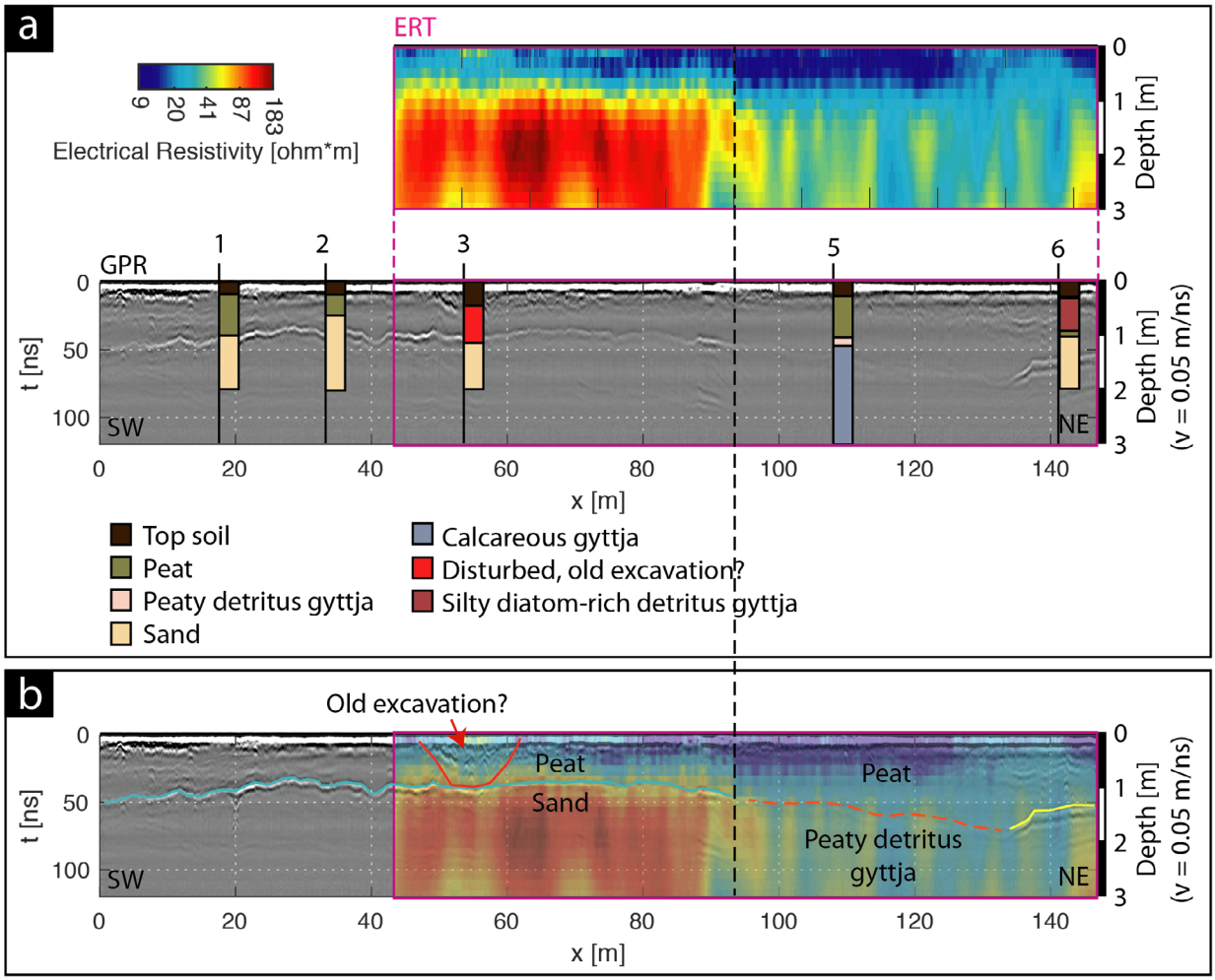

Fig. 2: Radargram P11 (location see Fig. 1) and ERT profile with corings (a). b) Shows the ERT model overlain on the radargram with a simplified interpretation based on the corings. The dashed black line shows the assumed transition between sand and lake marl in the bottom layer.

Materials and methods

Geophysics

Ground penetrating radar (GPR) measurements were conducted with a SIR4000 system (GSSI) and a 200 MHz antenna. Positioning was achieved with a RTK-DGPS in cm accuracy. On the complete site GPR profiles were measured with an average spacing of 1 m. After first interpretation of the results some smaller areas were measured again with 30 cm GPR profile spacing. The data were acquired over a time range of 180 ns and each GPR trace digitised with 1024 samples. Data processing was conducted using the program MultichannelGPR (Wunderlich 2021) and comprised DC amplitude removal, computation of a constant in-line trace spacing of 2 cm, time zero shift application, cutting of the time range to 120 ns, bandpass filtering to between 50 and 500 MHz, and application of a time gain.

In addition, Electrical Resistivity Tomography (ERT) measurements were conducted along one 103.5 m profile with an electrode spacing of 0.5 m. Data were collected in dipole-dipole, Schlumberger and Wenner alpha configuration. All configurations were inverted together with the program BERT (Boundless Electrical Resistivity Tomography, Günther et al. 2006).

Corings

Based on the geophysical results and available archaeological maps, several corings were conducted with a Pürckhauer corer of 22 mm diameter. The cores were described in the field and photos were taken for documentation.

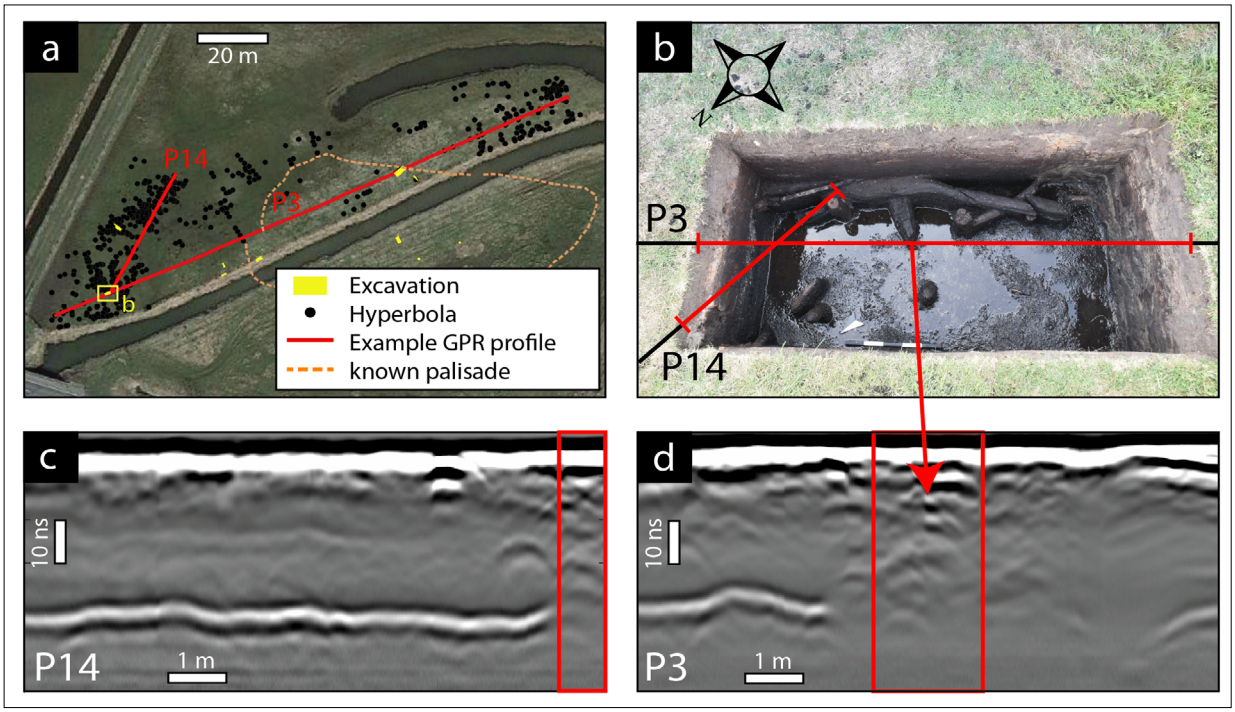

Fig. 3: Clearly visible hyperbolae were picked on all GPR profiles showing areas of high and low hyperbola density. The dashed line may represent the remains of the palisade examined by Reinerth (1939) (base map: Google © 2023 GeoBasis-DE/BKG, GeoContent, Maxar Technologies). (a) An excavation in the southwestern part of a cluster of hyperbolae revealed wooden piles and timbers (b) that can be directly connected to hyperbolae in two example radargrams (c and d) (photo: J.P. Brozio).

Excavation

The outlined questions and preliminary geophysical interpretations resulted in five excavation sections and several sondage trenches.

Results

The radargrams have a good signal-to-noise ratio in the uppermost 120 ns, which corresponds to approximately 3 m depth when using a propagation velocity of 5 cm/ns derived from hyperbola analysis. In almost all profiles a clear reflection can be traced over the area between approx. 40 to 80 ns (Fig. 2a). Correlation with the corings shows that this reflection is caused by the interface between the overlying peat and the underlying sand. On the example profile shown in Figure 2 this interface becomes hardly visible between x = 95 m and about 130 m distance. The ERT profile measured at the same location reveals lower electrical resistivities in this part both in the upper and lower layers. A coring in this area revealed lake marl at the bottom, instead of the sand layer found in the rest of the profile. Thus, the weakening of the reflection has two causes: higher attenuation due to lower resistivity and a weaker reflection coefficient of the interface. Strong chaotic reflections between approx. 50-60 m distance along the profile can possibly be attributed to an old excavation, as it could be confirmed by a coring.

In the southwestern part of the profile several diffraction hyperbolae can be seen. Picking these hyperbolae on all measured profiles reveals a higher density of hyperbolae in the southwestern part of the area north of the river Hunte (Fig. 3a). The geophysically identified hyperbola signatures were investigated in two areas by excavation sections. The detected causative features were wooden piles and timbers (Fig. 3b). These formed parts of a previously unknown, further palisade in the south-western and north-eastern part of the settlement area that had been excavated in the 1930s and 40s. Therefore, the settlement site actually is much larger than previously assumed.

Discussion and conclusion

With the help of GPR measurements the entire site could be covered relatively fast. This allowed for the targeted

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positioning of corings, and excavations that in turn helped in the understanding of the geophysical results. Tracing the layer interface between peat and sand (or lake marl) over the complete area revealed a depression in the northeastern corner, approximately correlating with the occurrence of the lake marl. This could relate to a former lake or river with the settlement located nearby on a sandy elevation. With the help of geophysical measurements the old excavation maps from the 1930s and 1940s could be relocalised and a former unknown prehistoric palisade and undisturbed settlement area were discovered in the southwest. Thus, the excavations in the 1930s and 1940s did not reveal the entire settlement, and we now know that the Neolithic domestic site was much larger in extent and more complex than known before our research. The dating, analysis and detailed evaluation of the data from both the survey and the excavations will be the next step in reconstructing the structure of the site and the past human-environment relationship in this area.

Acknowledgments

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Results of geophysical methods in the study of the ancient settlement Dalvarzintepa (Uzbekistan)

Azamat Zakirov [1]*, Ilyas Yanbukhtin [1], Timur Mamarozikov [1], Djangar Ilyasov [2], Otabek Aripdjanov [2]

1 Laboratory of Geophysics and Nanomineralogy, Centre for Advanced Technologies, Tashkent, Uzbekistan
2 Department of Art History, Institute of Fine Arts, Tashkent, Uzbekistan
* Corresponding author: E-mail: azamatzakirov@mail.ru

Abstract

The purpose of the study was to use a variety of geophysical techniques to uncover the shape, size, internal structure, and contour of archaeological artifacts buried beneath the surface. Magnetic prospecting, electrical resistivity tomography, and ground penetrating radar were the three main geophysics techniques. Various abnormalities are clearly traced on the maps created from the processing results of all methods in the form of figures with different lengths and forms. Archaeologists were able to identify the most important excavation sites using geophysical study.

Keywords

ancient settlement; anomaly; archaeological prospection; geophysics; processing of data

Introduction

The given abstract represents the results of geophysical measurements using magnetic prospecting, ground penetrating radar (GPR) and electrical resistivity tomography (ERT) methods in the study of the ancient settlement of Dalvarzintepa (Fig. 1).

The settlement is situated in Republic of Uzbekistan's southern region. It was one of the Kushan kingdom's significant trade and artisan centers in the third and fourths century (Pugachenkova 1975). 47 hectares make up the entire area. Typically, the settlement's surface is flat. However, extensive erosion over many years has led in numerous areas of the surface subsiding. The findings of employing a set of geophysical techniques discovered by looking into a site in the northwest of Dalverzintepa are shown further down.

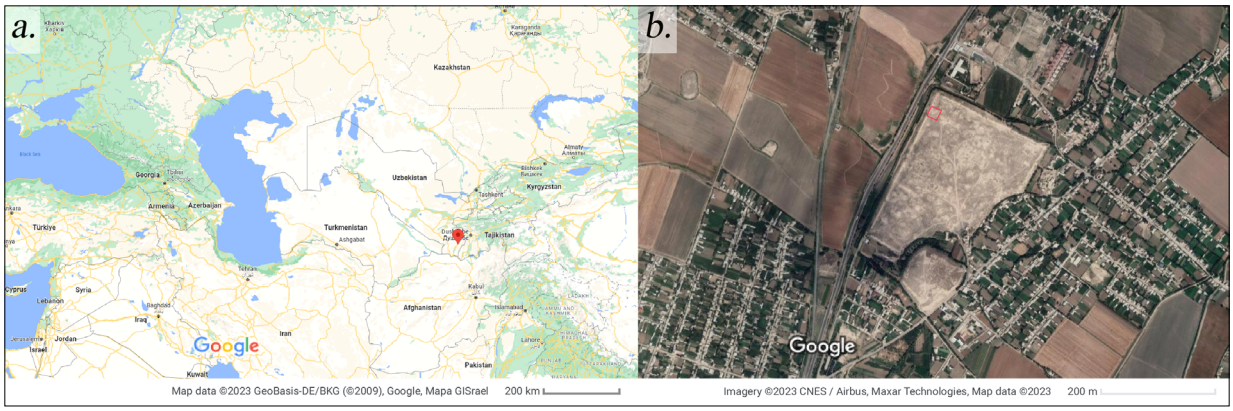

Fig. 1: Location of ancient settlement Dalvarzintepa. a) Google Earth image of the site. b). The area of interest is visible inside the red square.

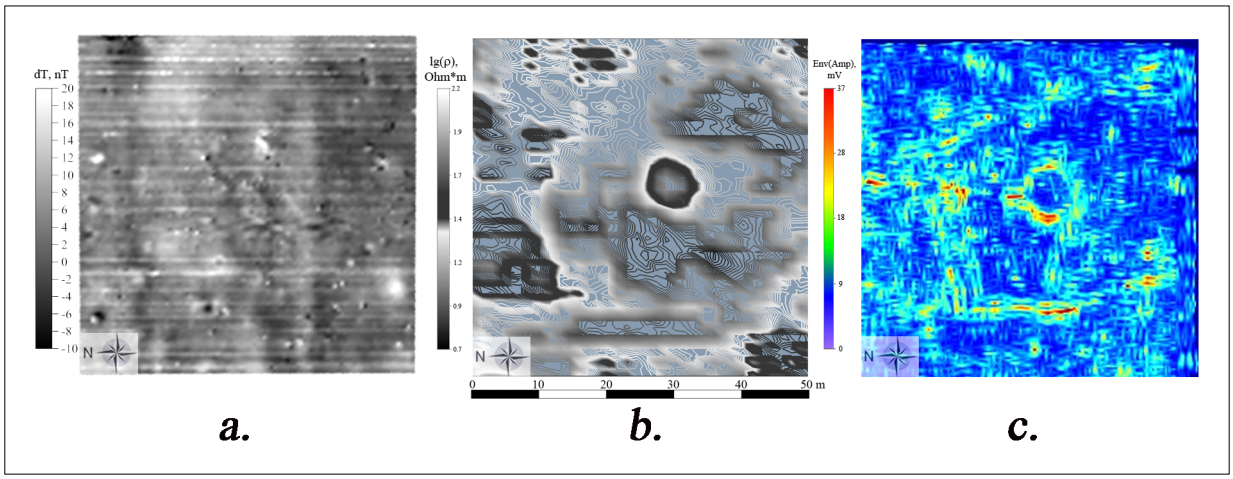

Fig. 2: Maps of geophysical anomalies within the research square obtained from the data of: a) magnetic survey, b) ERT (cut at an interval of 1-1.25 meters), c) GPR (cut at an interval of 1-1.25 meters).

Materials and methods

A proton magnetometer Geometrics 856AX (USA) was used to conduct magnetic surveys. Using 72 electrodes and a multichannel georesistivitymeter M.A.E. X612-EM72 (Italy), electrical exploration work was conducted. A 100 MHz antenna of Sensors and Software equipment (Canada) were used for the GPR.

Two sensors were used in a micromagnetic survey, and one magnetometer was connected to both of them via a beeper. A unique design was created in order to measure simultaneously along two profiles at the 50 cm distance between the sensors.

The number of electrodes was 72, the distance between them was 1 m, and ERT measurements were performed on 26 profiles with a step of 2 m. It made use of the Dipole-Dipole protocol.

Grid profiles were used to conduct the GPR measurements. The measurement network was made up of parallel profiles that were spaced 1 m apart in both the longitudinal and transverse dimensions. 100 MHz was the central frequency of the antenna.

Results

Maps of magnetic anomalies, sections and slices of resistivity over the area, as well as deep slices in accordance with GPR data were created as a result of field geophysical research and processing of the material obtained (Fig. 2).

Figure 2 illustrates how clearly anomalies are seen that describe specific items which are located at depth and covered by cover deposits. These anomalies are distinguished from others by a particular geometric feature, such as angularity, length, or roundness. Such anomalous manifestations may be related to certain ancient artifacts, such as structures or objects that were used for crucial activities in the past. An abnormality in the shape of a circle piqued everyone's interest. After conducting geophysical measurements in 5x5 m squares with 1 m broad edges, archaeological excavations within the research site were begun (Fig. 3).

The outcomes of archaeological digs in squares No. 7, 8, 10, and 11 confirmed an anomaly in the shape of a circle (Fig. 3c). Figure 3a demonstrates how the layer's thickness grows in the area of squares 8 and 11 close to the center edge. The walls are also clearly evident spatially and hypsometrically in Figures 3b and 3c, in plan and in section, and coincide with the anomalies discovered by using geophysical data.

Discussion

An efficient solution has been demonstrated to be an integrated area of geophysical research that uses magnetic prospecting, ERT, and GPR to explore ancient sites. Archaeological investigations in numerous locations have led to the confirmation of such a complex of geophysical techniques (Zakirov et al. 2022, Novikov et al. 2020, Hegyi et al. 2021).

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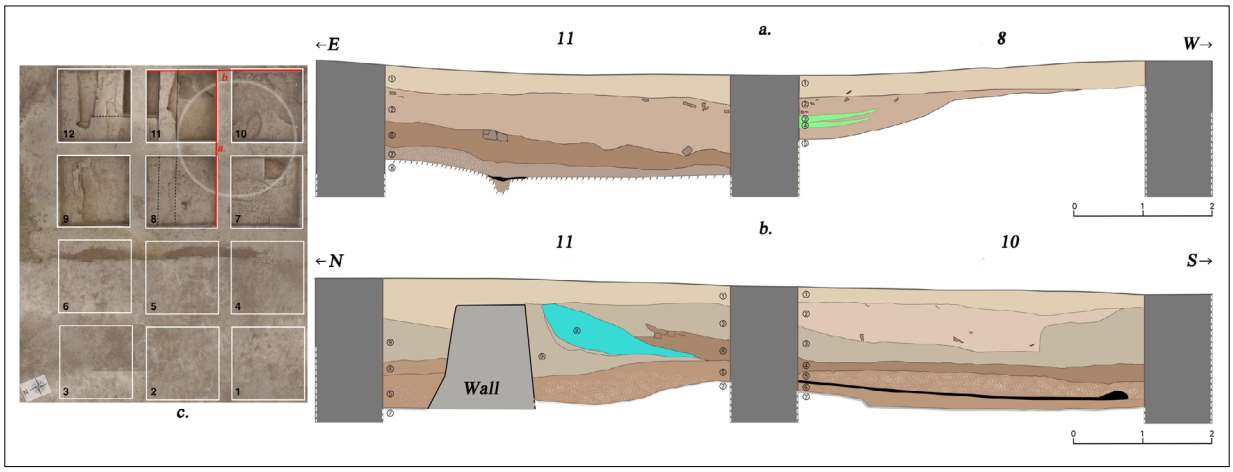

Fig. 3: Results of excavations. a) section of the southern edge. 1 - inflatable layer; 2 - a layer of ash and ashes with a large number of fragments of ceramics and bones; 3 - the remains of a round hearth made of baked clay with pieces of bricks; 4 – remains of a round fired clay hearth; 5 - burnt clay; 6 - a dense layer of a sinter character; 7 - ash layer; 8 - floor 1. b) Section of the eastern edge. 1 - inflatable layer; 2 - soil with ash and ashes, as well as with fragments of ceramics and bricks; 3 - a layer of ash with a large number of ceramics and fragments of bricks; 4 - a dense layer of a sinter character; 5 - burnt layer with ash; 6 – ash layer; 7 - floor 1; 8 - ash layer; 9 - layer of lumpy clay. c) phototopography of the excavation area.

Conclusion

By examining the geophysical data analysis findings, we can draw the conclusion that the techniques employed in this approach to investigate ancient artifacts were highly effective. Based on the findings of the work done, locations for additional non-invasive geophysical analysis of ancient artifacts were identified.

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First results from stratigraphic investigation of Chiselet tell (Romania) using seismic full waveform inversion

Manuel Zolchow [1*], Natalie Pickartz [2], Adrian Serbanescu [3], Ercan Erkul [1], Daniel Köhn [1], Dennis Wilken [1], Stefan Dreibrodt [4], Robert Hofmann [5], Johannes Müller [5], Catalin Lazar [3], Wolfgang Rabbel [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 State Office for Cultural Heritage Baden-Württemberg, Ludwigsburg, Germany
3 Research Institute of the University of Bucharest (ICUB), University of Bucharest, Bucharest, Romania
4 Institute for Ecosystem Research, Kiel University, Kiel, Germany
5 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
*Corresponding author: Email: manuel.zolchow@ifg.uni-kiel.de

Abstract
In this paper we analyze the applicability of seismic full-waveform inversion (FWI) for investigation of tells, which are often characterized by heterogeneous and small-scale stratigraphy. Major aim is to identify location and shape of settlement layers and house remains. Furthermore, a paleochannel, which is important to understand the interaction between tell and the surrounding landscape, was found at the tell flank.

Keywords
archaeological prospection; full-waveform inversion (FWI); seismic; stratigraphy; tell

Introduction

Neolithic tell settlements are, due to their size, topography and heterogeneity, challenging targets in the field of archaeological prospection. Since traditional geophysical prospection methods are often limited by penetration depth or resolution, a sufficient 3D reconstruction of an entire tell is often unachievable. To overcome these issues seismic full-waveform inversion (FWI) has been proven as promising method and is therefore increasingly integrated to multi-method approaches for geophysical prospection of heterogeneous stratified archaeological targets like settlement mounds.

For a case study we performed measurements at a Chalcolithic tell (Fig. 1d) from Gumelnița culture (4600 – 4250 BC) in the lower Danube basin near Chiselet in Romania (Fig. 1a) to prove the applicability of our seismic FWI integrated multi-method strategy to geophysical investigation of prehistoric settlement mounds. Aim of our investigation was to reconstruct stratigraphic units of different settlement phases, to identify archaeological features like house remains, pits or trenches and to analyze the relation between tell and the surrounding paleo landscape.

Methods

The seismic data were recorded using a GEOMETRICS seismic system in SH-configuration along two profiles (Fig. 1b, c) of 95 m length with 10 Hz horizontal component geophones in 1 m distance. Whereas profile 1 is crossing the entire tell in direction from west to east, profile 2 is running down the southern tell flank into the surrounding plane. For excitation of shear waves a sledge hammer source was positioned along the profiles in intervals of 2 m.

The data was analyzed using two-dimensional, elastic FWI in time-domain based on inversion of dispersive Love- and refracted SH-waves. For this purpose, we

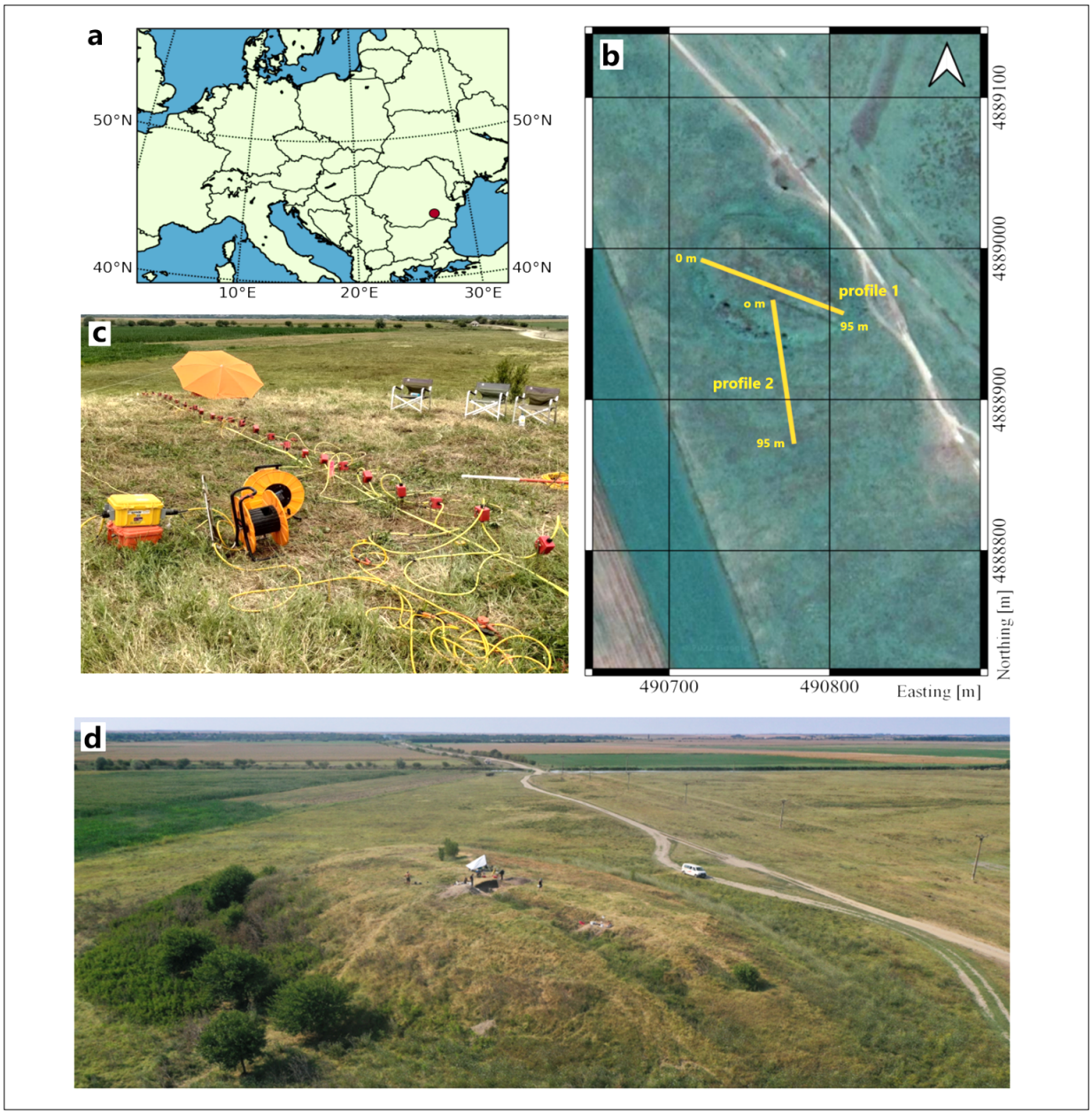

Fig. 1: a) Location of Chiselet; b) Map of Chiselet tell including measured seismic / ERT profiles (orange lines) (base map: Google ©2023 CNES / Airbus, Imagery; ©2023 CNES / Airbus, Maxar Technologies); c) Photo of seismic and ERT setup (M. Zolchow); d) Aerial photo of Chiselet tell (G. Bilotti).

used the FWI-code DENISE (Köhn et al. 2012). The data fit was improved by inverting for shear wave velocity v_s and density ρ simultaneously, while seismic quality factor Q_s was assumed to be constant. The required initial model of the shear wave velocity was determined using ray-based first arrival traveltime tomography (FATT) on the basis of refracted SH-waves with the software Reflexw (Fig. 2a, 3a). Proceeding from this initial seismic velocity model, a density model was calculated via an empirical relation (Ulugergerli and Uyanik 2007) valid for unconsolidated sands. The constant value of the quality factor Q_s = 30 was optimized by best data fit after multiple forward modeling runs with different quality factors. Since the existing code is based on rectangular grids, we used an oversampled spatial discretization of 0.05 m together with the improved vacuum formulation (Pan et al. 2018)

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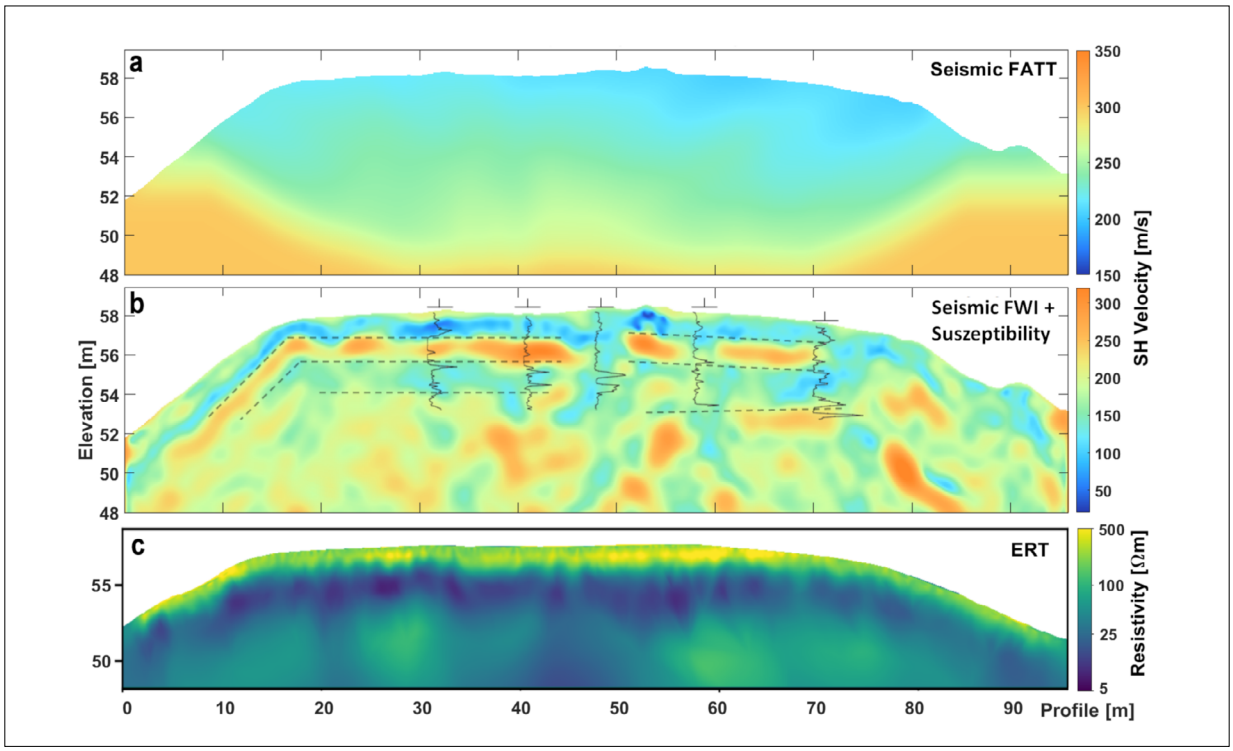

Fig. 2: a) Comparison of seismic FATT (a), seismic FWI (b) including 1D-depth curves of magnetic susceptibility (black curves) and marked layer boundaries (dashed lines) and ERT (c) of profile 1.

to implement accurate free-surface boundary conditions in the presence of strong topography. In order to obtain stable and interpretable results despite the strong non-linearity of the full-waveform inversion, a multi-stage inversion strategy was implemented. This combines a sequential lowpass filter strategy including alternating offset windowing with a high frequency bandpass filter strategy (Köhn et al. 2019) in order to ensure a similar waveform-adaptation of Love- and SH-wave.

To enhance and verify interpretation, the FWI results are compared to results of electrical resistivity tomography (ERT), down-hole measurements of magnetic susceptibility, corings and small-scale archaeological excavations.

Results and discussion

The results of seismic FWI (Fig. 2b) at profile 1 show several horizontal layers of alternating low (< 200 m/s) and high (> 200 m/s) shear wave velocity with thickness of 1 - 2 m, while the uppermost layer is characterized by comparatively very low (< 120 m/s) velocity. The layer boundaries correlate with peaks of increased magnetic susceptibility in 1D - depth curves, measured with down-hole probes at five positions along the profile. The anomalies of positive magnetic susceptibility can be related to settlement layers known from coring and excavation. Therefore, it remains open, whether the high shear wave velocities are caused by consolidated leveling layers or by massive layers of house remains and ceramics, which could be identified in a small test excavation trench. Furthermore, the FWI result shows no clear layer boundary or velocity difference between anthropogenic settlement layers and underlying natural sediments, which was identified by corings in a depth of 7 – 8 m. Therefore, both units must be assumed to feature comparable seismic material parameters. ERT measurements on profile 1 (Fig. 2c) are interfered by a high degree of dehydration at the ground surface resulting in low penetration and weak depth resolution.

On profile 2 at the southern tell flank anomalies of low seismic velocity (Fig. 3a) and electric resistivity (Fig. 3b) may refer to a former paleochannel. A vertical boundary between high seismic velocities (> 250 m/s) of the tell and lower velocities (< 150 m/s) of the surrounding plane sediments indicate an erosional impact of the paleochannel at the tell flank.

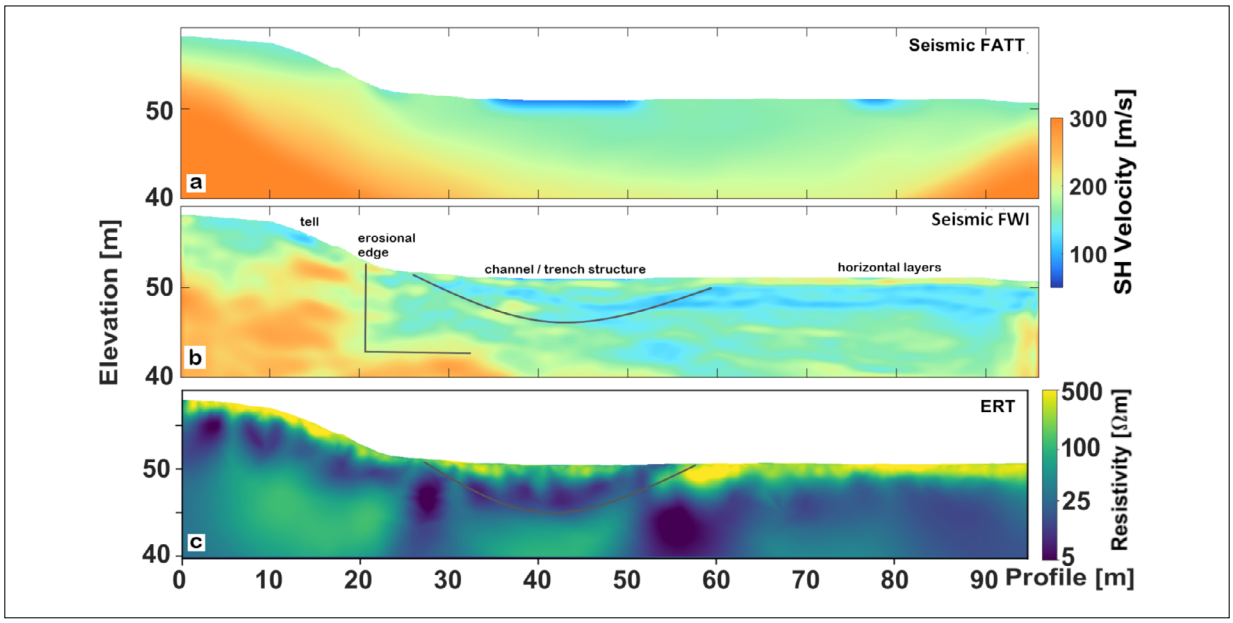

Fig. 3: a) Comparison of seismic FATT (a), seismic FWI (b) including interpretation (black lines) and ERT (c) of profile 2.

Conclusion

Although further investigations including seismic cross profiles and intensified bore-hole geophysics are necessary to verify the current results and enhance interpretation, the presented seismic FWI results illustrate the potential of the method for archaeological prospection of settlement mounds.

Acknowledgments

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5

ENVIRONMENTAL STUDIES AND LANDSCAPE EVOLUTION

829 hectares of preventive archaeological magnetometry surveys in Ireland: upscaling data collection and interpretation strategies

Jochem Dorrestein[1*], Rudolf Kniess[1], Hartmut Krahn[2], Martin Wetze[1], Jessica Meyer[1], Burkart Ullrich[1]

1 Eastern Atlas GmbH & Co. KG, Berlin, Germany
2 Minerex Geophysics Ltd., Maynooth Business Campus, Maynooth, Co. Kildare, Ireland
* Corresponding author: E-mail: info@eastern-atlas.de

Abstract
We present examples of preventive archaeology magnetometer surveys at macro scale. Qfield can be used for effective landscape documentation to allow better data analysis, even if done by another team. We show how to improve the reusability of datasets for future Big Data research methods.

Keywords
big data; magnetometer surveys; preventive archaeology; Qfield; re-usability of data

Introduction

During the autumns of 2021 and 2022 a total of 829 ha divided in 8 different preventive archaeology magnetometer survey projects were conducted by the Eastern Atlas team from Berlin in collaboration with the Irish geophysical company Minerex Geophysics. The surveyed areas consist of agricultural fields with an archaeological potential which have been designated as locations for yet to be developed solar farms. The main objectives of the survey were to determine possible archaeological features and deposits and to recommend targets for avoiding or direct archaeological testing. The spatial scale of the surveys required a new data collection and interpretation strategy to cope with the amount of fieldwork and data, which will be presented in this paper.



Fig. 1: The LEA-MAX system in Ireland.

Equipment

Technical developments of geophysical survey technology lead to ultra-light, and high flexible multichannel magnetometer survey systems with RTK-GNSS positioning (Meyer et al. 2015). For large scale surveys we use the LEA system (Eastern Atlas), which is usually 5 m wide and equipped with 10 (LEA-MAX, Fig. 1) or 19 sensors (LEA-MAXIX) (Lambers et al. 2021). This technology available today enables us to cover large areas very efficiently and produce magnetic maps in 1-3 nT range. The system consists of a flexible array of 10 Fluxgate-Foerster gradiometer probes (FEREX 4.032 Con 650) towed by an ATV. The distance between each of the ten gradiometer probes is 50 cm, the row spacing of the measuring points between 5 and 10 cm,

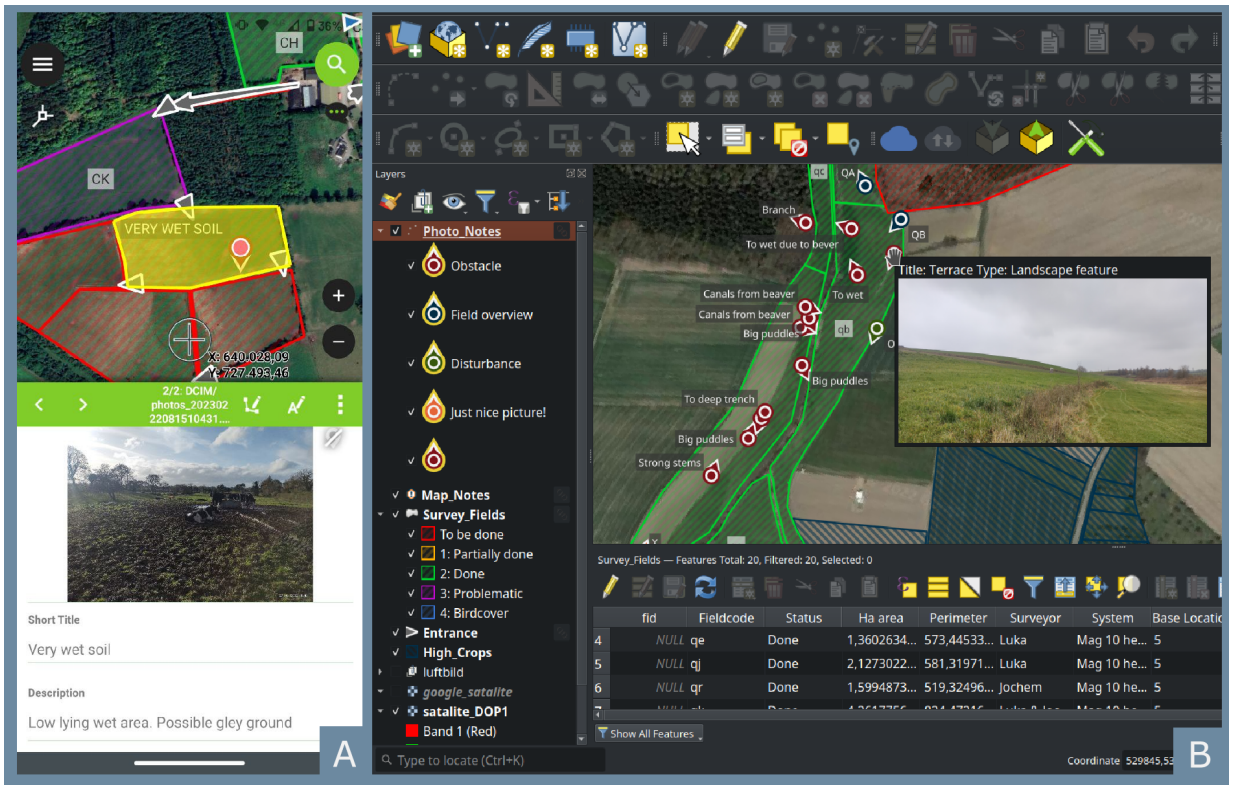

Fig. 2: (A) screenshot of how Qfield looks on your phone, (B) Opening photos and other gathered data with Qfield in QGIS.

depending on the speed. The positioning was realized with the help of an RTK-GNSS. Part of the measurements were conducted using two LEA-MAX systems simultaneously.

Upscaling strategies

By dividing the tasks of (1) the field work (conducting the measurements and documenting the area), and (2) the office work (post processing and interpreting the magnetic data), two teams can work parallel on the same project. For this to work however it's important that there is an elaborate landscape documentation of the area so that the data can be post processed and interpreted as best as possible. To achieve this Qfield turned out to be a very useful application. Qfield is a mobile app that works together with QGIS on a computer. When an QGIS project and prepared Qfield layers are prepared correctly on a computer, it can be transferred to a phone and be opened in Qfield. Using your phone GPS you can now see where you are, add photos with location and direction describing the area, add notes, and add data to shape files of the field that is useful, such as field code, measuring frequency, state of soil, and more (Fig. 2A). The Qfield data can be uploaded and be opened from the office using normal QGIS) and be consulted during post processing and interpretation (Fig. 2B). The Qfield data will be backed up together with the magnetometry data.

Results

Some impressive examples of archaeological features are shown in Figure 3. Not all of the areas had archaeology visible in the data and did only show Geology or an old drainage systems. More interesting examples will be shown in the presentation.

Discussion

A total of 1442 hectares of magnetometer data have been collected from which 76% were excavated and have been used to ground proof geophysical methods in 2014 (Bonsall et al. 2014). The findings of the evaluation were that magnetometry is a good, effective and fast geophysical method, as long as you a not looking for stone founda-

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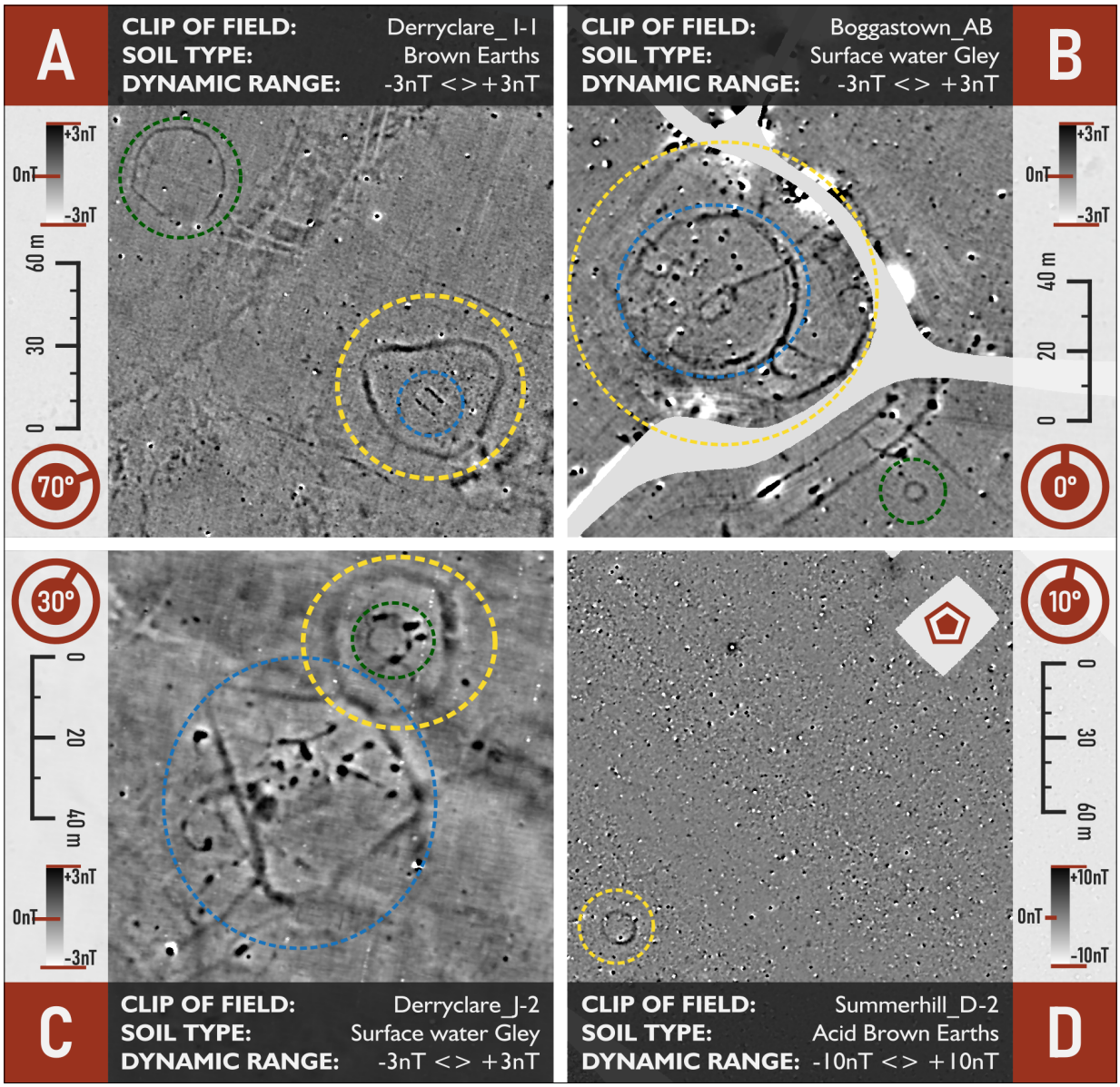

Fig. 3: Some results from the conducted Magnetometry surveys in 2021 and 2022, (A): Highlighted in Yellow can be seen an enclosed area of 1451m² with a deep moat and an entrance in the east. Within this feature a square anomaly can be seen, highlighted in blue, which is probable to be a house of 10 by 6m. In green is a smaller enclosure highlighted of 861m². (B): Highlighted in blue is a round feature encircling 1450m². Concentric to the inner part another ring of defensive ditches is highlighted in Blue at 15m distance. In green is also a possible barrow/tumuli visible of around 5m diameter. (C): In the green circle is a possible round tower visible. This feature is enclosed by a deep ditch highlighted by yellow, which is connected to another enclosure highlighted in blue. (D): At the red pentagon a known barrow/tumuli is documented and protected. Highlighted in yellow you can see the ditch remains of a probable other barrow in the same field.

tions, whose magnetic contrast, and thus visibility in magnetic data is often very minimal, or try to survey in peat soils (Bonsall et al. 2014). Since this study 13 year of new road construction and other infrastructure projects like the solar farm projects we conducted the last two years have resulted in an enormous database of additional magnetometry data. Next to geophysical data also a lot of remote sensing data, mainly Lidar elevation data, has been collected and released for research and the public. Together with classic sources as other archaeological records and soil science have reached a qualitative and quantitate level of data that enables big data methodologies. Questions regarding social-spatial organization or methods as predictive modelling can help to bring archaeo-

logy to the next level. A drawback of using geophysical and remote sensing methods is that there are no divisive indications towards the age of the found features. But this can be done in retrospect.

Conclusion

The magnetometer surveys presented contribute significantly to „big data“ available today. Further research may continue the evaluation of the methodology for preventive archaeology in Ireland, and can be extended to wider and larger datasets. Additionally, data are still available on which new approaches to interpretation, e.g. routines from remote sensing, can be tested and applied. New developments as Qfield also make it easier to store valuable information about gathered data so that it is easier to use old data again and for other questions.

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Various use of geophysical measurements during new archaeo-hydrological project along the Jizera river, Czech Republic

Roman Křivánek [1*], **Barbora Machová** [2]

1 Department of Scientific Resources and Landscape Archaeology, Institute of Archaeology of the Academy of Sciences of the Czech Republic, Prague, v.v.i., Czech Republic
2 Department of Natural Sciences and Archaeometry, Institute of Archaeology of the Academy of Sciences of the Czech Republic, Prague, v.v.i., Czech Republic
* Corresponding author: E-mail: krivanek@arup.cas.cz

Abstract
The new archaeo-hydrological project has been based on the combination of old and new archaeological and hydrological data from riverine cultural landscape of the Jizera river. The role of geophysical methods is additional terrestrial survey along the river banks, inside of flood plain areas or on settled or enclosed terraces.

Keywords
bathymetry; geophysical survey; hydrology; river archaeology; underwater archaeology

Introduction

The new project "Riverine cultural landscape of the Jizera river from the Mezolithic to the Early Middle Ages in the light of archaeological resources and hydrological data" has been supported by the Grant Agency of the Czech Republic since 2022 (Machová et al. 2022-2024; project no. 22-05413S). The project is based on wider interdisciplinary cooperation of different specialists from the Institute of Archaeology in Prague and the Czech University of Life Sciences, Faculty of Environmental Sciences.

Goals and methods

The archaeological goal of the project is based on a large-assessment of archaeological structures surrounding the Jizera River and the study of the relationship of past societies to various parts of this watercourse. Comprehensive understanding to riverine cultural landscape and land-use requires a wide range of interdisciplinary methods, such as bathymetric measurement (Hradilek et al. 2015), hydrological modelling, underwater archaeological research (Machová 2017; Machová 2021), historical river banks reconstructions, dating methods (dendrochronology and 14C) and also particular geophysical prospections. Three working packages (WPs) were defined for this three-years project.

Geophysical surveys belong to WP1 (Cultural and historical development of the settlement pattern surrounding the Jizera River and elements of the Jizera riverine cultural landscape), where their close integration with other field research methods (bathymetric measurement, underwater archaeological research, archaeometric analyses, dendrochronological dating etc.) is assumed. The most intensively applied geophysical method was an areal magnetometer verification survey with a five-channel Sensys fluxgate gradiometer array in a network of 0.5 × 0.2 m along the banks of the Jizera River especially in places with positive indications for settlement and other activities derived from aerial photographs. Additional near surface resistivity measurement (RM-15, Geoscan Research) were planned in particular areas of archaeological sites, i.e. rampart fortifications of hillforts, supposed places of



Fig. 1: Example of typical agricultural landscape area along the middle part of the Jizera River from aerial photography in 2020 compared with a segment of an old map of the second Austrian military mapping from the middle of 19th century (source: www.mapy.cz; © GEODIS BRNO, s.r.o. and © 2nd Military Survey, Austrian State Archive).

abandoned communications to flood plain area or across the river. Further, additional ERT profile measurements are planned in places of old meanders.

Results

In the first year of field surveys of the project, an archaeologically and hydrologically perspective (modernly uncontaminated) parts of the watercourse and floodplain of the Jizera River were selected. For future interdisciplinary research, several sections of the river with a close connection to a certain type of prehistoric or early medieval settlement were selected (Fig. 2). From some parts along the river exists earlier archaeo-geophysical results and experiences (i.e. Neolithic roundel and settlements near Benátky nad Jizerou – Křivánek 2004; Křivánek 2006). New magnetometer results from the first year of the project showed wider possible use of prospection in case of various hillforts, their additional communications to the river, different enclosed or settled areas overlooking river area. Some situations were also repeatedly verified by resistivity measurements. The test magnetometer measurements inside of flood plain areas also announced possibility of identification of old meanders on levelled meadows (Fig. 3).

Discussion

The choice of geophysical method in such a project is dependent also on the selected part of the riverine cultural landscape and character of present land use. Magnetometer survey in forested terraces with fortified or unfortified settlement is sometimes very restricted. But in case of fortifications, enclosures or expected abandoned communication ways to the river, we can combine it with resistivity measurements. Magnetometer survey seemed also useful in verification of places of old meanders in the flood plain area. This type of riverine situation is also planned to be verified by additional ERT profile measurements.

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Fig. 2: Example of Lidar map along the middle part of the Jizera River and the main archaeological sites with clear relation to the riverine landscape. 1 – Middle Age stronghold Hrušov, 2 – Prehistoric settlement, 3 – Bronze Age and Early medieval hillfort area, 4 – Late Bronze Age and Hallstatt hillfort area.

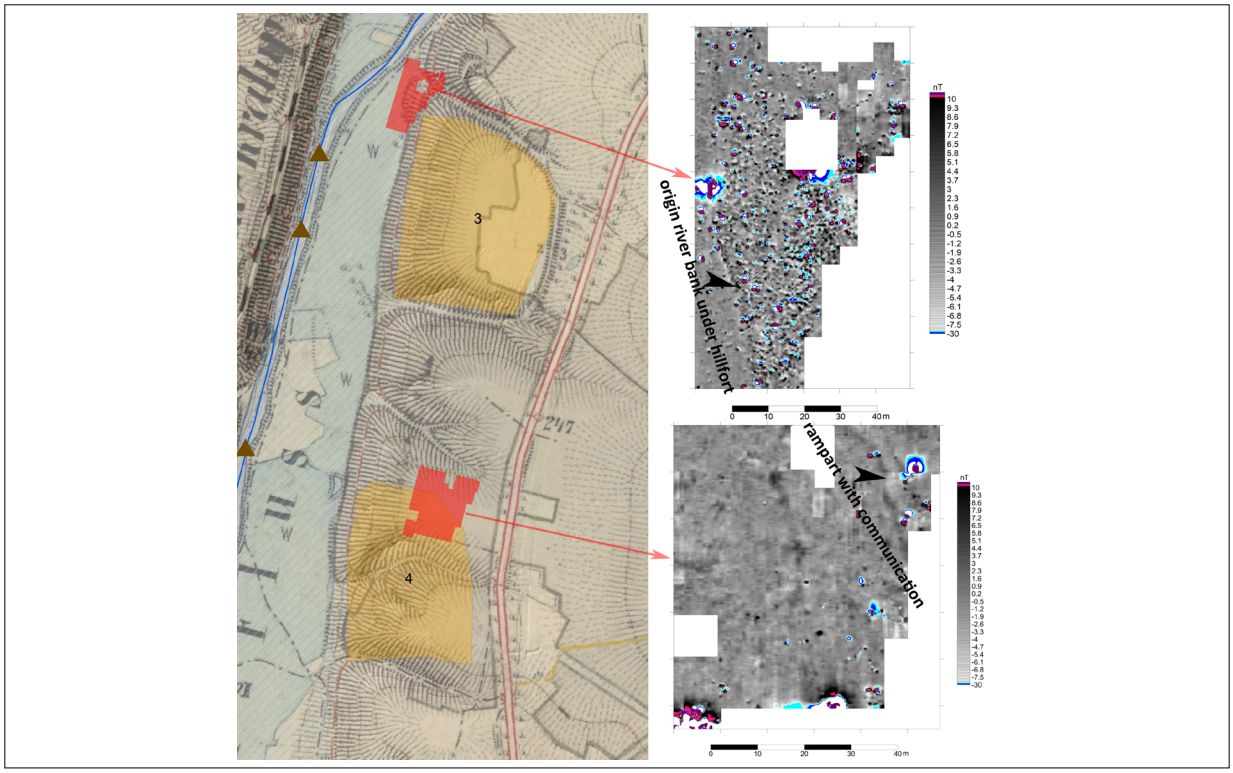

Fig. 3: Example of particular fluxgate magnetometer measurement inside a flood plain area and on lower terraces of the river combined with segment of the third Austrian military mapping.

Conclusion

A new archaeo-hydrological project is based on wider interdisciplinary cooperation of many field prospection and research methods. Application of geophysical measurements is then connected with particular archaeological and other questions primary focusing on the character, intensity or extent of archaeological activities along the river banks of the Jizera River. The first results showed that the different geophysical methods can efficiently be used for different archaeological sites and/or the identification of defunct meanders or communications in the flood plain area.

Acknowledgments

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Much more than just a Roman camp: diachronic interpretation of magnetic data from Danube Limes in Croatia

Cornelius Meyer [1*], **Tino Leleković** [2]

1 cmprospection, Berlin, Germany
2 The Archaeological Division, Croatian Academy of Science, Zagreb, Croatia
* Corresponding author: E-mail: cmp@cmprospection.com

Abstract
First large-scale magnetic gradiometer surveys with flexible sensor arrays started at the Danube Limes in 2020 and continue. The investigation of Danube Limes sites with extensions of several dozens of hectares revealed unknown Roman military structures as well as archaeological and historical features from Prehistory to modern era. The diachronic approach to magnetic data interpretation is most appropriate for the palimpsest-like historical landscape of the southern Pannonian Basin.

Keywords
Danube Limes; diachronic archaeology; interpretation; magnetic prospection; Roman military

Introduction

Roman Limes sites were systematically investigated using large-scale magnetic measurements along the right riverbank of Danube in Osijek-Baranja County (Croatia). The objective of surveys was to evaluate assumptions of the existence of complex Roman military installations that were drawn from field surveys, prior archaeological excavations and geophysical investigations, and aerial photographs. At the centre of interest is the magnetic data set obtained at the site of Dragojlov brijeg (Kneževi Vinogradi, Osijek-Baranja County, Croatia). Prior investigations revealed the existence of a 2nd century AD Roman auxiliary camp with a citadel on a surface of about 4 hectares (Vukmanić and Mušič 2012). In two campaigns the magnetic survey area was extended to almost 60 hectares.

Materials and methods

For the magnetic measurements the multi-probe fluxgate gradiometer array LEA MAX combined with a GNSS-RTK positioning system was used. Most of the area could be measured by use of an ATV. Hand-driven systems were used at neighbouring sites, where surface and terrain conditions did not allow for motorized measurements. For the archaeological interpretation the data sets were overlaid with LiDAR data. Since the data sets revealed fragmented features of Prehistoric and modern origin, they were subjected to a diachronic interpretation with the aim to create comprehensive interpretation maps which take into account the complexity of the palimpsest-like historic landscape. The term palimpsest has long been used in archaeology. Here it stands as a metaphor for a static and seemingly chaotic reflection of technically and culturally different processes, during which soil layers and structures, and thus the magnetic properties of the soil, were changed by human activity over long periods (Bailey 2007).

Results

Based on the results of the geophysical measurements from 2012 (Vukmanić and Mušič 2012), the large-scale



Fig. 1: Magnetic data from the site of Dragojlov brijeg.

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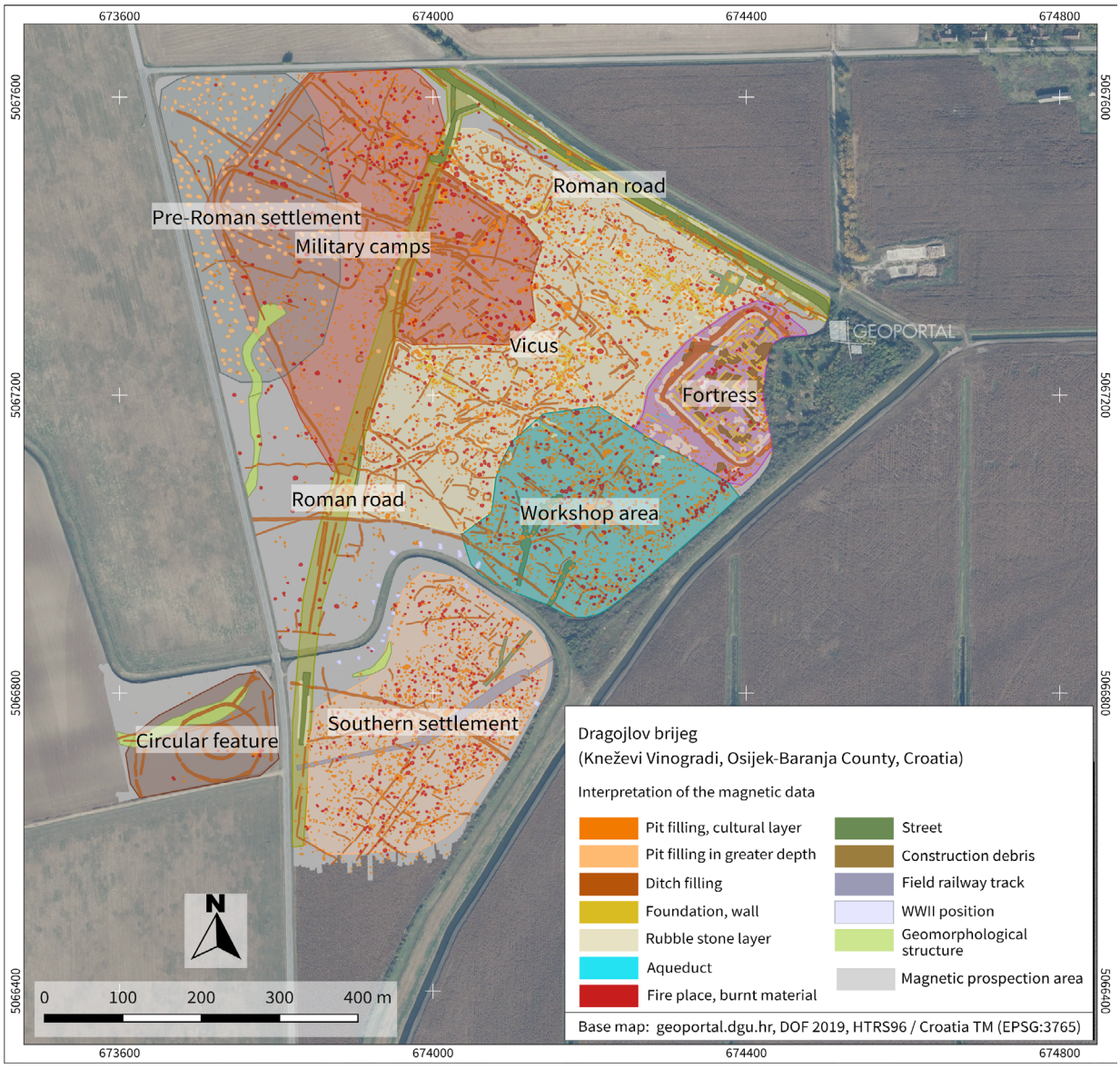

Fig. 2: Summary of the diachronic interpretation at Dragojlov brijeg.

surveys of 2020 and 2021 revealed a complex pattern of Roman features on almost the entire surveyed area of 60 hectares (Fig. 1 and 2). Besides the actual fortress, several larger units could be identified: To the west of the fortress, groups of stone buildings were detected, most likely associated with a Roman civilian settlement (vicus). Secondly, an assumed production area was found to the south of the fortress. The Roman military installations such as camps and minor fortresses, defined by ditch complexes, were found in the terrain 500 m towards the northwest of the main fortress. On the northeastern edge of the field, the course of a road can be traced. Two bifurcations, probably related to accesses to the vicus and to the military camps, respectively, are recognizable. A north-south running feature most probably reflects the course of the main Limes road connecting the site with the colonia Aelia Mursa (Osijek) in the south and the sites of Ad Novas and Ad Militare in the north. The 2021 data reveal the existence of another settlement core, located to the east of the main Roman road. Eventually, a nearly concentric circular ditch system with a total diameter of more than 100 m, was identified to the west of the southern settlement. Its origin remains unclear. Traces of a pre-Roman settlement can be assumed in the north-western part of the field: A nearly

regular arrangement of pits, characterized by low magnetic intensity and thus pointing to low thickness or greater depth, indicate the presence of pit house remains. This settlement zone overlaps partly with the zone of the military camps and most likely continues towards the north and the west. Besides the Prehistoric and Roman structures further magnetic anomalies were connected to installations related to the exploitation of the fertile land by large-scale agricultural farms operated by Habsburg nobles since the 18th century. Further features were associated to military positions used during the Battle of Batina in November 1944, a decisive battle of Second World War between units of the Red Army and the Yugoslav Partisans against the Wehrmacht and their allies. WWII military positions could also be identified at other Roman Limes sites, which underlines the strategically favourable positions of them.

Discussion

The result of the interpretation using the diachronic approach, i. e. the deciphering all information possible in the palimpsest-like magnetograms, raises the question how far a veritable interpretation of archaeogeophysical data sets can go without additional data from direct archaeological interventions. Despite all uncertainties, it is proposed to squeeze the data as much as possible using additional sources such as historical maps and other archives, in order to set up plausible hypotheses which can be evaluated when needed and when time and resources allow.

Conclusion

Flexible magnetic prospection, i.e. large-scale surveys with motorized array and small-scale investigation with hand-driven systems, is a powerful tool for systematic archaeological investigation of archaeological landscapes. In case of the Danube Limes sites, an impressive amount of information could be obtained, not only related to the history of the Roman Limes along the Danube. The diachronic approach to magnetic data interpretation revealed the existence of a complex archaeological record. Prehistoric to modern structures could be detected which complete the picture of the development of human societies at the Middle Danube and thus allow a more comprehensive narrative of the history of this Central European region.

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The search for pre-clovis in the ice-free corridor: archaeological geophysics at Wally's Beach

William T.D. Wadsworth [1*], **Gabriel Yanicki** [2]

1 Institute of Prairie and Indigenous Archaeology, Department of Anthropology, University of Alberta, Edmonton, Alberta, Canada
2 Canadian Museum of History, Gatineau, Quebec, Canada
* Corresponding author: E-mail: wwadswor@ualberta.ca

Abstract
Wally's Beach is an important archaeological/paleontological locality in southern Alberta where pre-Clovis dates have been reported from butchered faunal remains, but associated cultural materials are poorly known. Significant challenges exist for research at the site, including poor access, limited stratigraphy, and the extreme size of the site (>2km^2). Ground penetrating radar and drone imagery were conducted to identify higher-potential areas, which discovered a possible paleochannel. This discovery aids future research efforts at Wally's Beach to better understand the earliest human occupation of the ice-free corridor.

Keywords
Alberta; GPR; ice-free corridor; paleochannel; UAV

Introduction

The ice-free corridor (IFC) was a habitable zone that emerged between the retreating Cordilleran and Laurentide ice sheets during the terminal Pleistocene in what is now western Canada. The IFC holds great significances an early route from Beringia in the first peopling of the Americas, or as a path of back-migration (Potter et al. 2018; Ives et al. 2019). Wally's Beach (DhPg-8) is an archaeological and paleontological locality located in the southern funnel of the IFC where the butchered remains of late Pleistocene megafauna have been found and radiocarbon dated to more than 13,300 calendar years ago (Waters et al. 2015). The cultural affiliation of the people who hunted these animals several centuries before the attested range of the widely known Clovis culture (ca. 13,050–12,750 cal. yr. BP, Waters et al. 2020) remains unknown.

Background

Creation of southern Alberta's St. Mary Reservoir in the early 1950s resulted in the inundation of prairie surfaces that are now intermittently exposed, at times of low water, to aeolian and lacustrine erosion. As sediments stripped away, the footprints of Pleistocene megafauna are exposed, along with scattered faunal remains. Bones of extinct horse and camel species—some with cut marks attributed to stone tools—have yielded the earliest known dates for human presence in the IFC. Cultural materials from the late Pleistocene through to the modern era are also left scattered on the surface. The actively eroding contexts of the faunal and cultural finds makes their association uncertain; a goal of this project is to identify parts of the site area where late Pleistocene-aged deposits may be found still buried, prior to their exposure by wind and waves.

Preliminary remote sensing was conducted in 2019 to assess subsurface topography through the central portion of the site, where intact capping strata indicate erosion has not yet reached Pleistocene-aged deposits. Ground penetrating radar (GPR) survey identified a suspected paleochannel of the St. Mary River that has subsequently infilled. Principal faunal exposures are associated with the west bank of this former channel, while newly discovered

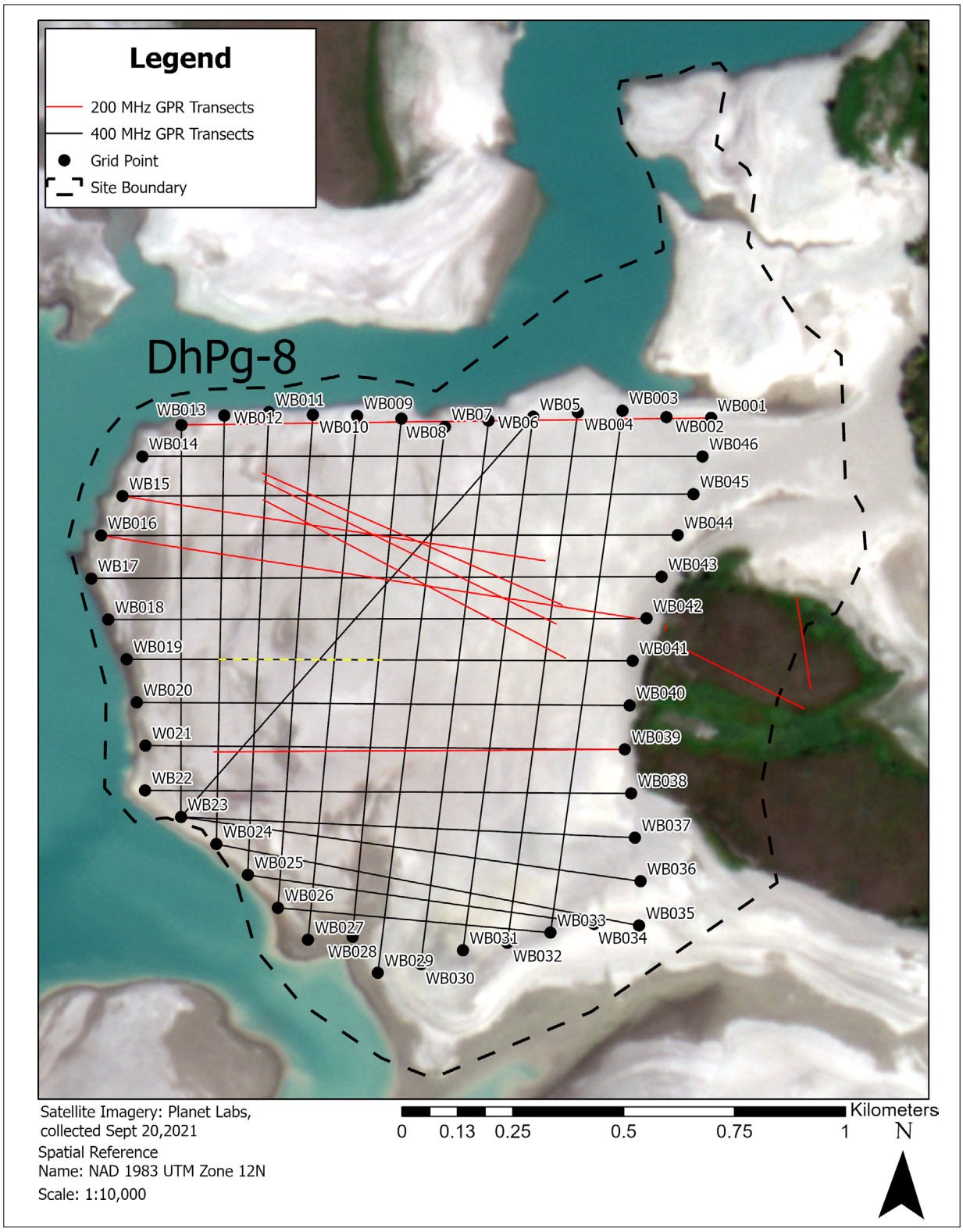

Fig. 1: Satellite photo of exposed St. Mary Reservoir bed showing Wally's Beach (dashed black line) with GIS-plotted survey grid waypoints (black circles with labels), 400 MHz GPR transects (black lines), 200 MHz GPR transects (red lines). Yellow dashed line shows profile section in Fig. 2 .

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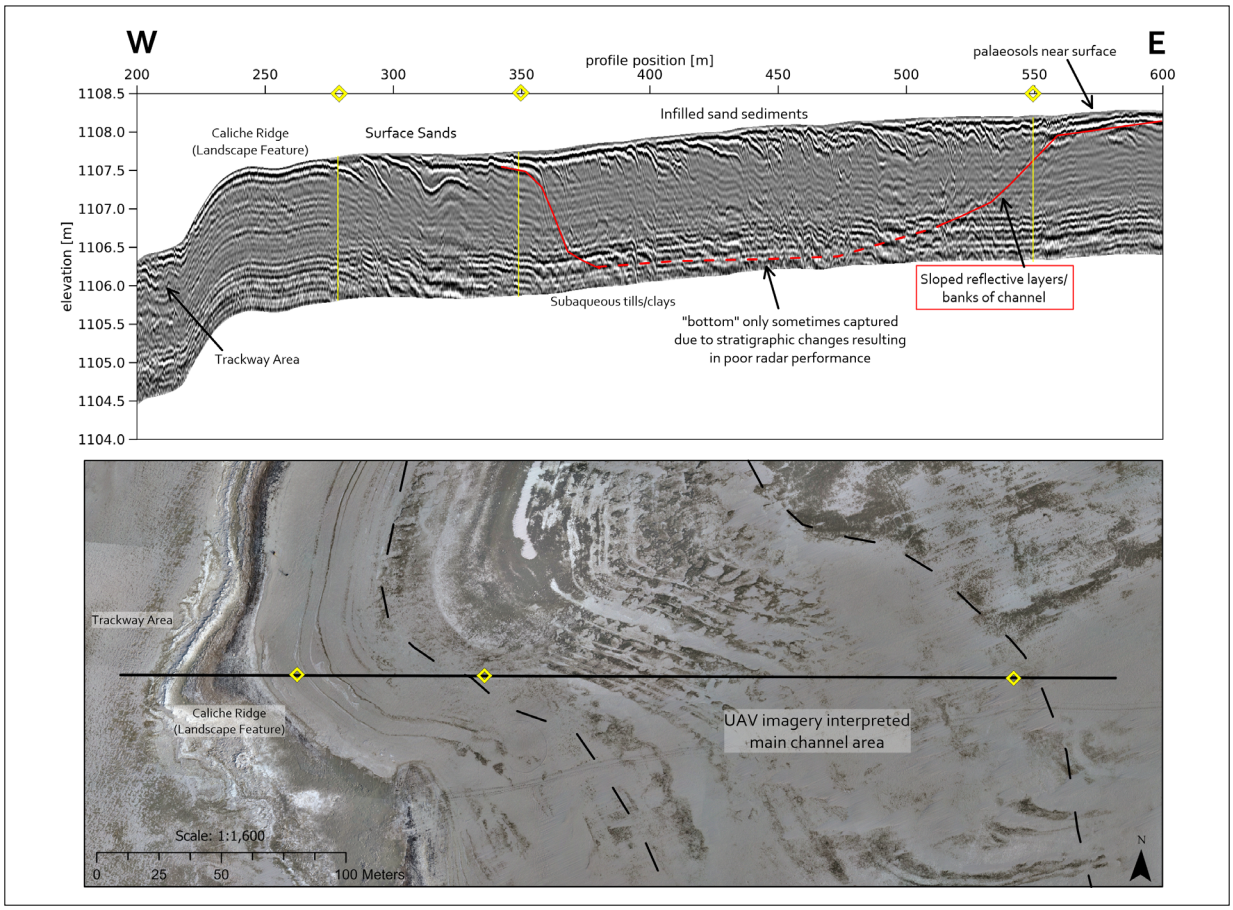

Fig. 2: Annotated 400 MHz GPR profile (transect section from WB19 to WB41) with yellow distance marks (top) and annotated drone imagery showing GPR profile section with corresponding marks (bottom). Both highlight key features and interpretive process (see reference 5 for added description).

terminal Pleistocene materials have been found on the paleochannel's east bank (Yanicki et al. 2022). Additional GPR data, coupled with unmanned aerial vehicle (UAV) orthoimagery, were collected in October 2021 to better characterize the paleochannel feature.

Methods

Prior to fieldwork in 2021, a systematic survey grid was created in ArcGIS Pro (Fig. 1). Perimeter waypoints were plotted every 100 m and staked in the field using a handheld GPS. Fifteen east-west and twelve north-south GPR transects were walked with a GSSI SIR-3000 using a 400 MHz antenna mounted on a 3-wheel cart. Additionally, 200 MHz data was collected at various intervals to test replicability. During transects, surfaces were examined for exposed artifacts and their location coordinates were recorded.

Drone photography was conducted with a DJI Phantom 4 Pro using Drone Deploy. The UAV was flown at a constant height of 80 m above ground level, yielding a spatial resolution of ~2.4 cm/pixel; over 1400 images were collected. Drone data were processed in ArcGIS Pro to generate a digital elevation model (DEM) and orthomosaics. Imagery from multiple years was also processed in AgisoftMetashape to produce point clouds and assess erosional changes using Cloud Compare (2022).

GPR data processing was undertaken using GPRPy, an open-source python-based software program (Plattner 2020). Python scripts were written and adapted to perform basic GPR processing including time-zero, dewow, AGC gain, velocity analysis, trace averaging, and mean background removal corrections. GPR profiles were topographically corrected from the drone-derived DEM. Profiles were interpreted and manual picks were taken to identify a horizontal reflector underlying the infilled sediments of

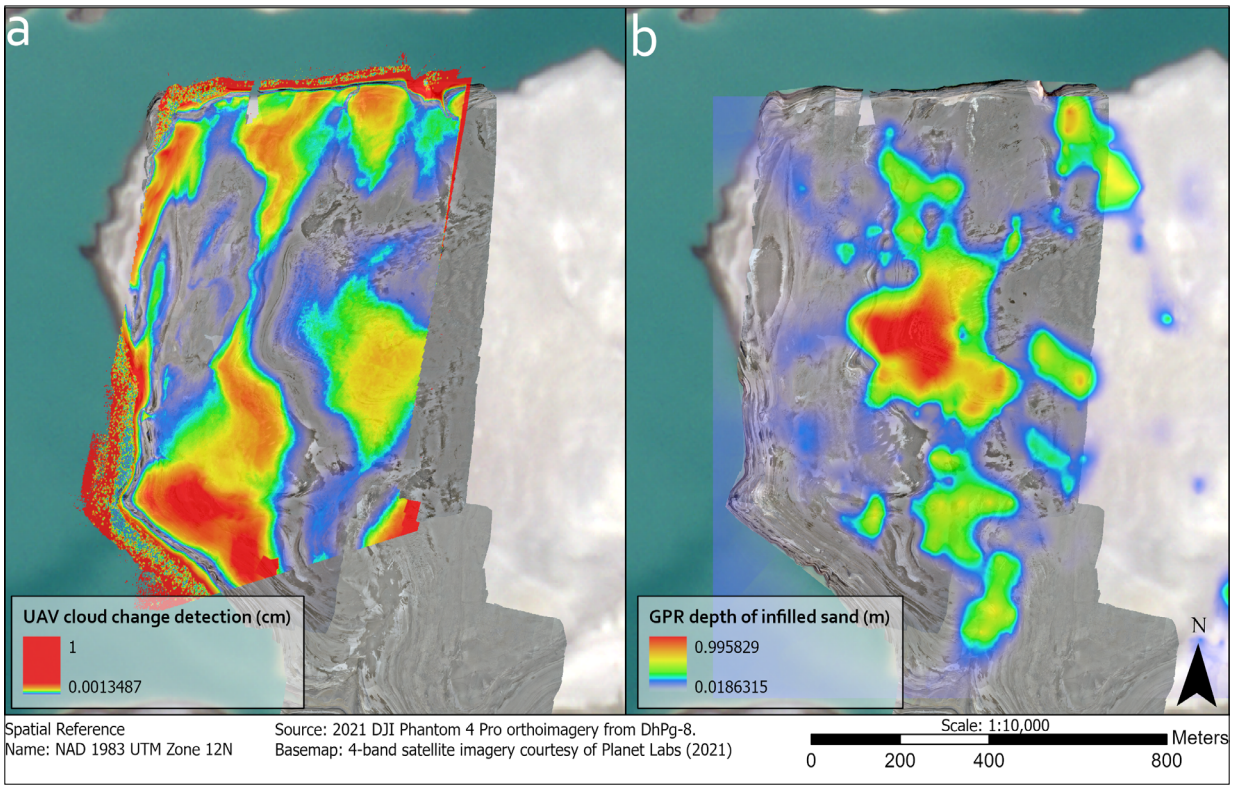

Fig. 3: Comparison of year-to-year cloud change detection results. a) and isopach map showing depth of infilled paleochannel feature, interpolated from 2021 GPR picks b), overlain on UAV orthomosaic.

the paleochannel feature. These picks were then interpolated (inverse distance weighted) in ArcGIS Pro.

Results

The 2021 GPR survey successfully reproduced the 2019 findings. The same buried horizontal reflector overlain by sand deposits was identified (Fig. 2). Where Pleistocene materials are found at the surface, this prominent reflective feature is not present in the GPR data and has likely already eroded away. When it is observed, it appears as a broad, shallow, dipping channel across the site area, usually only 0.5–1 m deep, but in places >200 m wide, overlain by recently redeposited silts and sands. Like 2019, this buried feature was lower amplitude than the reflective surface sands and, in some areas (especially with stratigraphic changes), its presence varied.

Combining GPR and UAV data, surface sediments, topographic features, and potential subsurface features were interpreted (Fig. 2 & 3). Year-to-year comparison of point clouds from UAV orthoimagery supports both the interpretation of paleochannel infilling and erosion of the remaining areas. While many exposed topographic features are actively eroding (Fig. 3a, yellow and red), some parts of the site appear relatively stable (Fig. 3a, no colour). The stable areas correspond well with the GPR-identified paleochannel (Fig. 3b).

Discussion

Expanded GPR surveys at Wally's Beach, coupled with change detection results from UAV imagery, are refining our understanding of this internationally significant site. A paleochannel once not only bifurcated the site, but in the past would have influenced site utilization by ancient peoples and game. Channel-adjacent areas can be pinpointed and may still contain intact early cultural and faunal deposits, potentially dating to the earliest periods of human occupation in the IFC. Areas at imminent risk of further erosion are also highlighted.

While the most eroded parts of the site have been the focus of past study, the areas east of the paleochannel

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identified here have yet to be investigated in detail. As future field work at Wally's Beach is planned, the highest-potential and highest-risk areas will be especially targeted in the search for intact late Pleistocene deposits.

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6

METHODS AND INNOVATIONS

A new approach to the acquisition of microtopography associated with geophysical survey (Bat/Al-Arid, Sultanate of Oman)

Lionel Darras [1]*, **Corinne Castel** [1], **Olivier Barge** [1]

1 UMR 5133 - Archeorient, CNRS, Lyon, France
* Corresponding author: E-mail: lionel.darras@mom.fr

Abstract
We present a new approach to acquire microtopography without a GPS System with decimeter precision. This can be used for acquiring microtopography on all environments (forest, urban, underground). It enables an easy interpretation of geophysical maps with microtopography easily acquired.

Keywords
altimeter; easier interpretation; magnetic prospection; microtopography without GPS system

Introduction

Geophysical surveys on archaeological sites provide a useful complementary information for the archaeological study of a site. Once the geophysical survey has been carried out, the geophysicist wishs to quickly interpret the geophysical map on the field. The knowledge of the local topography allows correlation and discrimination between geophysical anomalies and topographic features to have a quick and better interpretation. To have a topographic map of the prospected area, there are two main solutions:

The first solution is to use a centimetric GPS-RTK synchronized with the geophysical device. The second solution is to have a topographic map acquired by conventional methods, by LiDAR, or by aerial photogrammetry (UAV, kite).

The first solution requires the use of positioning equipment of a certain weight and a volume that it is sometimes more complicated to transport by air and to have importation authorizations in addition to geophysical material. On archaeological sites, it is frequent to have only one GPS system available for the entire team. When the positioning equipment has to be used during all geophysical prospection it might prevent other essential studies, depending on this system, to be occurred at the same time. In addition, if the geophysical prospecting is in an environment with the more or less dense presence of trees or walls, the precise positioning may be interrupted, which may prevent the continuity of the topography measurements taken by the GPS-RTK system.

The second solution obviously requires the work of a topographer, whereas in the context of certain campaigns, the presence of such a specialist is not always honored.

From this inventory, a reflection was initiated to properly interpret a geophysical map: is the positioning (x, y, z) of each measurement so essential? Geophysical prospecting can be carried out using a grid marked on the ground providing a local reference (x, y) and a profile tracking in this same landmark. The georeferencing of the map can be done by noting the precise position of the angles of these prospected areas using a GPS or a total station.

With this method, the positioning in (x, y) of the measurements can be carried out in post-processing. However, the z coordinate at each measurement point is still unknown. It is for all these reasons that our new approach has been focused solely on measuring the z-coordinate of the position of each measurement in the simplest possible way with a good precision of the decimeter order. This project was developed under the name of ZheoPS (Z Positioning System).



Fig. 1: Bat/At-Arid site general view, © archaeological Mission Bat/al-Arid. C. Castel.



Fig. 2: Magnetic prospection coupled with ZheoPS system, © archaeological Mission Bat/al-Arid. C. Castel.

Materials and methods

We got inspired by the barometric altimeters used by paragliders to know their altitude variation in real time. Their displayed differential precision is 10cm. The advantage of this sensor is a reduced size with a very low magnetic impact: it can be placed in close range to a geophysical sensor without disturbing its measurement. It can be connected to a compact acquisition board which performs the measurements and which transmits the altitude measurement information in a NMEA frame format. This frame can be transmitted to the geophysical instrument, to synchronize the altitude and the geophysical measurements. In this first version, the raw altitude is used. Each altitude measurement is subtracted from the average of the measurements along the profile to remove the influence of the variation in meteorological conditions. Two transverse profiles are carried out to calibrate the profiles with each other. This calibration method allows the construction of a microtopographic map of the area.

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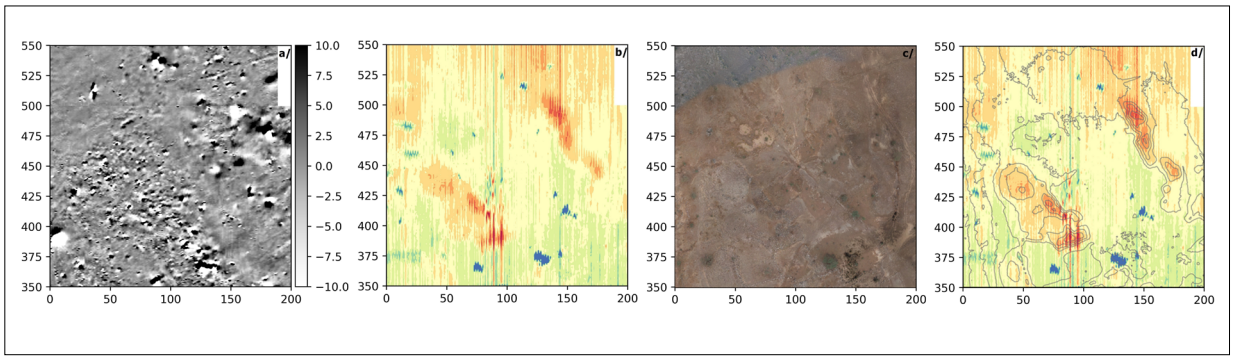

Fig. 3: a) Magnetic map, b) microtopographic map (ZheoPS), c) Aerial view, d) microtopographic map combined with topographic map (isolines every 50cm).

Results

As part of an archaeological mission in Bat/Al-arid (Sultanate of Oman), a second magnetic prospecting campaign was scheduled for January 2020 (Castel et al. 2020). Al-Arid is an Early Bronze Age settlement site in the interior of the Oman peninsula. The purpose of this geophysical campaign was to continue the overall study of the site initiated a year earlier. The environment was of relatively low topography with, however, the presence of towers, canals, small mounds and some trees (Fig. 1).

We placed the altimeter sensor of ZheoPS project on the magnetic sensor (Fig. 2a). We placed the altimeter datalogger in a bag behind the operator and we connected it to the geophysical datalogger to synchronize measurements during magnetic prospecting (Fig. 2).

In the same local landmark, a magnetic map could be constructed (Fig. 3a) synchronized with altitude measurements made by ZheoPS system. These measurements make it possible to construct a microtopographic map (Fig. 3b), without scale due to the use of this first prototype and its relative measurements (a future version (ZheoPS-RTK) will allow the acquisition of real altitude measurements and the construction of a map with a precise scale).

A digital elevation model (DEM) was produced independently thanks to the photogrammetric processing of aerial photographs (Fig. 3c) taken at low altitude (Barge and Régagnon 2017). This DEM, with a resolution of 25 cm and an accuracy of about 3 cm (Fig. 3d), allowed the comparison of our experimental data.

Discussion

The simultaneous construction of magnetic (Fig. 3a) and microtopographic maps carried out with ZheoPS measurement (Fig. 3b) thus makes it possible to establish the correlation between these different measurements. Thanks to the Figure 3d, the topographic map can be compared to the microtopographic map and it is interesting to observe that in the two maps, earth embankments (Fig. 3d, in red) are well detected. With this first version of ZheoPS, we built a microtopographic map corresponding to the variations of the topography of the prospected zone. It facilitates the interpretation of geophysical measurements in its microtopographic environment but it does not yet allow the construction of a precise topographic map. A new ZheoPS-RTK version taking into account weather-dependent measurement errors has been developed (Darras 2022) and already tested to get the elevation of measurement points along an electrical tomography and we will test this system later during a complete geophysical survey to build a real topographic map.

Conclusion

This paper presented an approach on how to measure the microtopography of the area prospected with a decimeter precision. With these results, it is easy to understand the advantages of this new approach and it is still more interesting knowing that this system can be used in forest, urban and underground environments.

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St. Petri Cathedral Schleswig: non-destructive geophysical damage analysis of medieval plaster

Yunus E. Esel[1]*, Ercan Erkul[1], Sandra Hintz[1], Detlef Schulte-Kortnack[1], Christian Leonhardt[2], Julika Heller[2], Thomas Meier[1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Werkstatt für Kunst und Denkmalpflege GbR, Kiel, Germany
* Corresponding author: E-mail: yunus.esel@ifg.uni-kiel.de

Abstract
Non-destructive geophysical methods were applied to detect moisture at the St. Petri Cathedral in Schleswig. One of them is thermography, which allows to distinguish between intact and defective medieval plaster. Additionally, the success of a restoration can be determined by ultrasonic surface measurements.

Keywords
moisture detection; monitoring; non-destructive; thermography; ultrasonic

Introduction

Historical buildings such as the St. Petri Cathedral in Schleswig (Federal State Schleswig-Holstein, Northern Germany) are considered as important cultural monuments. Many buildings of this type show serious damages due to moisture content. The application of geophysical methods such as ground penetrating radar (GPR), Infrared Thermography (IR) or Ultrasound (US) are everyday methods in the engineering geology and construction industry. There are examples for the combination of these methods for non-destructive examination of building structures (e.g. Arndt et al. 1994; Rodrígue-Abad et al. 2010; Meier et al. 2015) but it is not yet commonly applied in the field of restoration and conservation. The analysis of deeper structures is currently being carried out with drilling. Coring allows for measuring the moisture content quantitatively, it is however not non-destructive and yields only local information that is to be complemented by non-destructive testing revealing average properties of the entire structure. Here we report on geophysical investigations of altered medieval plaster in the cloister of the Cathedral in Schleswig (Fig. 1) in the framework of a project of the German Federal Foundation for the Environment (Deutsche Bundesstiftung Umwelt - DBU) entitled "Investigations on transformation, mobilization and recrystallization of gypsum on heavily salt-loaded surface of important wall paintings using the Schwahl of St. Petri Cathedral in Schleswig" (Stahlbuhk 2019; Meier et al. 2019). In cooperation with the "Werkstatt für Kunst und Denkmalpflege Kiel" geophysical investigations with ultrasound surface measurements and thermography were carried out in September and October 2017.

The cathedral was built at the beginning of the 13th century and houses early gothic paintings in the cloister (called Schwahl). One reason for the gypsum crystallization could be moisture content in the walls. The following measurements were carried out: Ultrasound surface wave measurements, passive and active IR and GPR.

Materials and methods

The idea of combining more than two non-invasive geophysical methods to characterize masonry structures exist since the early 1990s. The federal office for material research and testing (so-called BAM) started in 1994 first tests to characterize moisture with non-invasive methods. According to Arndt et al. (1994) they could confirm that a characterization of moisture is basically possible, for

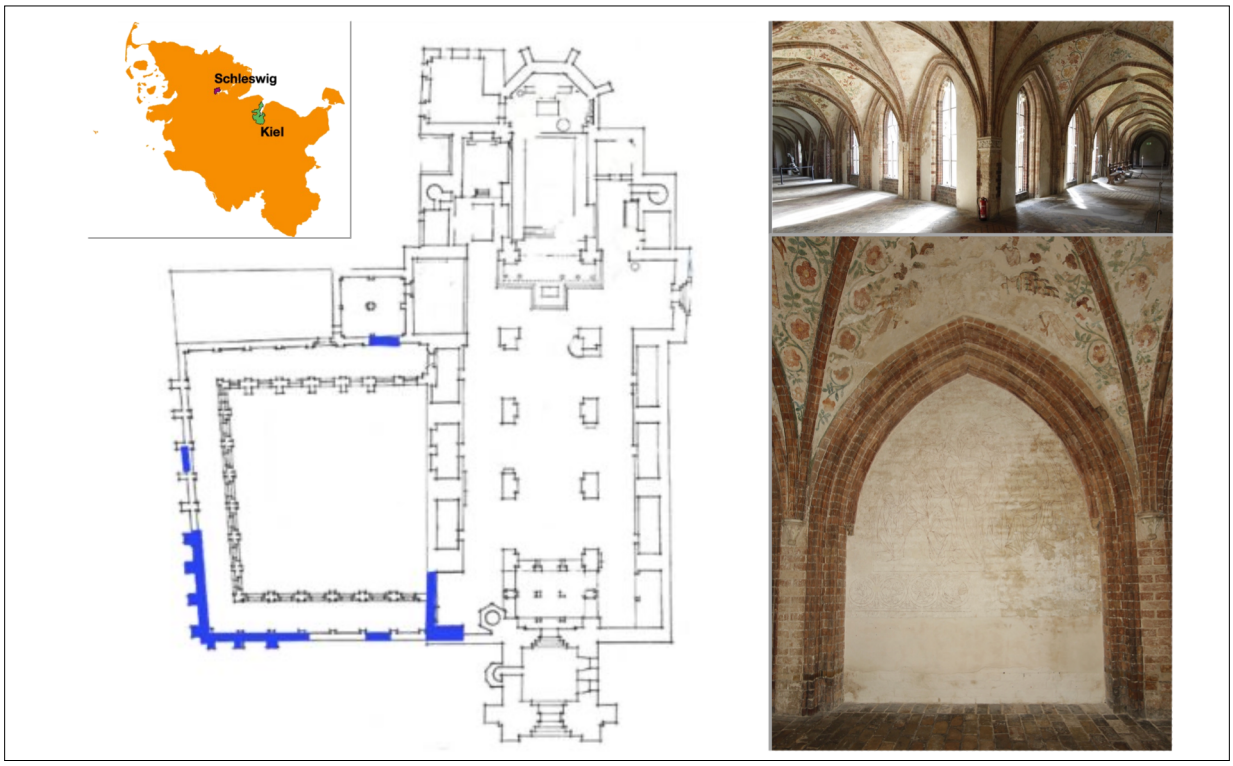

Fig. 1: Left: Site plan. Marked in blue are the areas that were measured. Top left: Overview Location. Marked in purple is the city of Schleswig in the state of Schleswig-Holstein, where the church is located. Top right: View into the cloister. Bottom right: Medieval wall paintings with plaster deposits. Photo: D. Schulte-Kortnack.

example, with electromagnetic waves. The success depends among other things on the influence of the salt and moisture content. For these investigations we combined infrared thermography (Fig. 2, left) and ultrasound measurements (Fig. 2, right). Infrared Thermography can give a precise overview of the areal distribution of moisture. Therefore, the investigation of the surface temperature is carried out with a thermal imaging camera from the company InfraTec GmbH. The spectral range lies in between 7.5 and 14 µm. Temperatures can be measured between -40 °C and 2000 °C with an absolute measuring accuracy of 1.5 °C and resolved with a pixel-to-pixel relative resolution of approx. 0.03 K (InfraTec-GmbH 2015). The method can be applied in two different modes. The first one is called passive thermography. It is based on the detection of natural surface temperature variations over a pre-defined time period. The second type is called active thermography. Through controlled heating with infrared heating lamps up to 2 K over a period of 5 minutes and the recording of the cooling phase over 45 minutes after switching off the heat source, a temporal spatial analysis of the measuring surface can be carried out. To get more information about the near surface properties under the plaster ultrasonic surface measurements along profiles were carried out. For this purpose, we used equipment from the manufacturer Geotron. Measuring a profile is possible by using a manual coupling device with a receiver and a transmitter. The transmitter is fixed and the receiver is offset in 1 cm increments from 5 cm to 20 cm resulting in 16 measurements per profile. The frequency range lies in between 10 kHz to 300 kHz. The sampling frequency is at 5 MHz.

Results

Passive measurements on yoke 5 indicate a defect at the horizontal barrier on the lower right side, which can be identified due to low temperatures above the barrier (Fig. 3b). It also shows temperature differences in the area of the plaster above the barrier (Fig. 3b). The original medieval upper part shows higher temperatures than the lower younger part in the middle. Active measurements in a small part on the right side of yoke 5 were made on so-called test surfaces (Fig. 3, white box in a, c, d). Subsequently,

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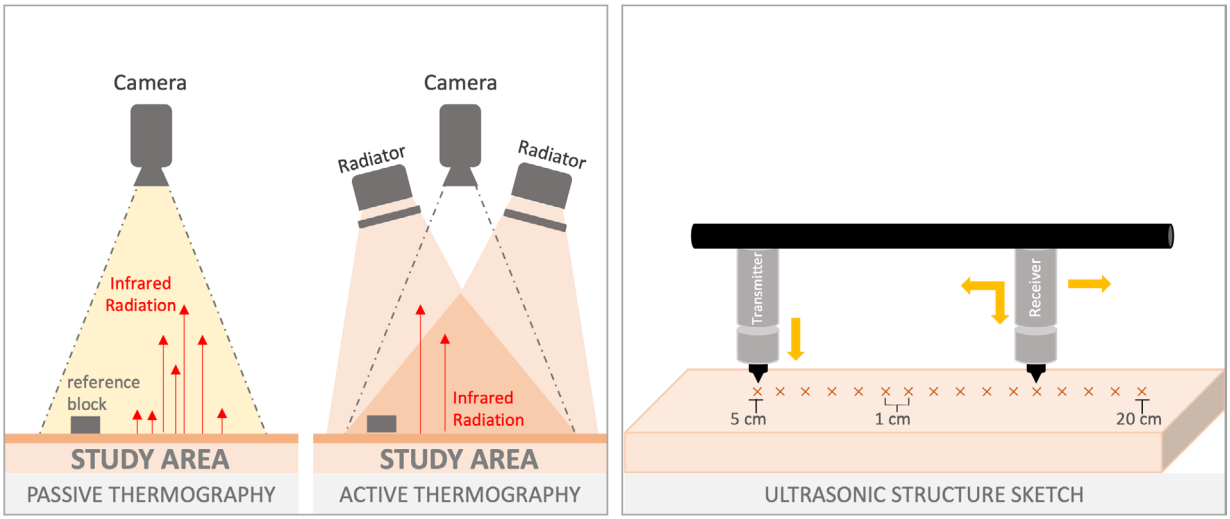

Fig. 2: Structure Sketches. Left: Passive and active thermography with camera, reference block and Radiator. Right: Ultrasonic measuring device with transmitter and receiver position. Crosses mark the measuring points.

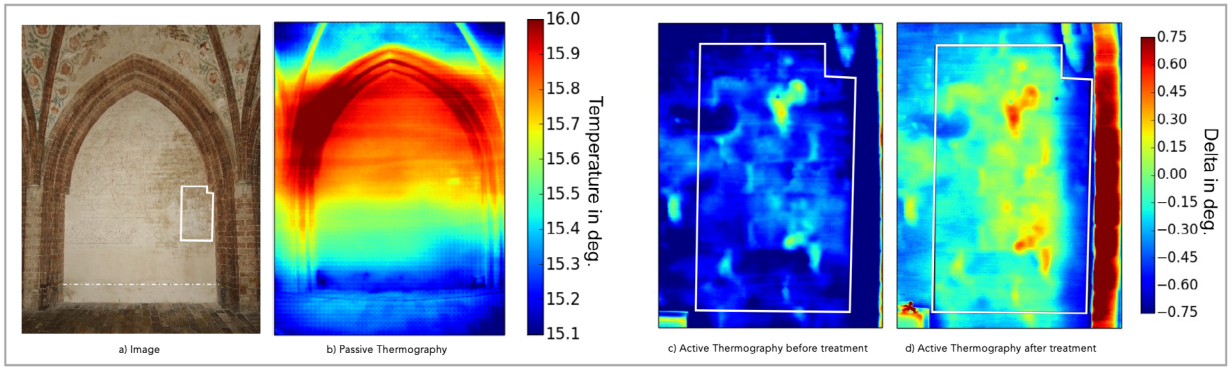

Fig. 3: a) Photographic Image of yoke 5 in the cloister. Dark discolorations show deposits due to moisture. The white square shows the area with test treatments. The horizontal barrier is marked by the dashed horizontal line. b) Passive Thermography – Average temperature over about 2000 images. Red colors are warm, blue colors are cool. Visible is a defect of the horizontal barrier on the right side. c): Active Thermography before treatment: Temperature difference to the reference block Immediately after the switching off the radiators in September. d) Active Thermography after treatment: Temperature difference to the reference block in October. Detachments increase the temperature. Cooling is significantly slowed down.

various solvent compresses were applied to reduce the deposit. The measurements were repeated after treatments in test areas to see what effects the different solvents had on the properties of the plaster. Due to successful treatments the porosity is increasing. This leads to a reduction of heat conduction detectable by slower cooling and larger temperatures after active heating (Fig. 3d). Our results show that specially a defect horizontal barrier at section 5 in the cloister could be responsible for moisture ingress. Changes in the plaster due to successful treatment can also be detected by ultrasonic surface measurements (Meier 2019). Damaged plaster with gypsum inclusions leads to higher Rayleigh-wave velocities and decreased scattering of Rayleigh waves. A reduction of the Rayleigh-wave velocity and increased scattering are indications for successful treatments.

Conclusion

Passive thermography as non-destructive method is appropriate to get a fast and informative overview on damages and moisture at the surface of objects. Results of active thermography show that defect plaster cools down faster than intact medieval plaster. Also, ultrasonic surface measurements can be used for quantifying the plaster condi-

tions. On damaged plaster Rayleigh wave velocities are around 2000 m/s. The average velocity of intact plaster is about 1000 m/s and the waveforms show a higher complexity due to scattering. In conclusion, both measurement methods are useful for the non-destructive analysis of near-surface material properties of plaster.

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Investigating remains of an early modern manor in Noer (Schleswig-Holstein) using 3D ERT and GPR – first results

Simon Levin Fischer [1]*, Ercan Erkul [1], Tina Wunderlich [1], Michael Gräber [2], Katja Grüneberg-Wehner [3], Wolfgang Rabbel [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 GeoServe – Angewandte Geophysik, Kiel, Germany
3 Institute of Pre- and Protohistoric Archaeology, Kiel University, Kiel, Germany
* Corresponding author: E-mail: simon.fischer@ifg.uni-kiel.de

Abstract
Buried remains of an early modern manor are investigated using ERT and GPR. For this purpose, 3D approaches are applied for high-resolution imaging. The results of both methods are interpreted in combination with archaeological findings.

Keywords
archaeological prospection; early modern manor; Electrical Resistivity Tomography (ERT); ground penetrating radar (GPR); 3D inversion

Introduction

Manors are a cultural-historically important part of the landscape in Schleswig-Holstein (Germany) giving insights into land tenure of wealthy families, life and agriculture in the early modern age (i.e., Rasmussen 2010). There are two manors known to be present near Noer, 20 km northwest of Kiel (Fig. 1). One of them, being subject of this study, is suspected to have been a brick building with glass windows from the 16th to 17th century (Grüneberg-Wehner et al. 2016). Nowadays, there are no remains left above ground. Only a small hill reminds of the former manor.

The site and its direct surroundings were already investigated by Costard et al. (2022). They could show that geophysical methods are generally suitable to resolve remains of the former manor, such as wall structures or parts of the floor. Costard et al. (2022) conclude that the magnetic prospection could provide a fast overview of the manor's structure. However, the result was disturbed by many short-wavelength magnetic anomalies caused by surficial brick debris. Their Electrical Resistivity Tomography (ERT) results delivered a floorplan of remaining walls, while ground penetrating radar (GPR) could resolve some floor structures.

Methods

In this study, 3D ERT and GPR measurements were conducted to get a higher resolution image of the remaining buried manor structures. The GPR data were collected on 4th March 2022 while the ERT data were measured on 26th and 27th March 2022.

3D ERT

The 3D ERT measurements took place on a quadratic area of 31m x 31m, located above the known manor remains. The electrodes were arranged along a grid with 1m in- and crossline spacing. A RESECS multi-channel system (GeoServe 2017), developed by GeoServe, was used to conduct the measurements. As it is possible to measure up to eight parallel channels with the RESECS system, there were



Fig. 1: Site plan of the investigation area in Noer (Schleswig-Holstein). Source: Google Earth.

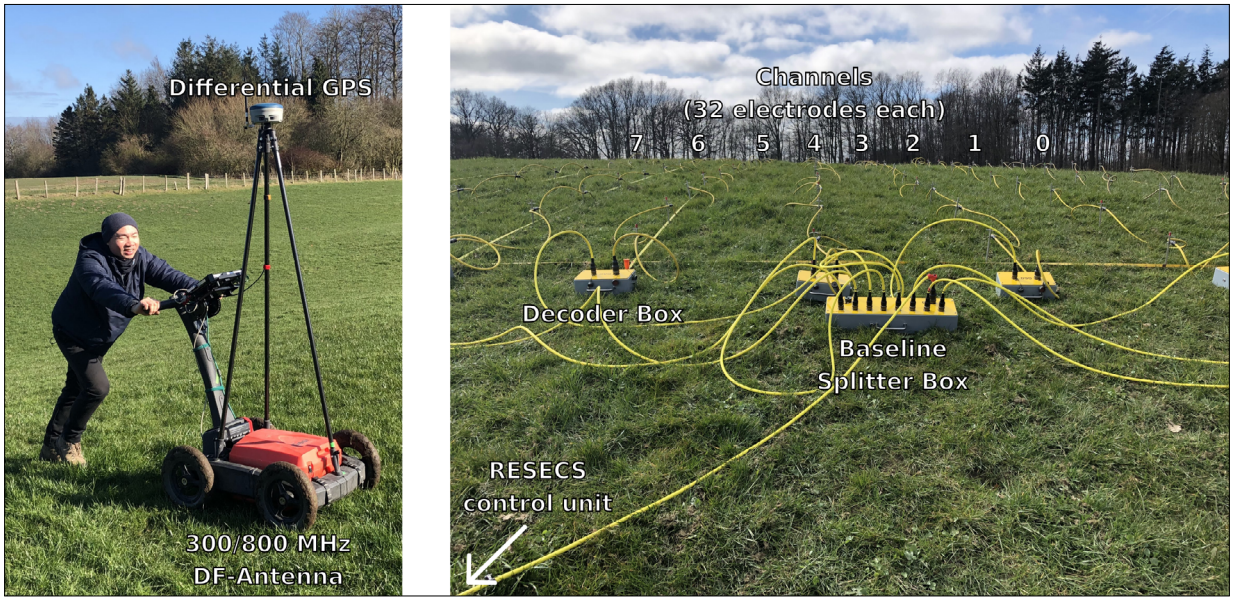

Fig. 2: Setup of GPR (left) and ERT measurements (right).

always eight lines (with 32 electrodes each) built up simultaneously. Each line was connected to two decoder units making it possible to address each electrode for current injection or potential measurements. The decoder units were in turn attached to a baseline splitter box, addressing the different channels (Fig. 2, left).

For this study, the dipole-dipole configuration was chosen because of its high lateral resolution (Okpoli 2013) and the shallow target depth. The 3D configurations were implemented by using one Master line, where the electrical current was injected, and 7 Slave lines with additional potential measurements. After finishing all measurements on one Master line, the whole setup was shifted in positive crossline direction. This process was repeated until the Master line reached the final crossline position. All in all, 93024 data points were collected, which took two people two days of work.

As a first step of data processing, measurements with bad data quality were excluded. That includes data points with current strengths below 0.5 mA, potential differences lower than 0.1 mV, geometric factors higher than 7000 m and/or standard deviations exceeding 10%. Following, an

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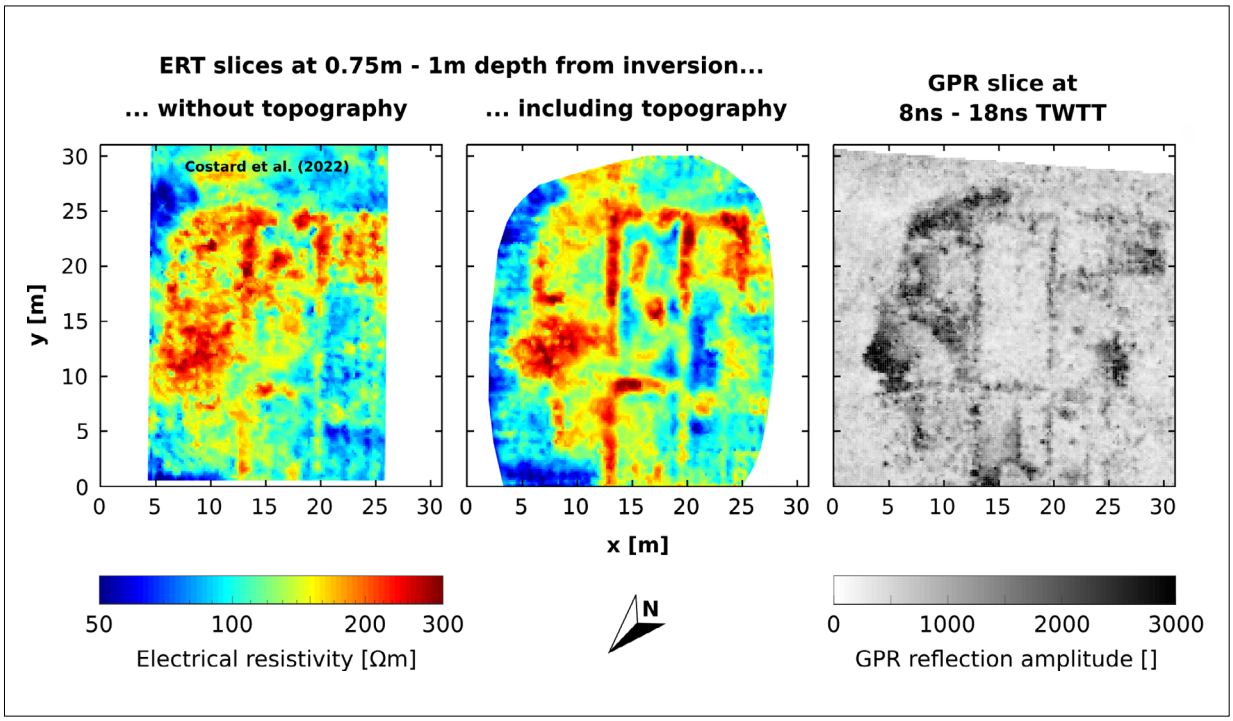

Fig. 3: Results of geoelectric 3Dinversion without (left) and with inclusion of topography (center), both shown as depth slices 0.75-1 m below the surface. Results of GPR measurements, shown as time slice from 8 ns to 18 ns (right).

underground model was created and discretized with the three-dimensional finite element mesh generator GMSH (Geuzaine and Remacle 2022). In doing so, the topography was included which is a difference to the approach by Costard et al. (2022). The underground model was then used for a 3D inversion by means of the open-source Python software package PyGimli (Rücker et al. 2017). Finally, the results were illustrated using MATLAB.

GPR

GPR measurements were done using a survey system designed by *GSSI*. It consists of a Dual-Frequency Antenna (300/800 MHz) mounted on a frame with four wheels (Fig. 2, right). A Differential GPS by *STONEX* was used for positioning of the system.

The profiles were orientated in northeast-southwest direction, which is perpendicular and parallel to the known manor remains. The crossline spacing between two profiles was 30cm. The GPR measurements covered the entire ERT area and some parts beyond.

The time range of each scan was set to ca. 100 ns (300 MHz) and 50 ns (800 MHz) respectively, while each scan consisted of 512 samples. Scans were triggered every 1 cm by a survey wheel, which is installed on the cart.

Processing of the GPR data was conducted with an In-house software named *DTplot*, and included the following steps:

1. Excluding GPS outlier
2. Setting spacing of traces to 2cm
3. Correcting for time-zero offset
4. Subtracting in- and crossline offsets
5. Applying gain
6. Calculating and plotting time slices

Results

3D ERT

An exemplary depth slice through the inversion result shows linear structures with higher resistivity values of ca. 200-300 Ohmm in an otherwise less resistive background model (Fig. 3, center). The high resistive patterns are mainly orientated parallel to the in- and crossline direction. There are four southeast-northwest aligned structures at local coordinates x = {7 m; 13 m; 20 m; 25 m} and two southwest-northeast lineaments at y = {9 m; 25 m}. The linear structures are perpendicular to each other and thus

form rectangular shapes. Another high resistive and elliptical anomaly is present in the northeastern part of the investigation area. Apart from that, the inversion result shows relatively low and homogeneous resistivity values of ca. 50-100 Ohmm.

Compared to the inversion result by Costard et al. (2022), the high-resistive structures are more defined and higher in contrast.

GPR

The results of the GPR measurements are shown in shape of a time slice at 8-18 ns (Fig. 3, right). All absolute reflection amplitudes in this time window are stacked for each pixel. The resulting figure shows linear structures with high amplitudes which are very similar to the high resistive anomalies in the geoelectric inversion. However, the lineaments are much sharper and well-defined than in the ERT result. This leads to the visibility of more substructures like the feature at x = 17 m and y = 2-7 m. The reflection pattern gets more diffuse in the northeastern part of the investigation area. Nevertheless, higher amplitudes are visible at the point where the elliptical anomaly is in the ERT depth slice. In between the lineaments and especially in the outer parts of the survey area, the GPR reflections are rather weak.

Discussion

By including the topography in the 3D geoelectrical inversion and using a Dual-Frequency GPR antenna, it was possible to get more detailed images of the electrical resistivity distribution and the GPR reflectivity.

The presented anomalies with high electrical resistivity, high GPR reflection amplitudes and linear character are a strong indication for man-made structures. Putting these findings into the cultural-historical context of the site, it is quite sure that these are the remains of an early modern manor. While the linear structures are probably wall remains, the other extensive anomalies could be remains of floors or something similar as discussed by Costard et al. (2022).

The varying electrical resistivity values along a common lineament could be due to different conservation states. Assuming the moisture content to be constant in the surrounding soil, high resistivity values are an indicator for well-preserved wall parts, while lower resistivity is a sign of advanced weathering.

Other archaeological findings such as fragments of glazed tiles and pottery suggest that the manor was inhabited by wealthy residents (Grüneberg-Wehner et al. 2016). As mentioned by Costard et al. (2022), the floor plan, which could be reconstructed by the geophysical measurements, is very similar to another mansion in Nuetschau close to Lübeck, Germany. Another similarity is a surrounding moat (Lafrenz 2015). Taking all these findings into account, the manor in Noer could be dated from the middle of the 16th century to the end of the 17th century AD (Grüneberg-Wehner et al. 2016).

Conclusion

Three-dimensional Electrical Resistivity Tomography and ground penetrating radar surveys were conducted on an early modern manor site near Noer in Schleswig-Holstein. It could be shown that it is possible to map remains of former walls and floors with both methods. While the GPR is capable of imaging the structures more precisely and well-defined, the ERT seems to help interpreting the conservation state of different parts of the building.

Inclusion of topography in the 3D geoelectrical inversion and the usage of a Dual-Frequency 300/800 MHz GPR antenna led to significant improvements in the ERT and GPR results and thus in mapping the manor remains.

In combination with the archaeological interpretation, it can be stated that the manor was used from the 16th to the 17th century by wealthy residents.

Acknowledgments

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Enhancing FD-EMI in-phase observations by means of 3D inversion: the case of Orcines, France

Julien Guillemoteau [1*], **Bertrand Dousteyssier** [2], **Luisa Heinig** [1], **Stella Nzouatchoua Tchana** [1], **Jens Tronicke** [1]

1 Institute of Geosciences, University of Potsdam, Germany
2 Maison des Sciences de l'homme, Université Clermont Auvergne, Clermont-Ferrand, France
* Corresponding author: E-mail: julien.guillemoteau@geo.uni-potsdam.de

Abstract
FD-EMI in-phase data were collected at a Gallo-roman site in Orcines, France. 3D inversion unveils features, which are not visible in the recorded in-phase maps.

Keywords
archaeological prospection; electromagnetic induction; magnetic susceptibility; 3D inversion

Introduction

Loop-loop frequency domain electromagnetic induction (FD-EMI) sensors are efficient tools to rapidly sense the electrical and magnetic properties of the subsurface. Maps of either conductivity or in-phase data can be used for delineating buried archaeological remains, which typically produce rather small-scale anomalies while large-scale anomalies are often associated to paleo-environmental deposits. Furthermore, due to the integrative/averaging nature of FD-EMI data, the small-scale anomalies often show relatively low amplitudes in comparison to the large-scale background response. This is particularly challenging for the case of FD-EMI in-phase data, which is significantly affected by noise related to various sources. Classical reduction and enhancement workflows can help but remain inconsistent in an exploration context, for which one does not know the characteristics of noise, the geometry of the targets as well as the characteristics of the background medium in advance. 3D inversion can be considered as an enhancing filter to discriminate pure noise from physically consistent signals of similar amplitude, because we test the lateral consistency of the observed data with respect to physically-based assumptions (a model of subsurface properties). Recent progress in instrumentation including the development of multi-configuration systems, high-resolution kinematic acquisition strategies, and fast 3D spectral inversion procedures, allows the reconstruction of 3D subsurface electrical and magnetic property distributions with unprecedented details (Guillemoteau and Tronicke 2016; Thiesson et al. 2017; Guillemoteau et al. 2017; Klose et al. 2018; Guillemoteau et al. 2019). In this study, we analyze a synthetic and a field data example in which the target archaeological structures generate an FD-EMI in-phase signal that is in amplitude comparable to the noise level and below the signal amplitude of the geological background medium. This signal is thus hardly detectable with a direct analysis of non-inverted data maps. Using these two examples, we investigate and evaluate how such targets can be detected and characterized by a 3D inversion procedure based on the multi-channel deconvolution (MCD) approach described in Guillemoteau et al. (2019).

Materials and methods

We consider a dense grid (interline spacing of 0.5 m and inline sampling of 0.1 m) of FD-EMI in-phase multi-configuration soundings as collected by a mono-frequency (9 kHz) four-configuration DUALEM21s system, which is placed at a constant height of 0.25 m above ground. The four configurations are two horizontal co-planar geome-

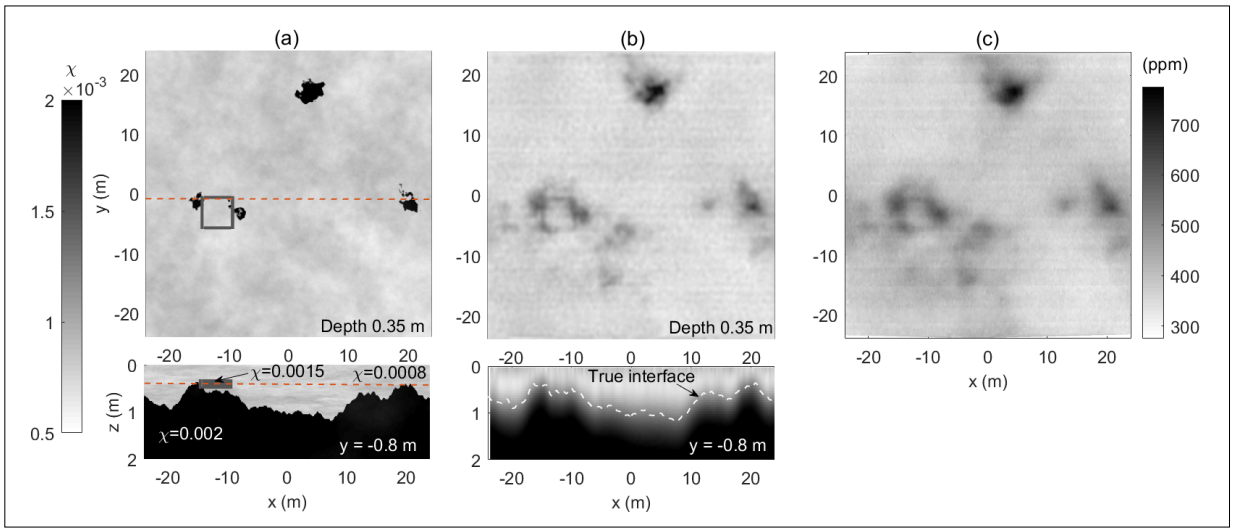

Fig. 1: Synthetic experiment. a) Input model for computing the FD-EMI in-phase data set, b) 3D model of magnetic susceptibility after 3D MCD inversion, and c) best in-phase data channel (PERP1.1) for delineating the archaeological target selected from the four channels available for a DUALEM21s instrument.

tries of coil spacings of 1 m and 2 m (HCP1 and HCP2), and two perpendicular configurations with spacings of 1.1 m and 2.1 m (PERP1.1 and PERP2.1).

The synthetic data have been generated for the input model shown in Figure 1a by considering a DUALEM21s instrument heading toward positive x. The modelled data consist of four maps of in-phase response in ppm corresponding to the four configurations of the instrument. To simulate realistic conditions, we modelled the data on irregular recording locations, taken from a real data set, and adding different kinds of noise.

The field data have been collected with the same acquisition setup as used in our synthetic study, except for the system heading which is toward positive y. The survey has been performed near Orcines (France) on the flank of the Puy de Dômes volcano, where the remains of buried Gallo-roman foundations were expected from several pedestrian archaeological surveys and the analysis of mole mounds. The collected materiel are ceramics of I-II century AD and basaltic rocks used for the constructions.

Results

For the synthetic case, a horizontal slice of the 3D susceptibility model obtained by 3D MCD inversion is shown in Figure 1b. We see that the rectangular target is more clearly delineated than in the selected data map (Fig. 1c). Performing a 3D inversion also allows the vertical separation of this rather shallow body from the underlying magnetic bedrock; i.e., the inversion result provides the relative position/depth of the different units of interest.

For the real data case, the model obtained from 3D inversion (Fig. 2b) provides an image with better resolved signatures. Moreover, it highlights signatures where the background geology (basaltic bedrock) shows high responses (noted A in Fig. 2b) and even unveils some part of the buried foundations (B in Fig. 2b).

Conclusion

By a synthetic study, we demonstrate how a full 3D inversion of noisy in-phase data can unveil subsurface magnetic signatures, which might be hardly detected by a qualitative analysis of the data without inversion. We further confirm these observations using a field data set acquired at a Gallo-Roman archaeological site in Orcines, France. Here, the 3D inversion of FD-EMI in-phase data unveils the presence of archaeological remains that are not visible in the original in-phase data maps. In addition, the overall appearance of the image is improved with sharply imaged signatures. This study confirms the limitations of a qualitative analysis of in-phase data maps and thereby demonstrates the potential of 3D acquisition and interpretation procedures, which are able to optimally exploit the information provided by FD-EMI in-phase data.

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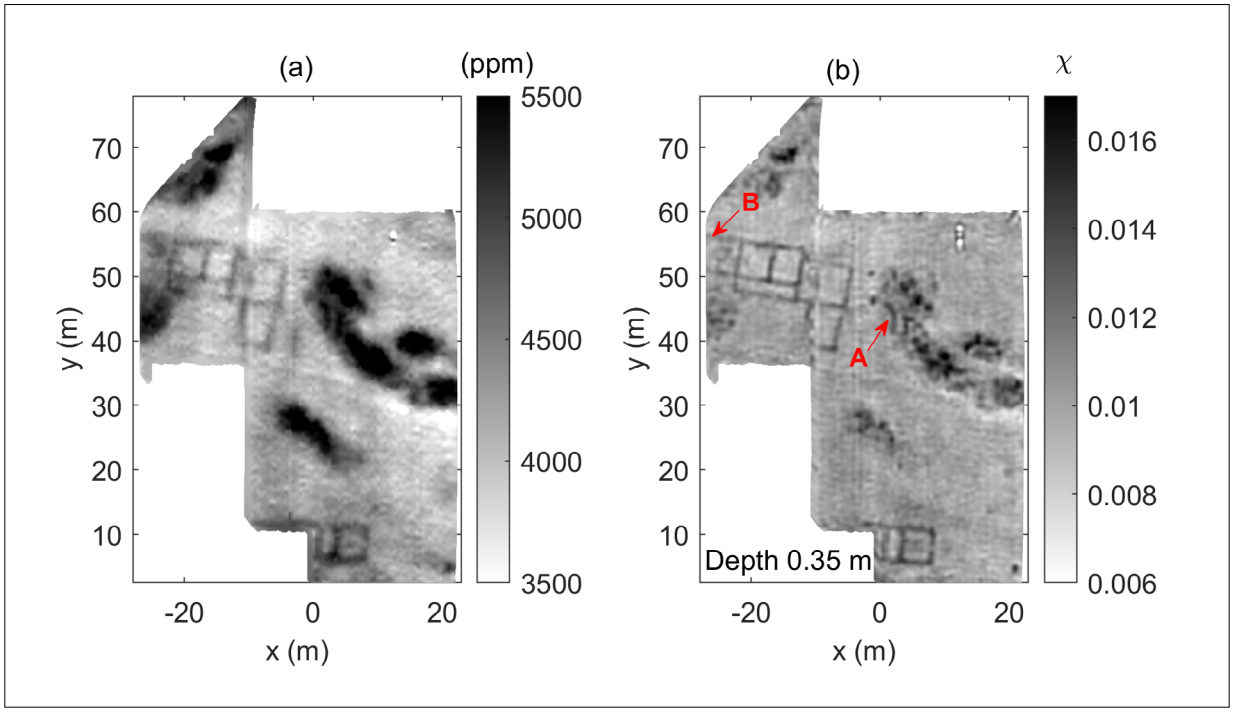

Fig. 2: Field data example from Orcines, France. a) Best in-phase data channel (PERP1.1) for delineating the archaeological target selected from the four channels available for a DUALEM21s instrument. b) Horizontal slice (depth 0.35m) of the 3D susceptibility model provided by the 3D MCD inversion.

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Starting to fill the gaps of the Selinus geophysical map

Morten Harms [1*], **Dennis Wilken** [1], **Melanie Jonasch** [2], **Erica Corradini** [1], **Ercan Erkul** [1], **Wolfgang Rabbel** [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 German Archeological Institute, Rome Department, Berlin, Germany
* Corresponding author: E-mail: morten.harms@ifg.uni-kiel.de

Abstract
We analyze ground-penetrating radar (GPR) data which was recorded in the tight confined spaces of an overgrown sand dune. The topography of the dune has the same scale as the penetration depth. We developed a 3D topographic migration algorithm and enable the generation and interpretation of layer parallel depth slices.

Keywords
archaeological prospection; GPR; Selinus; 3D topographic migration

Introduction

Selinus was an ancient Greek colonial city at the south-western coast of Sicily destroyed in 409 BCE by Carthage. A street layout for Selinus was proposed by Mertens (2003). The layout has been disclosed on the large-scale magnetic gradiometry prospection, see Figure 1. The city was surveyed only in parts. The main obstacle was a 12 ha sand dune which is located right in the center of the city. With a thickness of up to 4.5 m and dense vegetation magnetic gradiometry was not feasible. This work aims at filling data gaps in the dunes area of the street layout. We have conducted two Ground-Penetrating Radar (GPR) surveys since 2021.

Materials and methods

For this study a GSSI SIR4000 GPR controlling unit with a 400 MHz center frequency antenna was used. The zero-offset data was logged continuously with an inter-profile spacing of 30 cm or less. The data received standard pre-processing. A wave velocity of 14 cm/ns has been determined by diffraction hyperbola fitting.

The traces are binned to a data cube D(x,y,t) with a bin size of 25 cm. The data cube is then topography migrated using a 3D semicircle superposition approach (Wilken et al. 2016). For spatial interpretation, the data cube is usually cut horizontally into depth slices. Due to the strong variations in topography and depth of the cultural layer, this technique would constantly cut into these horizons. Thus, in this study we picked the cultural layer in the profiles and created 60 cm thick slices following the layer. We created 7 x 30 cm overlapping slices, covering an area from 1.2 m above the horizon to 1.2 m below the horizon.

We used coring data provided by Schneider Environmental Reconstruction (Jonasch et al. 2022) to validate the observed GPR reflection events.

Results

The example profile in Figure 2 shows a bright reflective horizon which is visible in almost all profiles recorded during this study. This horizon is independent of the dune's topography. We take this to be the dune's base and the cultural layer of ancient Selinus. This assumption correlates well with the interpretation of the core. While the borehole reached the limestone bedrock, its visibility in the radar data of this profile is unclear. In different profiles a faint horizon below the dunes base



Fig. 1: The figure shows the magnetic gradiometry map of the ancient city of Selinus in front of the proposed street layout. The sand dunes extend is shown in red. The dense vegetation of the dune and its surveyable areas are visible below the red shading. The area surveyed by GPR is marked in blue. The extent of Figure 3 is shown by a gray square.

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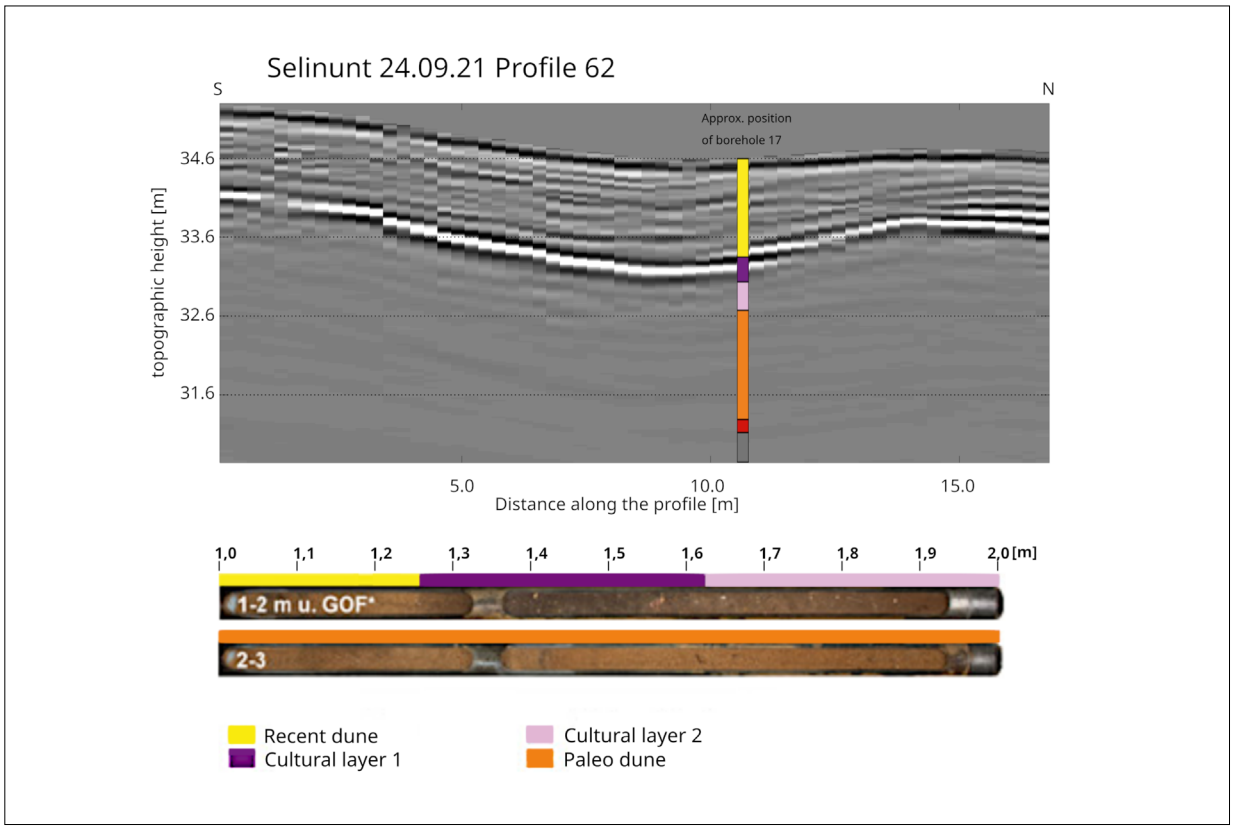

Fig. 2: Example profile 62. The approximated position of borehole 17 is marked. The corresponding core and its preliminary interpretation are shown. Note that the first meter of the core, containing only the dune's sand is not presented.

is visible. In these cases, we assume to have reached the bedrock.

In Figure 3 slice A marks two orthogonal wall-like structures in blue. They are of 1.5 – 2 m width and 1.5 m height. Profile A shows a cross-section with the wall-like structure marked in a blue square. Adjacent to this wall and 60 cm below, a rectangular structure with several subdivisions is visible. The orientation of the blue-marked structures does not match the proposed street layout in this area.

Slice B includes several spots of low amplitudes marked in green circles. The spots are orientated on what appears to be a section of a circle. The circle would have a diameter of 24 m. While the position of the spots is not regular enough to be an architectural feature, they might be collapsed remnants of a once circular building. Profile B shows a cross-section through two of the spots. From this perspective the spots appear more like dug-out holes.

Discussion and outlook

This abstract is an insight into an ongoing project. Therefore, any results stated here are preliminary. We can conclude, that GPR is a reasonable method in the sand dunes complex terrain. The shown data looks promising and allows a glimpse into unknown parts of Selinus. An analysis of the remaining data set will hopefully produce a coherent picture of the actual street layout. For now, at least in some areas the proposed street layout does not match the remnants found underground. Either the proposed layout is inaccurate in the dunes area or we see a younger phase of settlement in the data, after the colonies' destruction.

The dunes topography and heavy vegetation restricts the area recordable with GPR. The area consists of several irregularly shaped free spaces of 150 to 850 m². In the future we want to expand the surveyable area by surveying below free-standing bushes with a pair of antennas in transmitter and receiver arrangement.

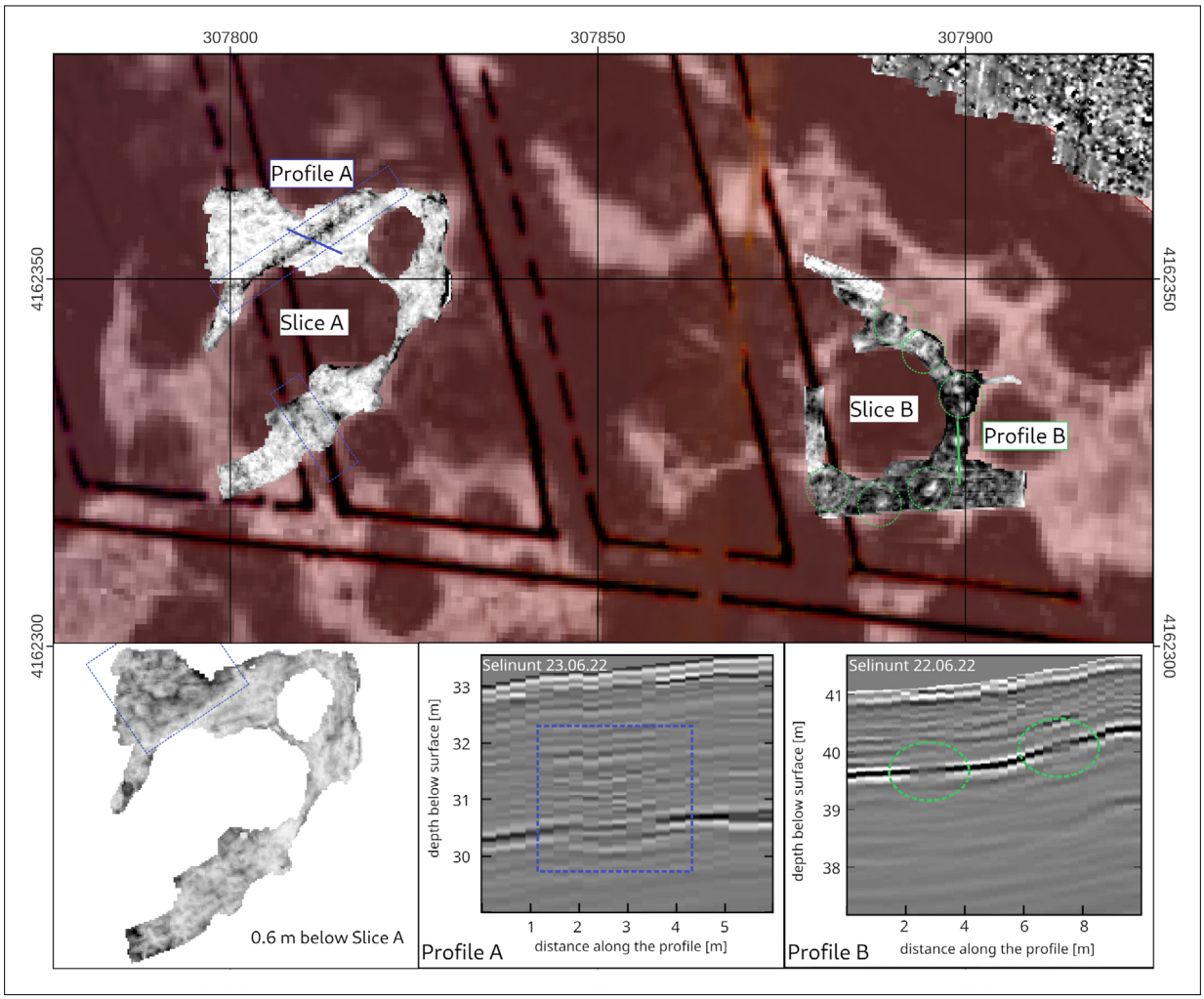

Fig. 3: Three depth slices. The background is composed of the proposed street layout and the red shaded dune as in Figure 1. In slice A a large wall like structure is marked in a dotted blue line. The blue solid line marks the position of the cross-section profile A. The bottom left corner shows a slice 0.6 m below slice A with a rectangular structure marked in blue. Slice B shows a circular structure of white low amplitude spots marked in green circles. The corresponding profile B below is marked with a greed line.

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Experimental examination of the possibilities of geophysical methods in wooded and rugged terrain: case study of the defunct medieval glasswork Vysoká Jedle in the Ore Mountains

Roman Křivánek [1*], **Eliška Vošvrdová** [2]

1 Department of Scientific Resources and Landscape Archaeology, Institute of Archaeology of the Academy of Sciences of the Czech Republic, Prague, v.v.i., Czech Republic
2 Department of Archaeology, Faculty of Arts, Charles University, Prague, Czech Republic
* Corresponding author: E-mail: krivanek@arup.cas.cz

Abstract
Rugged and wooded terrains of mountains limit possibilities of archaeological prospection. Various production or exploitation areas are typical for Czech mountain regions. Magnetometer survey of medieval glassworks has been standard geophysical method for decades. The other geophysical methods could be also successful in glass furnaces identification or study. Magnetic susceptibility survey with a Multi Kappa instrument observes the state of production feature.

Keywords
archaeological prospection limitation; glasswork; magnetometry; rugged forested terrain; testing of different geophysical methods

Introduction

The mountain terrains of the Czech Republic contain many archaeological remains of specific production, mining areas or communications. However, many such sites are situated in very rugged and forested terrain. These conditions limit possibilities of application, extent of survey and interpretation of geophysical methods (Křivánek 2007).

Nevertheless, there are already a dozen of successful examples of the application of geophysical surveys of production or exploitation areas of iron, non-ferrous metals and tar production sites. However, defunct medieval glassworks belong to the most numerous geophysically investigated production areas.

Goal and methods

High magnetic anomalies caused by significant thermoremanent magnetization of materials in the places of destroyed glass furnaces, but also on glass waste, are typical for most situations at the defunct glasswork (Venclová and Křivánek 2021; Podliska et al. 2021). Different types of magnetometers have been used in the medieval glass production areas for four decades (Křivánek 1998; Křivánek 2001). Several of defunct glassworks have also already been archaeologically verified (Černá and Steppuhn 2012; Černá 2016), when an additional measurement by a kappameter was also used.

The goal of the new complex geophysical measurement was to practically test the possibilities and limits of several other geophysical methods in the case of the defunct Vysoká Jedle glasswork. From the larger area of magnetometer measurement (with a five-channel fluxgate gradiometer Sensys in a network of 0.25 x 0.2 m), a segment of the area 15 x 15 m above the place of the supposed relict of the glass furnace was deliberately selected (Fig. 1). Considering the sloping terrain with mature trees and

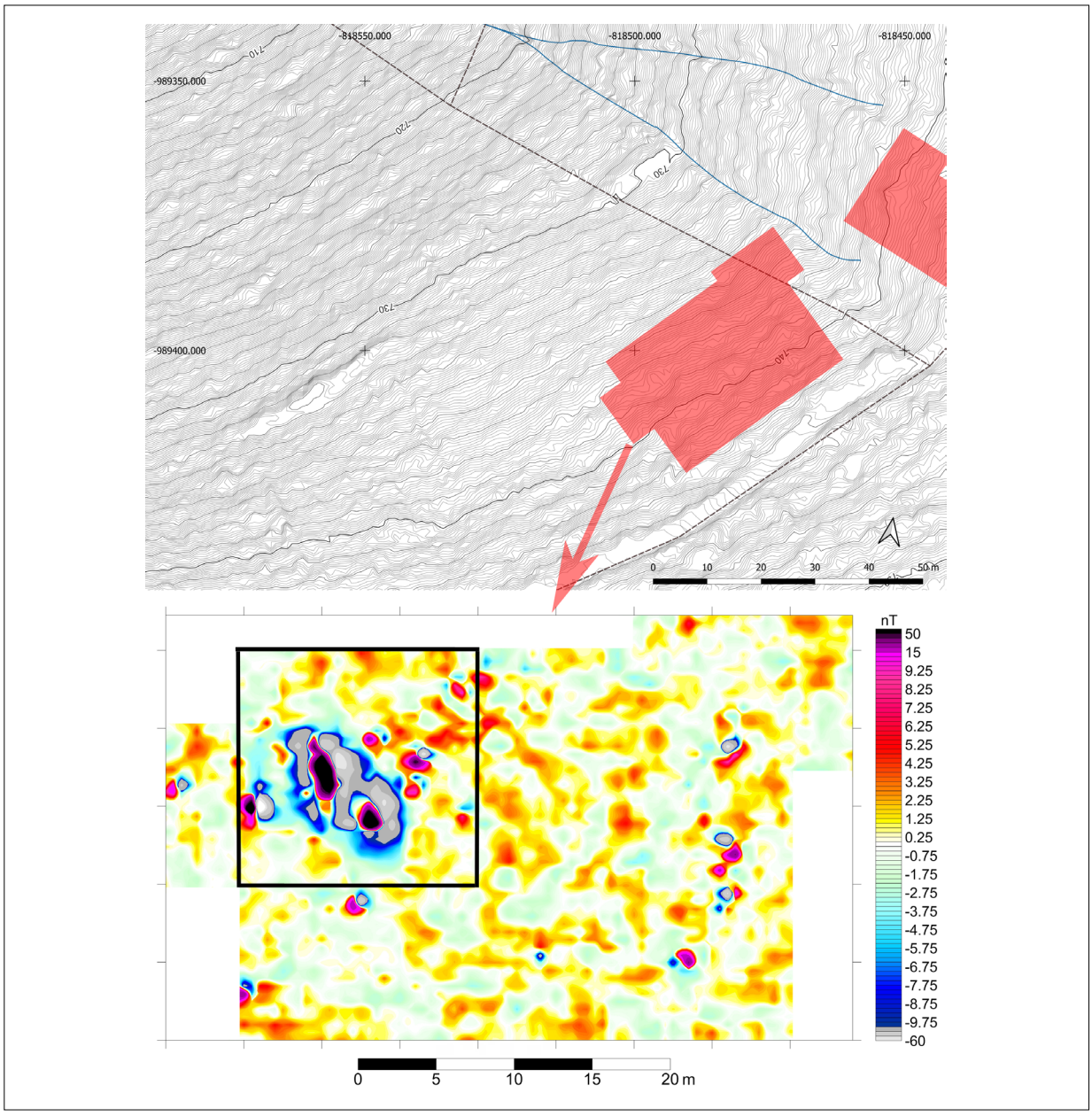

Fig. 1: Example of location of glasswork in variable terrain of Ore Mountains with magnetometer survey result. Red – area of magnetometer prospection, black line – detail for complex measurements.

many scattered stones, the area was repeatedly measured only in a 1 x 1 m grid. A repeated survey was carried out by a resistivity measurement (RM-15, Geoscan Research), an electromagnetic measurement of apparent conductivity and magnetic susceptibility (EM-38B, Geonics), and two depth levels of 0.5 m and 0.25 m of magnetic susceptibility (apparatus Multi Kappa, GF-instruments). The surveys were also supplemented with test measurements by GPR (Cobra-Wifi II, Radarteam) on several available profiles.

Results

The potential of various applied geophysical measurement methods can best be seen from a mutual comparison of the results of an identical examined area with a uniform profile orientation (Fig. 2). Heavily burnt materials from the destruction of production features of the glasswork (and one place of metal additionally confirmed by a detector survey) can be seen both in the results of magnetometry,

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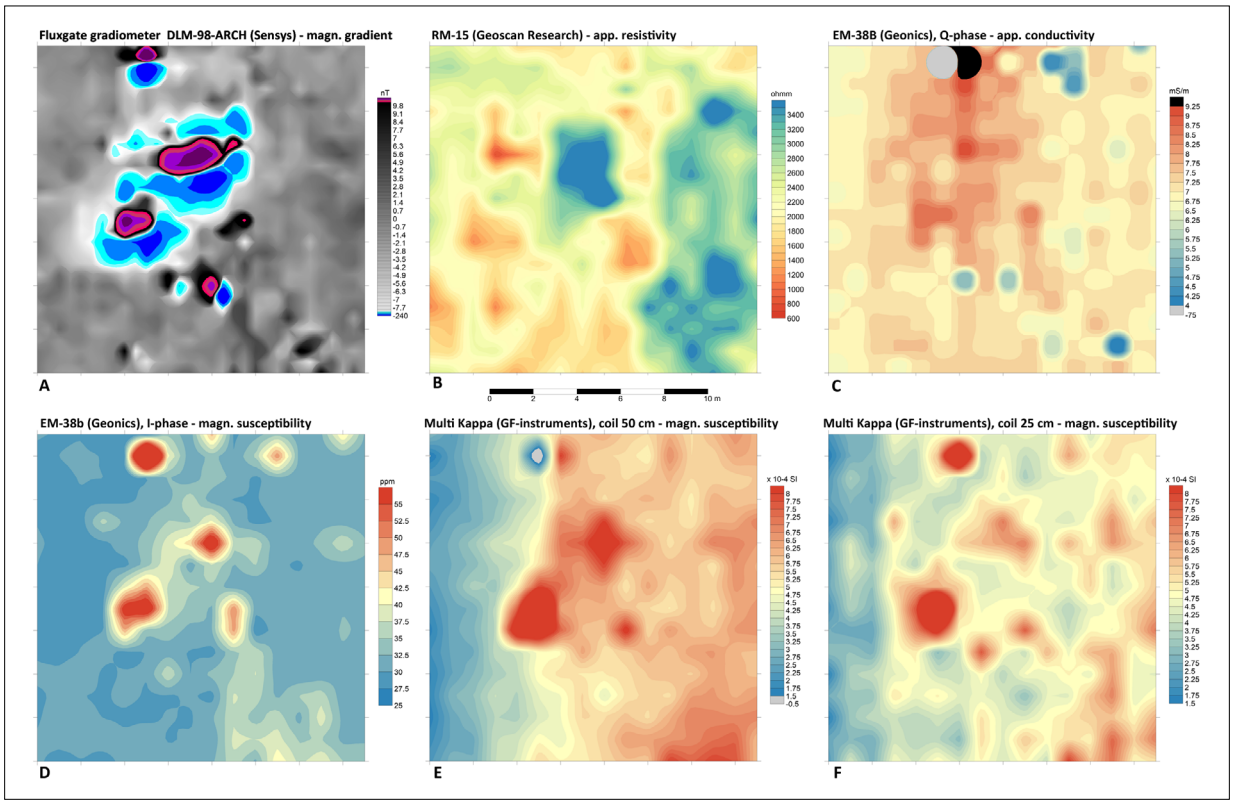

Fig. 2: Comparison of the results of different applied geophysical methods. a) detail of fluxgate magnetometer measurement, b) resistivity, c) EM-conductivity (Q-phase), d) EM-magnetic susceptibility (I-phase), e) magnetic susceptibility from Multi Kappa and coil 1 m dimeter, f) magnetic susceptibility from Multi Kappa and coil 0.5 m diameter. tometer prospection, black line – detail for complex measurements.

in the results of the I-phase electromagnetic measurement and in the results of the magnetic susceptibility with the Multi Kappa instrument. The changes in magnetic susceptibility reminiscent of drift (Fig. 2 e or 2 f) were caused by changes in the sloped relief and contamination of a part of the surface by glass production waste. Stone destruction from the construction of the glass furnace can best be seen in the result of the resistance measurement, less so in the result of the Q-phase electromagnetic measurement. From the difficult-to-realize profile measurements by radar, only on a few profiles across the elevations with the destruction can we detect significant reflections at the base of the disappeared furnaces (Fig. 3).

Discussion

I-phase measurement of magnetic susceptibility by EM-38B has a maximum depth penetration of about 75 cm. In case of Vysoká Jedle site we used Multi Kappa coils with maximum depth penetration 50 cm and 25 cm. This combination could bring us information about the subsurface state of preservation of burnt features (and on the dispersal of burnt waste material). In case of destroyed glasswork it can identify the most heated center (probable heating channel) of glass furnace. Remarkable changes in results of apparent resistivity and minor changes in Q-phase electromagnetic measurement of apparent conductivity we can explain by different influence of local terrain relief changes (stones) on contact (electrode) and non-contact (coil) measurement. For profile measurements by radar on a given type a significantly rugged site (with many of stones on the surface), the possibilities of effective measurements were very limited, even from the point of view of the interpretation.

Conclusion

The presented comparison of experimental measurements shows the well-known fact that strongly fired production features can be reliably identified both in the results of magnetometry and in the results of various magnetic sus-

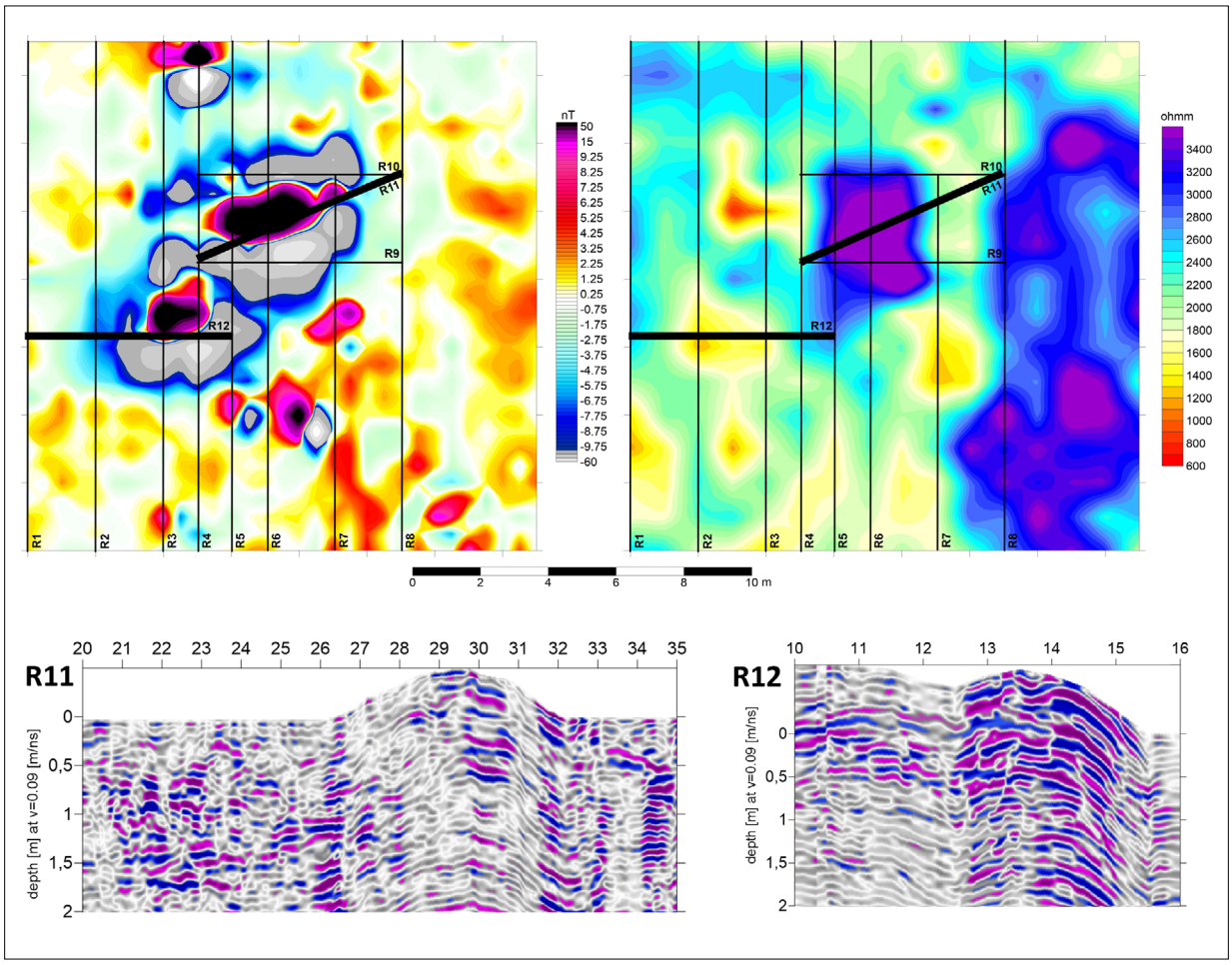

Fig. 3: Example of comparison of the results of the detail of fluxgate magnetometer measurement and two profile measurements by GPR (black lines) over accessible terrain elevations of glasswork.

ceptibility measurements. By combining several methods of measuring magnetic susceptibility with different depth penetration, we can monitor the state of preservation of the feature and the changing range of fired components. Contact resistance measurement is the most suitable for assessing the extent and quantity of the stone construction of production features. Electromagnetic conductivity measurement or radar measurement in rugged, forested and variable stony terrain is locally affected by terrain changes and the state of surface preservation of the production feature and can be more beneficial under conditions of more homogeneous and less rugged terrain of sites.

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Application of 3D ERT and GPR in modern archaeology – an example for mapping new-age urban remains

Erman Lu[1]*, Ercan Erkul[1], Simon L. Fischer[1], Michael Gräber[2], Wolfgang Rabbel[1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 GeoServe – Angewandte Geophysik, Kiel
* Corresponding author: E-mail: stu219656@mail.uni-kiel.de

Abstract
The aim of this study is to find out to what extent 3D geoelectric surface measurements can contribute better to a high-resolution subsurface model than conventional 2D measurements. 2D and 3D electrical measurements as well as GPR measurements were performed on a former working farm in Kiel. The results of the 3D electrical measurements show that individual structures in the subsurface can be detected better than in the results of the 2D electrical measurements. These structures are also visible in the GPR time slices.

Keywords
DC resistivity; GPR; urban archaeological prospection; 3D ERT; 3D inversion

Introduction

In engineering geophysics, 2D geoelectrical measurements are often used. 2D measurements assume a subsurface model which is as constant as possible perpendicular to the section plane of a profile. Hereby it must be considered that unknown 3D structures lead to distortion of the calculated subsurface model (Yang and Lagmanson 2006). In this study, 2D and 3D measurements were conducted on an urban test area (25 m x 25 m) in Kiel (Fig. 1) using the RESECS multi-channel measurement system by GeoServe (geoserve.de 2023). The aim of this study is to find out how far the 3D geoelectric surface measurements can contribute to a high-resolution subsurface model better than conventional 2D measurements. In addition, the high-resolution ground penetrating radar (GPR) measurements are used for the independent acquisition of the 3D structures. The results of the 2D and 3D inversions were compared and combined with the GPR results.

Methods

In this study 3D ERT data were acquired using a RESECS (PC controlled DC resistivity meter system) by GeoServe. Eight parallel survey lines and a total of 206 electrodes were used to set up an 8 m by 25 m rectangular survey grid (Fig. 2). The in-line and cross-line separations were 1 meter. By moving the survey grid, the square survey area was covered. Pole-pole and dipole-dipole configurations were measured. The data was processed with the open-source inversion program BERT (resistivity.net 2018) and the commercial programs Res2DInv, Res3DInv. ground penetrating radar (GPR) measurements were conducted with a GSSI dual-frequency antenna (300 MHz and 800 MHz), which was mounted on a four-wheel cart. A differential GPS by STONEX was used for positioning of the system. The results of the 3D ERT inversions were compared and combined with the GPR results.

Results and discussion

Four anomalies are observed in the 3D ERT depth slice at 0.5 m (Fig. 3). Anomaly A has a rectangular shape with high resistivity. Within this rectangular structure, the resistivity is lower than the background. Southwest of anomaly A is anomaly B. Its rectangular shape and high electrical

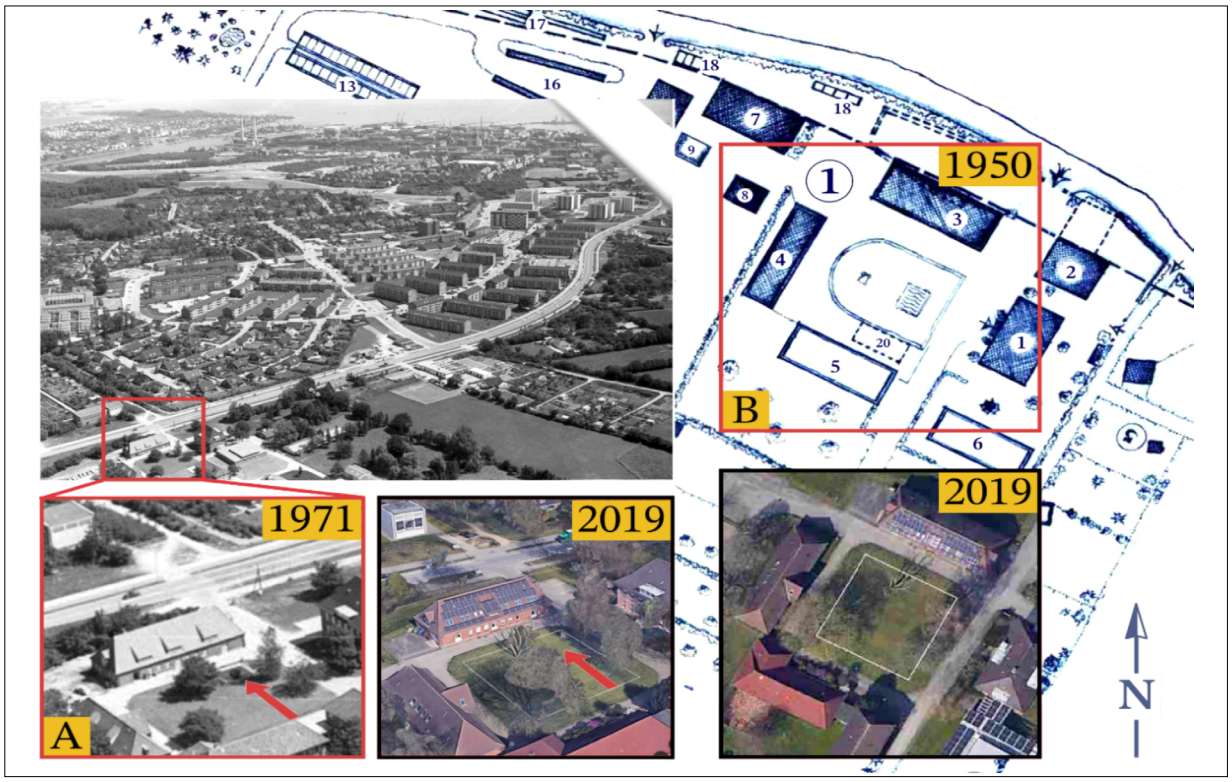

Fig. 1: a) The aerial photograph shows the survey area in 1971 (fotoarchiv-stadtarchiv.kiel.de 2023 , Sig. 49.261, CC BY-3.0 SA DE). The red arrow shows a rectangular structure that no longer exists. b) The survey area (base map: Google, ©2023 AeroWest, CNES/Airbus, GeoBasis-DE/BKG, Maxar Technologies, ©2023 GeoBasis-DE/BKG (© 2009)) had been a working farm in 1950, a U-shaped lawn with a smaller surface area than today's. On the U-shaped lawn was drawn a rectangular structure with waves symbol. The old basement (building number 20 on the yard plan, drawn with dashed line) was located outside the U-shaped lawn, but should be within the southern area of the survey area.

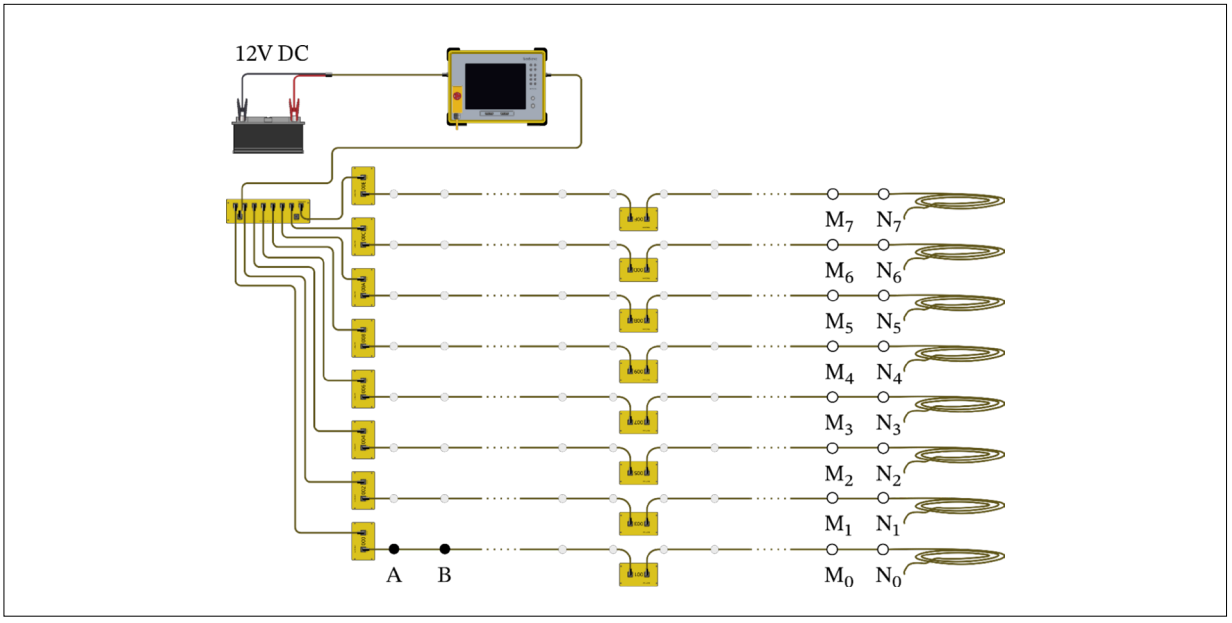

Fig. 2: Measurement setup for 3D ERT. A, B (in black) as current electrodes and M0 to M7, N0 to N7 (in white) as potential electrodes. The electrodes form a rectangular grid. The grid spacing is 1 m.

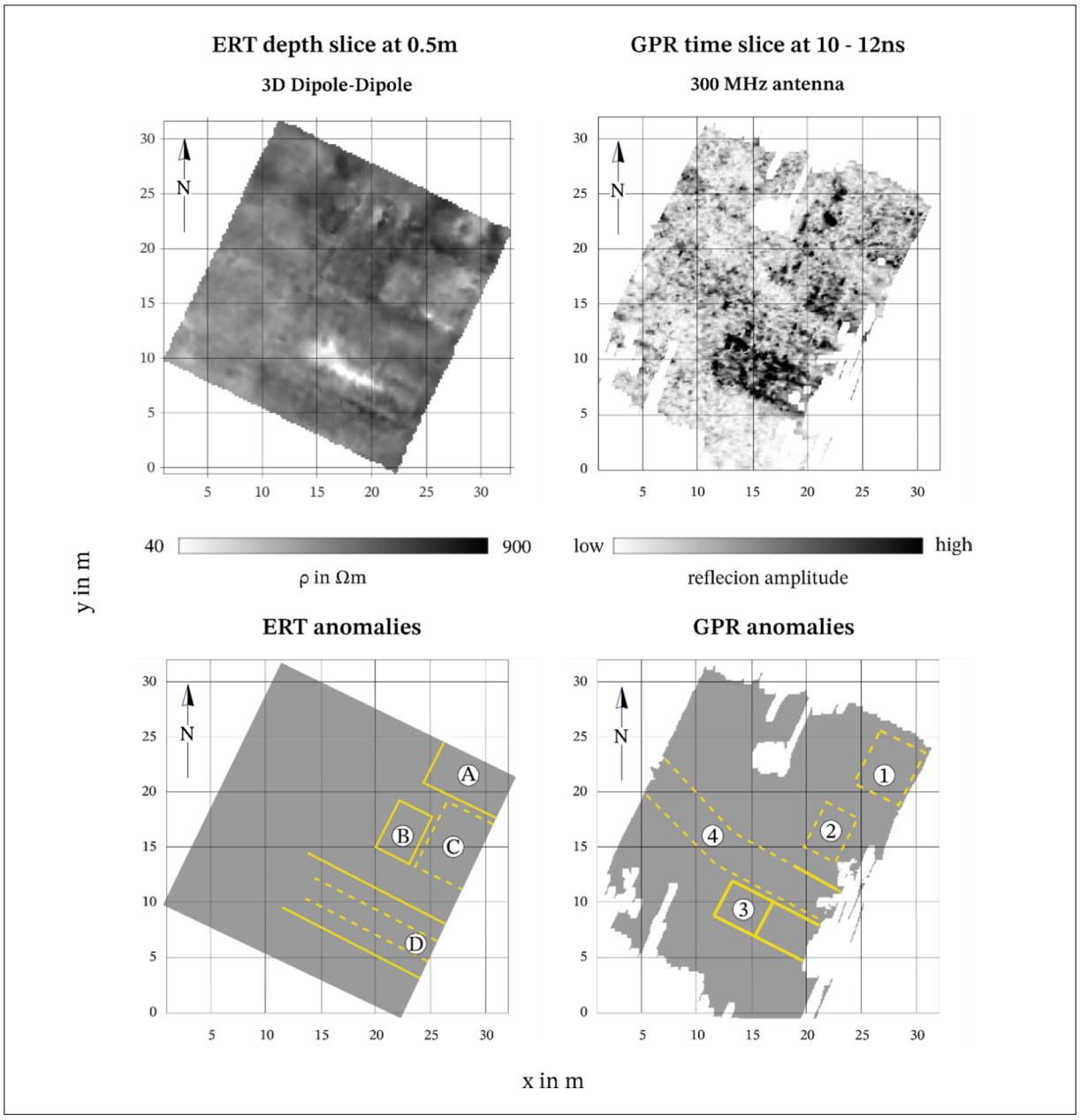

Fig. 3: Comparison of GPR and 3D ERT results. By evaluating the diffraction hyperbolas, an average radar wave propagation speed of 8 cm/ns was determined. 10 – 12 ns is equivalent to a depth of approx. 0.4 - 0.5 m. The two-dimensional patterns are marked with dashed lines. The linear structures are marked with solid lines.

resistivity stand out from the background. On the western side of anomaly B a rectangular area is characterized by low resistivity values (anomaly C, marked with dashed lines). Parallel linear structures are observed in area D. A region of low resistivity values can be observed between the dashed linear structures. The position of anomaly A in the depth slice correlates well with that of anomaly 1 in the GPR time slice. These anomalies could be caused by the remains of the rectangular structure in the northeast corner of the survey area (Fig. 1). anomalies B and 2 have approximately the same size and orientation. The position of the old basement, drawn with dashed lines on the yard plan (Fig. 1), coincides with anomaly 3 in the GPR time slice and anomaly D in the ERT depth slice. It is assumed that these anomalies are caused by the old basement. The low resistivity area within anomaly D can be interpreted as the

possibility that the fill or fill material within the basement is not consolidated and the water content within could be higher than the surrounding area. In the ERT depth slices at 0.9 m, the anomalies are still visible in the 3D inversion result, while they are poorly visible in the 2D inversion result. In the depth-resistivity section, the 2D and 3D inversion results show a similar distribution of the resistivity, but the 3D inversion result is more detailed and the transitions between high and low resistivity regions are more contrasting.

Conclusion

The results of the 3D measurements show that both in the electrical depth sections and in the depth-resistivity sections up to a depth of 1.5 m individual structures can be detected better than in the results of the 2D measurements. These structures can also be confirmed by the results of GPR. The linear and rectangular anomalies mapped in the depth slices of the 3D ERT inversion are seen in the GPR time slices to the corresponding depth.

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A semi-autonomous driverless geophysical survey system for efficient large-scale high-resolution archaeological prospection

Erich Nau [1*], Jostein Sandvik [2], Ole Svendgård [2], Knut Paasche [1], Immo Trinks [3]

1 Norwegian Institute for Cultural Heritage Research, Oslo, Norway
2 AutoAgri, Vanvikan, Norway
3 Vienna Institute for Archaeological Science, Vienna, Austria
* Corresponding author: Email: erich.nau@niku.no

Abstract
This research and development project aims to evaluate the feasibility of conducting large-scale autonomous ground penetrating radar (GPR) surveys. An electric autonomous implement carrier was used to integrate a 22-channel GPR array. This innovative approach shows promise for advancing GPR survey capabilities in the future.

Keywords
autonomous prospection; efficiency; ground penetrating radar; 3D subsurface mapping

Introduction

Buried archaeological remains constitute our common invaluable cultural heritage. Industrial farming, erosion, construction, and infrastructure development threaten this heritage on a massive scale. Near-surface geophysical prospection methods are well suited to search for archaeological remains in open fields. Ground penetrating radar (GPR) measurements, magnetometry, or electromagnetic induction surveys make it possible to search for, map, and document structures hidden in the subsurface. Over the past decade, substantial advancements have been made concerning geophysical archaeological prospection methods by introducing efficient motorized multi-channel magnetometer and GPR array systems in combination with precise data positioning solutions into archaeological research and rescue archaeology (Trinks et al. 2018). The exemplary application of the developed systems at selected archaeological sites throughout Europe has resulted in numerous outstanding archaeological discoveries.

The application of large-scale geophysical surveys for archaeological purposes has advanced even further in Norway. Here, motorised large-scale GPR surveying has become an important tool for archaeological mapping in advance of large infrastructure development projects, with survey areas often exceeding 1 km² for individual projects (Nau et al. 2017). Under Norwegian geological and environmental conditions, GPR has shown significant advantages over other, often faster, and more affordable geophysical prospection methods, and has thus become the preferred method. However, considering the huge survey areas affected by infrastructure development projects, even motorised multi-channel GPR systems with a potential daily coverage rate of up to 5 ha remain time-consuming for the operator in the field.

The next logical step for further development and substantial improvement of this successful approach is the setup of semi-autonomous driverless survey systems, permitting even greater fieldwork efficiency, but foremost increased data quality and measurement accuracy through controlled, ultra-dense spatial sampling.



Fig. 1: Computer rendering of the AutoAgri ICS20E implement carrier to be used in the presented project. The MIRA HDR system will be mounted centrally between the wheels.

Automation of GPR surveys

Several autonomous or semi-autonomous geophysical survey systems have been presented over the past years. The development of unmanned aerial vehicles (UAV) equipped with geophysical sensors has advanced the most in the field of archaeological geophysics (Linck 2019; Schmidt et al. 2020), but also small autonomous unmanned ground vehicles equipped with a GPR system have been presented recently (Gibb et al. 2018; Verdonck 2021). Such systems have shown their potential to successfully map archaeological structures below the ground. However, an insufficient spatial resolution and a rather limited survey speed hinder their application within large survey projects.

The presented project aims to overcome these shortcomings and develop a semi-autonomous multichannel GPR system allowing for the efficient, large-scale mapping of arable land. Semi-autonomous in this context refers to a self-propelled system that, after being programmed or set (in terms of line spacing, the main direction of travel, speed), travels within a defined outline polygon, which may contain obstacles, following predominantly parallel tracks, stopping only in the case of exceptional occurrences (e.g. the appearance of moving or unexpected obstacles, failure of GPR data collection, loss of contact with the operator) and then awaits interaction from a nearby operator.

The planned system consists of an innovative autonomous implement carrier (ICS20E, AutoAgri) and the latest generation of a multichannel GPR (MIRA HDR, MALÅ / Guideline Geo). The implement carrier is a recently developed, electrical-powered, driverless vehicle intended mainly for agricultural purposes (Fig. 1). Integrated positioning and navigation systems, such as a dual-head RTK-GSNS and an inertial measurement unit as well as sensors for obstacle detection, allow for autonomous, highly accurate, and safe navigation and operation. The MIRA HDR system provides 22 individual GPR channels with a cross-line sampling distance of 6.5 cm and a swath-width of 148 cm. The HDR technology will allow for an increased penetration depth with a significant reduction of noise and higher survey speed.

The full integration of both components is the main aim of the project. Hardware integration will be solved by an adapted antenna carrier frame mounted to the 3-point hitch on the vehicle, while the power for the GPR system will be provided from the main vehicle battery. A battery

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capacity of 60 kWh should allow for 10-12 hours of continuous operation and data collection. A communication channel between the individual computers of the vehicle and the GPR will be set up, allowing for two-way communication between the systems, the channelling of position data and sharing of the internet connection. A custom-made software solution will function as the interface between the vehicle and the GPR unit, enabling the vehicle software to trigger the start and stop of GPR data acquisition based on its position within the survey area. Control functions will be implemented to check for the validity of incoming data and potential errors or system failures. An onboard Wi-Fi and 4G communications module as well as onboard cameras will at any time allow the operator to remotely access the system for manual inspection. Individually controllable wheels on the implement carrier allow for optimised survey patterns, with navigation accuracy in the range of 1–2 cm permitting for efficient and optimised GPR data coverage. Several iterative rounds of lab and field-testing are planned to optimise the system.

Outlook

The anticipated developments and improvements will lead to superior high-resolution subsurface images and thus more reliable archaeological data interpretations. The increased efficiency in data acquisition will permit the investigation of larger areas, for the benefit of archaeological scientists, cultural heritage managers, and society at large. The highly interdisciplinary project involves the fields of applied geophysics, robotics, geomatics, and archaeology. Close parallels can be seen regarding the latest developments in agricultural engineering and precision farming.

The project is partially funded by *Innovation Norway*, with substantial in-kind contributions made by the Norwegian Institute for Cultural Heritage Research (NIKU) and AutoAgri. Funding was secured in August 2022 and the project was started in September 2022. The production of the implement carrier and integration of the MIRA HDR array will be finished by the end of 2022. Subsequent development of the necessary software interface and lab testing of the system is planned for early 2023. The fully operational system is expected to be ready by mid-2023. We intend to present an overview of the ongoing development and the first results from field testing at the ICAP 2023.

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How much rain is too much for a GPR survey? Results of the Borre Monitoring Project

Petra Schneidhofer[1]*, Christer Tonning[1], Rebecca J. S. Cannell[2], Erich Nau[3], Alois Hinterleitner[4], Geert J. Verhoeven[4], Lars Gustavsen[3], Knut Paasche[3], Wolfgang Neubauer[4], Terje Gansum[1]

1 Department for Cultural Heritage Management, Vestfold and Telemark County Council, Tønsberg, Norway
2 Institute for Archaeology, Conservation and History, University of Oslo, Oslo, Norway
3 Department for Digital Archaeology, Norwegian Institute for Cultural Heritage Research, Oslo, Norway
4 Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology, Vienna, Austria
* Corresponding author: E-mail: petra.schneidhofer@vtfk.no

Abstract
Soil moisture variation is complex and depends on a range of factors, which complicates the formulation of recommendations for GPR surveys. Low amounts of soil moisture produced GPR data of higher quality. However, precipitation rates as well as chronological sequence of precipitation/thawing processes and the GPR survey are of importance. Winter months can offer favorable conditions for GPR surveys if temperatures remain negative over a prolonged time period, allowing for frost to build in the ground. Results of the Borre Monitoring Project (BMP) are valid only for sites with similar settings as Borre; the monitoring approach, however, can be transferred to larger regions with more representative sites.

Keywords
archaeological prospection; cultural heritage management; electromagnetic wave propagation; ground penetrating radar; soil science

Introduction

In 2016, Vestfold and Telemark County Council, together with the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology and the Norwegian Institute for Cultural Heritage Research initiated the Borre Monitoring Project (BMP). This project emerged from a GPR survey in 2015, which failed to detect two large hall buildings at the Late Iron and Viking Age site Borre in Norway (Fig. 1), in contrast to three previous surveys conducted in 2007, 2008, 2013. Details about the discovery and interpretation of these archaeological structures can be found in Trinks (2007) and Tonning et. al (2020).

Preliminary findings of BMP were reported at ICAP 2017 (Schneidhofer et al. 2017), while data acquisition was still on-going. This paper presents the final results of BMP. A detailed description of the project and its findings can be found in Schneidhofer et al. (2022).

Methods

GPR surveys using a 500 MHz Noggin single-channel antenna were conducted across a test area of ca. 0.76 ha covering two large hall buildings roughly once a month between July 2016 and September 2017. The aim was to capture potential variations in data quality during different environmental conditions. To gain a better understanding of the underlying causes for these variations, volumetric water content (VWC), bulk electric conductivity (BEC), ground temperature as well as precipitation rates were measured in-situ at three locations within the test area. In addition, soil and sedimentological analyses of the subsurface materials present at the test site, including grain size distribution and organic content, were conducted at the Institute for Archaeology, Conservation and History (University of Oslo) to better understand water infiltration and movement underground. Data were processed using ApRadar (Trinks et al. 2018) and analyzed using the custom Python program Schlitzi + and ArcGIS 2.80.

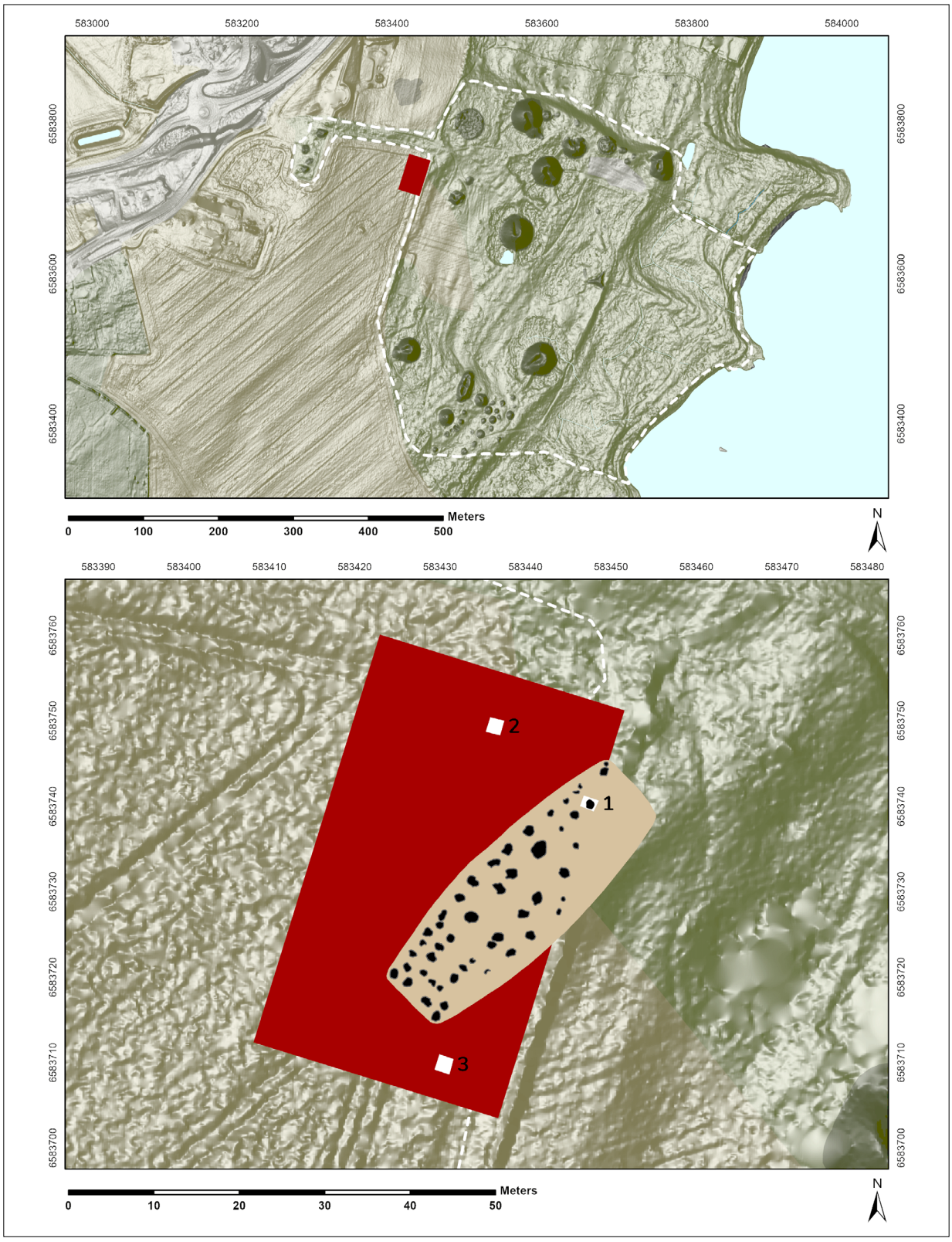

Fig. 1: Location of hall building A just outside the Borre National Park. The test area is marked in red.

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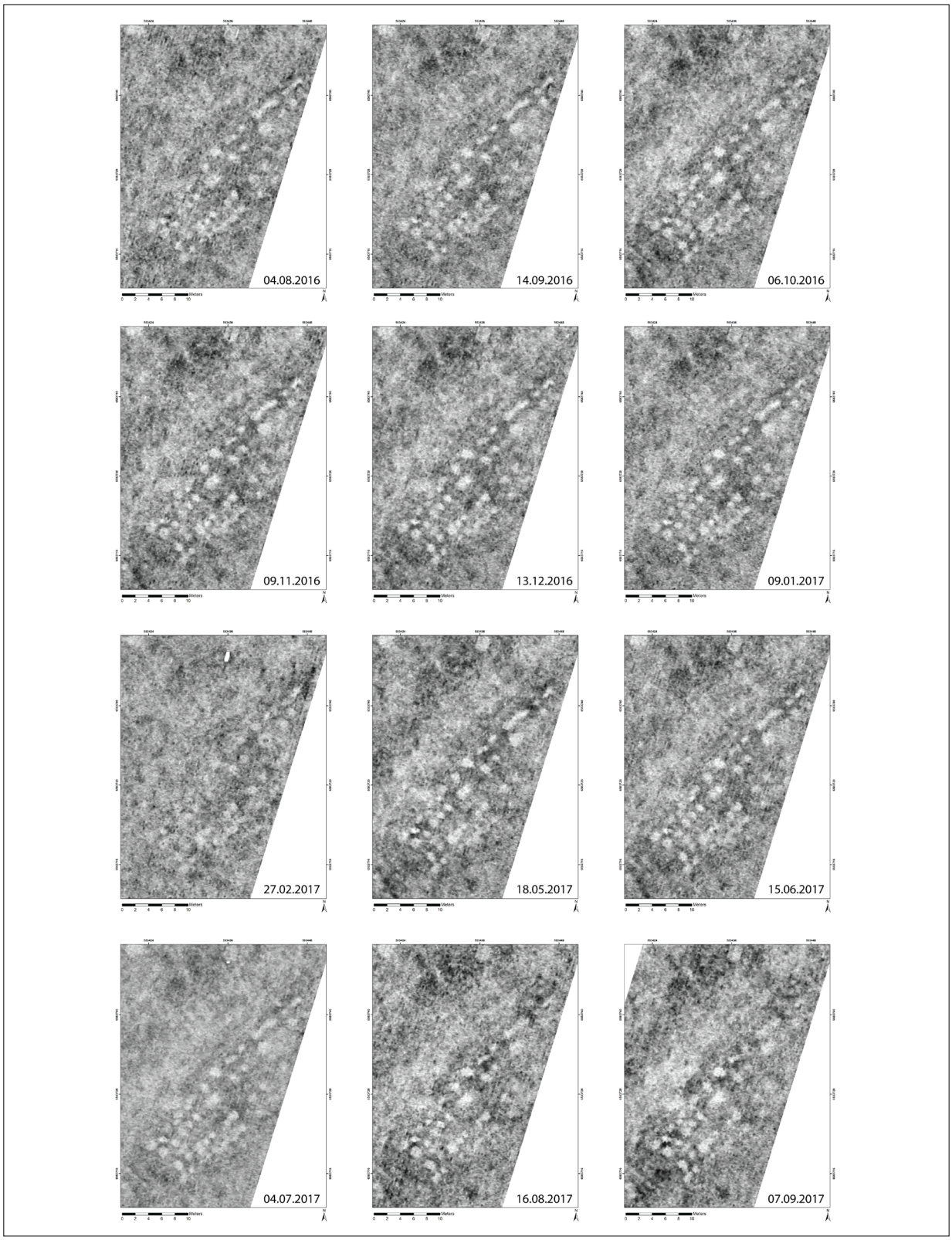

Fig. 2: Depth-slices 40-80 cm of all twelve data sets acquired between July 2016 and September 2017. High amplitude values are displayed in black, low amplitude values in white. Crossline spacing: 25 cm, in-line spacing 5 cm.



Fig. 3: Comparison of VWC, BEC and ground temperature values (Sensors 1-4) measured in-situ at monitoring station 1 during each of the GPR surveys. The blue bar represents precipitation rates in the week prior, the black line in the 24 h prior to the respective surveys.

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Results and discussion

Over the course of 14 month, twelve GPR data sets (Fig. 2) could be collected under different environmental conditions (Fig. 3) and subsequently were classified qualitatively into groups of high and low quality. Quantitative measures to categorize the data sets using statistical and pixel-based methods proved unexpectedly challenging and only confirmed data sets at the lowermost end of the quality spectrum.

Six of the twelve surveys (14092016, 06102016, 09112016, 13122016, 09012017 and 04072017) were conducted in dry conditions, when less than 5 mm of rain had fallen in the week before to the survey. The 24 hours before these surveys did generally not see any precipitation. Surveys 13122016 and 09012017 conducted in December 2016 and January 2017 under very cold and dry conditions with temperatures well under 0 degrees C displayed data of the highest quality.

Five surveys were conducted under wet conditions. In August 2016 (04082016), the survey was conducted directly after a rainfall event (ca. 10 mm in the 24 hours prior), while data collection in May (18052017), June (15062017) and August 2017 (16082017) was characterized by the highest amounts of precipitation (48-58 mm) recorded for the week before the respective surveys. Data set 27022017, classified both quantitatively and qualitatively as being of lowest quality, was acquired in February 2017 amid a thawing process, which created surface puddles and unfavorable conditions in the topsoil.

Of the twelve data sets, eleven did show the hall building; only the data set collected in February 2017 failed to do so. At first glance, this result seems encouraging for the use of GPR in Norway. However, as the test site is located on well-draining ground and surveys were generally not undertaken in very unfavorable conditions, this outcome needs to be treated cautiously.

In general, data showed no seasonality, but were instead governed by small-scale weather patterns, most notable precipitation rates and changes in air temperature. As expected, results supported the long-standing rule that dry conditions are beneficial for electromagnetic wave propagation, when signal attenuation is reduced and more energy can enter the subsurface. The longer these dry periods persisted at Borre, the higher the quality of the GPR data turned out to be. Data sets of lower quality, conversely, were characterized by higher amounts of soil moisture, whereby the chronology of events was of importance. Precipitation shortly before an intended survey would leave the water little time to drain. In this respect, the 24 hours before a survey proved particularly crucial for data quality.

The winter months, when conditions had been very cold and dry for several weeks and frost had built up in the ground, proved more promising for GPR surveys than previously anticipated. Water in its frozen state diminishes signal attenuation and this effect could be clearly seen in the data sets acquired in December 2016 and January 2017. However, a sudden rise in temperature as transpired right before the survey in February 2017, can quickly reverse these favorable conditions.

Upon completion of BMP, the results were tested by surveying a previously discovered ship burial located inside the Borre National Park under favorable conditions following the unusually dry summer of 2022. The collected GPR data were of high quality and a subsequent data interpretation revealed a previously unknown ring ditch around the interred ship.

Conclusion

The results of the Borre Monitoring Project have broadened our understanding of the influence environmental factors, first and foremost soil moisture, exert over the quality of GPR data.

The specific findings at Borre are valid only for sites with similar environmental and archaeological settings. Obviously, not every survey site can be subjected to a monitoring project. However, monitoring projects at sites representative for environmental settings and archaeological structures of a geographical region are feasible. Such an endeavor is currently under way for Vestfold County, Norway. The Vestfold Monitoring project VEMOP (https://www.vtfk.no/meny/tjenester/kultur/kulturarv/vemop/) aims to provide recommendations for the use of GPR in the Vestfold region based on the monitoring of four different test sites and over 100 surveys.

Due to time and financial reasons, GPR surveys can and will not always be conducted under ideal environmental conditions. A deeper understanding about this complex issue, however, can aid in limiting unwanted effects during data processing and interpretation as well as in post-survey measures.

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Magnetic survey in the process of large-scale construction sites

Tomáš Tencer [1]*, Peter Milo [1], Jan Havelka [1], Anna Mária Rekemová [1] David Šálka [1], Michal Vágner [1]

1 Department of Archaeology and Museology, Masaryk University, Brno, Czech Republic
* Corresponding author: E-mail: tencer@mail.muni.cz

Abstract
Archaeogeophysical prospection is necessary when planning large constructions. Motorized magnetometry systems offer an effective method to identify archaeology prior the construction. A sufficiently large area must be surveyed to estimate the archaeological potential correctly.

Keywords
archaeological prospection; development-led; evaluation; magnetometry; preventive archaeology

Introduction

In the past, non-destructive archaeological methods were often considered a supplement to archaeological investigations. In the last 20 years, these methods have crystallized into a separate discipline - archaeological prospecting also in Central Europe. The claim that through non-destructive prospecting, we can find out “little” about a “large” area has thus long been invalid. It is especially true in development-led (rescue) archaeology, where conducting and managing archaeological excavation has become an incredibly complex task. A tight schedule, limited human resources and, finally, a limited budget are usually the main characteristics of such projects. Thus, the application of archaeological prospection methods has become necessary when planning large constructions.

Estimating the cost of the research is usually the first reason for using non-destructive prospecting methods (literature and map searches, field visits, aerial photography). In combination with GIS analyses, these well-established approaches will significantly improve the chances of getting the construction schedule right and estimating the cost of the archaeological investigation.

However, conventional methods often require a more extended timeframe for successful implementation. Despite the undeniable advantages, the picture provided by these traditional methods is often limited and time-consuming, especially in the case of field surveys. It is usually not possible to systematically cover the whole area; thus, we create gaps. As development-led archaeology is usually under an obligation to investigate the entire archaeology due to the threat of destruction, these areas pose a potential risk from both an investor and conservation perspective. At this point, archaeogeophysical prospection usually comes to the rescue. In the context of extensive construction sites in the open landscape, the motorized magnetometry systems offer a rapid and effective method to fill the blank areas.

Despite many surveys and publications presenting their results, only a few studies critically evaluate geophysical prospection’s contribution to rescue archaeology. The absence of studies comparing the results of geophysical prospection and archaeological research is significant. In the paper, we compare the interpretation of the magnetic survey with the results of the archaeological excavation. The aim is to gain an understanding of the relevance of prospection and to identify the limitations and benefits of prospection for rescue archaeology.

Results

In cooperation with archaeological and heritage management bodies and investors, we analyzed data from several

development-led projects in the Czech Republic. The aim was to estimate the success rate of magnetic prospection and quantify the main factors influencing prospection's ability to detect archaeological situations successfully. We understand the success or effectiveness of prospection as the degree of agreement between the results of archaeological research and magnetic prospection. However, the overall contribution of prospection to the knowledge of the investigated site was also taken into account when evaluating effectiveness, for example, identifying its nature, extent or density and type of archaeological features.

In our work, we proceeded from the assumption that the results of geophysical prospection cannot be fully verified by archaeological excavation, as the latter is mainly subjective and interpretive.

In contrast, geophysical prospection is non-destructive, allowing the process to be repeated and reconstructed. The results themselves are objective and only gain subjectivity through interpretation. Therefore, the results of the prospection cannot be verified by archaeological research but only compared (Löcker et al. 2015; Seren et al. 2013).

The success of prospection largely depends on the appropriate combination of the geological subsoil and the nature of the archaeological objects. While the analyzed dataset does not cover the full spectrum of possible variations in the geological setting, the sites are located in locations common to anthropogenic activity, represented by the settlement and funerary features.

To determine the level of agreement, we used manual qualitative comparisons of the results and quantitative statistical methods: the kappa agreement index (a measure of agreement between categorical variables – excavated and interpreted) and the spatial correlation method (David et al. 2008; Linford and David 2001). All spatial analyses were conducted in a GIS environment.

We identified three main factors that influence the effectiveness of prospection:

- Spatial inaccuracies - misidentification of object position or anomalies
- Geological and pedological environment
- Morphological characteristics of objects - dimensions, shape and depth, state of preservation.

From the settlement objects category, magnetometry correctly identifies all archaeologically documented earthworks, settlement pits, hearths and kilns. Objects of a funerary type were significantly under-represented in the sample compared to the other objects. Geomagnetic prospection could identify only significant structures, such as a grave with a circular ditch, chamber graves, or extensive burial grounds.

Discussion

Based on our experience from these and other projects, it can be concluded that the problems that have arisen can be solved successfully. Spatial inaccuracy is an error that arises during data processing, excavation, or prospection. Nowadays, however, thanks to the availability of modern instruments, it can be easily eliminated.

A challenging or unsuitable geological environment is essentially the biggest issue for magnetometry. Due to the presence of ferri-magnetic minerals in the soil, it is usually impossible to detect archaeological objects. Sediments (alluvial or fluvial) are often an obstacle impossible to overcome for geophysical methods. However, this handicap can be overcome by large-scale prospection of the surrounding area and estimation of the archaeological potential of the site. Moreover, geological structures are sometimes only manifested locally. Some archaeological features, such as ditches, channels, trenches, and exploitation pits, have significant shapes and dimensions, and their identification is relatively simple. However, a sufficiently large area must be surveyed for their correct interpretation. In addition to the spatial extent of the object, the depth or preservation of the object is also important. Detection of shallow objects is very problematic, especially during mechanical topsoil removal. In most cases, the detected objects were almost half as deep as those that the magnetometer could not detect.

Conclusion

The results of the comparison demonstrate the advantages of archaeogeophysical prospection conducted prior to the excavation itself. Large-scale magnetometry significantly helped field archaeologists and investors plan archaeological excavation and construction work in advance and create a convenient time-schedule for both groups. Besides cost and time savings, integration of archaeo-geophysical prospection into the planning process points out several weaknesses of the traditional excavation method used in development-led archaeology.

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Passive seismic depth sounding by statistical array analysis

Martin Thorwart [1*], **Wolfgang Rabbel** [1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
* Corresponding author: E-mail: martin.thorwart@ifg.uni-kiel.de

Abstract
We can determine efficiently the Rayleigh wave dispersion curve for a frequency range between 2 Hz and 80 Hz by analyzing the seismic noise recorded on mini-arrays. Due to the short recording time of 15 min we are able to map an area up to 6 ha per day. The dispersion curve gives us a first qualitative image of the subsurface.

Keywords
archaeological prospection; array analysis; seismic noise; seismic structure; surface wave

Introduction

Surface waves are analyzed in different scales to determine the seismic structure of the earth. This includes investigations of the lithosphere but also investigations which targets are close to the surface. Surface wave have a frequency dependent penetration depth which leads to a frequency dependent propagation velocity (dispersion). The dispersion is characteristic for the underground model. The dispersion curve can be used to investigate the seismic structure of the subsurface.

The observed surface waves (in most cases the Rayleigh wave) can origin from a known source like an earthquake (2-station method) or a seismic source (Multichannel analysis of surface waves). Another approach is the analysis of the seismic background noise which is dominated by surface waves by an ambient noise tomography or with the spatial autocorrelation method (Okada 2003).

We present another approach to analyze the seismic noise and to determine the dispersion of the Rayleigh wave. Our target is to investigate the seismic structure of the uppermost 20 m. The data recorded on a mini-array is analyzed by the beamforming algorithm and statistical evaluated. This results in the dispersion curve of the Rayleigh wave between 2 Hz and 80 Hz.

Determination of the Rayleigh wave dispersion

Seismic arrays

Seismic arrays are widely used in global seismology for earthquake detection, earthquake location and for the monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The benefit of the usage of seismic arrays are an increased signal-noise-ratio for an improved detection of seismic events (earthquakes, nuclear tests, explosions, …) and the determination of back azimuth and slowness of the propagating seismic waves allowing the location of the event. The aperture (largest distance between two stations in the array) is in the range of 10^3 m – 10^5 m due to the large observed horizontal wavelengths.

We need to analyze Rayleigh waves with an wave length between 1 m and 50 m to investigate our target, the upper most 20 m of the surface. Therefore, we need a much smaller array of a size of 2.7 m x 2.7 m. Due to the small size, we call it a “mini-array”.

A mini-array consists of 9 geophones (Fig. 1). 4 geophones are placed in the corners of two squares with side length of 2.7 m and 0.75 m, respectively. The smaller square is located in the center of the bigger one. The 9th geophone is placed in the center of both squares. This arrangement has been proven to be sufficient for the determination of the Rayleigh wave dispersion.

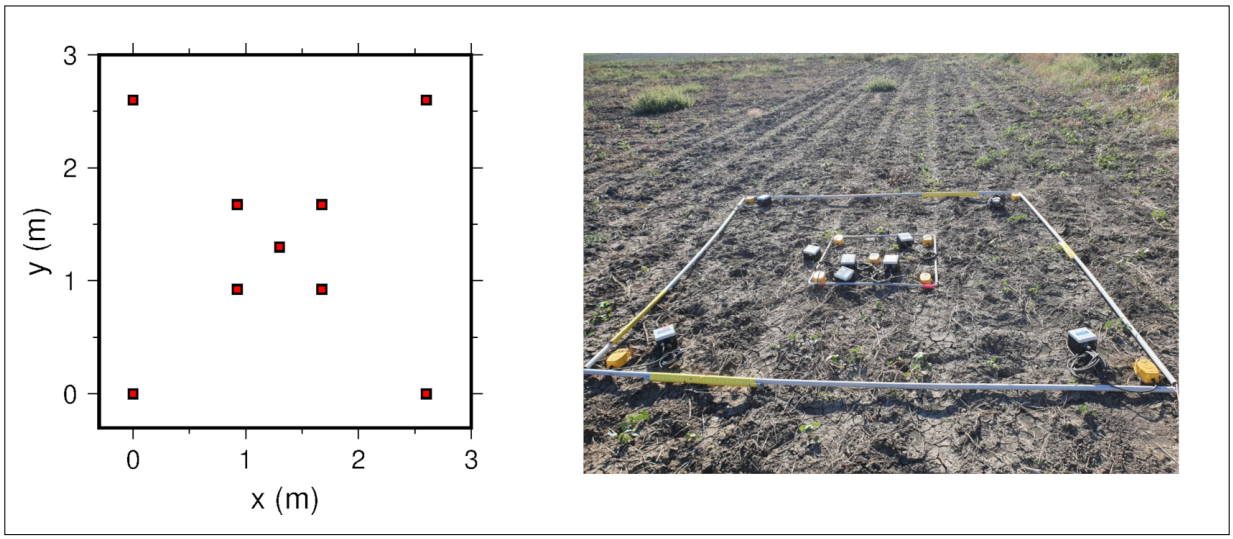

Fig. 1: Left: Layout of the mini-arrays. Right: installed mini-array in the field (photo by D. Schulte-Kortnack).

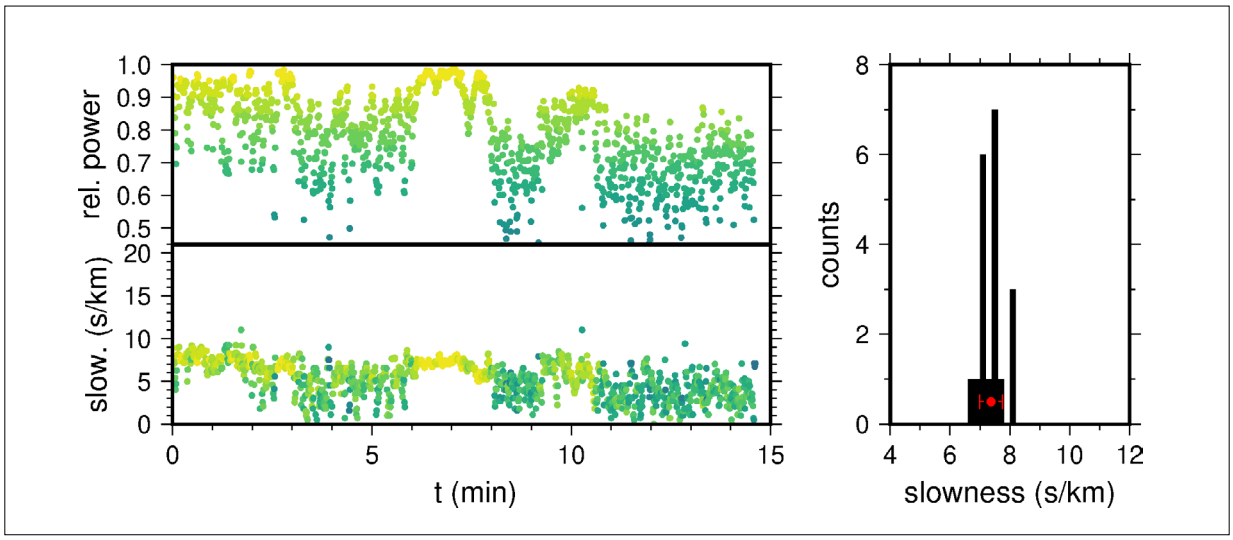

Fig. 2: Left: Pairs of slowness and relative power as the result of the beamforming algorithm. Right: statistical evaluation of the best 20 slowness values. Red dot with error bars indicates the mean and the standard deviation of the slowness values.

The seismic noise is recorded on DataCubes[3] from DiGOS Potsdam. The recorders are operated with a sampling rate of 400 Hz. The total recording time for a mini-array is 15 min.

Statistical analysis of the seismic noise

There are two approaches to determine the dispersion of surface waves from seismic noise data recorded on seismic arrays (Okada 2003): the spatial auto-correlation method (SPAC) and the beamforming method. We are applying the beam forming method to determine the Rayleigh wave dispersion in a frequency range between 2 Hz and 80 Hz.

The recorded data is band pass filtered around a center frequency f_c between [0.95*f_c, 1.05 f_c]) and divided into small overlapping time windows. The time window is chosen to be 40 periods long.

For each time window the beam forming algorithm is applied by the command "array_processing" from the python toolbox ObsPy (Beyreuther et al. 2010). The algorithm shifts first the data relative to each other in time for a given slowness (inverse of the propagation velocity)

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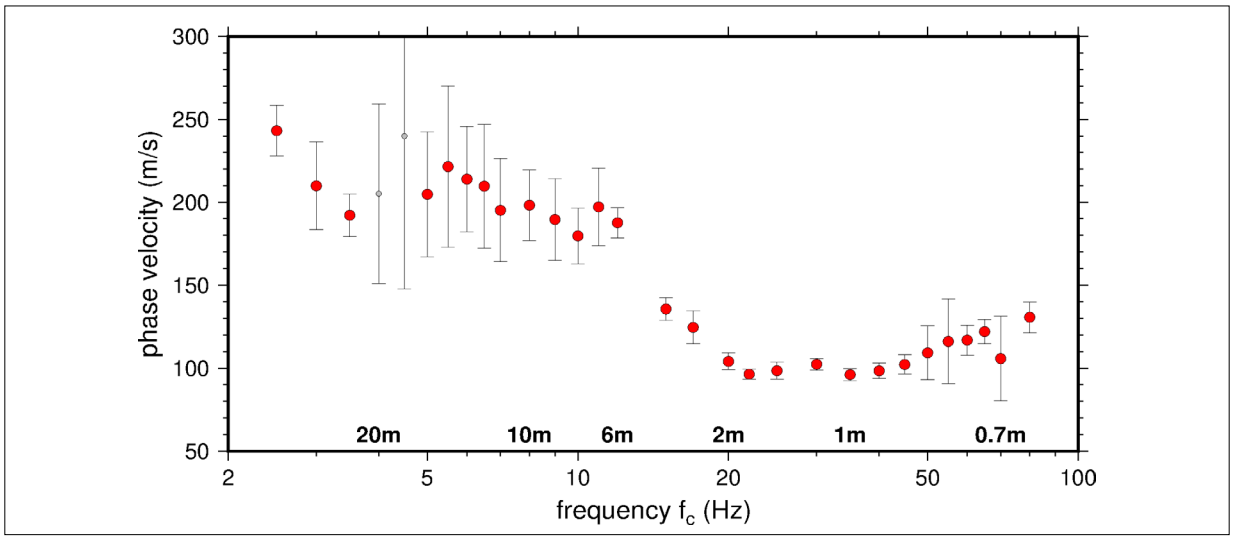

Fig. 3: Dispersion curve of the Rayleigh wave. Red dots are reliable values, small gray dots are unreliable. Error bars represent the standard deviation. Pseudo depths estimated for this dispersion curve are placed above the x-axis.

and back azimuth. It calculates then the relative power of the stacked data. The relative power is a measure for the quality of the beam forming (Fig. 2, left).

The 20 pairs with the highest relative power are selected. The mean and standard deviation of these 20 slowness values and the average of the relative power are calculated (Fig. 2, right).

Appling this analysis scheme to all the frequencies within the range between 2 Hz and 80 Hz result in the dispersion curve for the Rayleigh wave (Fig. 3). We consider values of the phase velocity as reliable, if the standard deviation of the slowness is lower than 25% of the mean value and the average relative power is larger than 0.8. The dispersion is a depth sounding curve since different frequencies represent different depths.

Discussion

The investigation of the seismic structure is rarely done in archaeological prospection on land due to the lack of efficiency. It is a common method in marine and amphibian environment due to an easy application (e.g. Wilken et al. 2019; Schwardt et al. 2021).

Our approach is an efficient way to determine the Rayleigh wave dispersion on land. The simple layout makes it easy to install the mini-array in the field in less than 10 min. Using two mini-array simultaneously it is possible to install and operate a mini-array at 3 – 4 site per hour and 20 – 35 sites per day. It is possible to cover an area of 1 ha – 6 ha per day depending on the spacing between the sites and to map the underground structure of the upper most 20 m.

Schwellenbach et al. (2020) performed a similar approach at the archaeological park of Selinunte. They recorded the seismic noise at four sites on arrays with changing spatial dimensions between 3 m and 60 m. The total recording time was up to 4.5 h per site reducing the efficiency of the measurements. The data was analyzed by the SPAC and by the beam forming method. They could determine Rayleigh wave dispersion over a frequency range between 0.2 Hz and 50 Hz and derive the underground structure in a good agreement with other methods applied.

With our approach we determine the dispersion curve is reliable over a frequency range of the order of 1. The exact frequency range depends on the observed wavelengths and the seismic velocity of the underground. The standard deviation normally increases towards the lower frequencies (f_c < = 10 Hz) due to the large wavelength compared to the array dimensions. To extend the dispersion curve to deeper frequencies the dimension of the array has to be increased as Schwellenbach et al. (2020) did. The standard deviation can be also large at the high frequencies (f_c > = 50 Hz). This could be caused by more complex interference pattern or the presence of higher modes of the Rayleigh wave.

The disadvantage of the SPAC method is the need of an isotropic distribution of the seismic sources around the

array. This can be difficult in urban areas or close to the coast where the main seismic source is the surf. In contract, the beamforming algorithm will result in the correct phase velocity if only one dominant seismic noise source is present. It is likely to find some time windows within the recording time of 15 min where a source dominates the seismic noise. This could be passing cars, the surf or activity of other seismic measurements.

The dispersion curve is sufficient for a first qualitative image of the subsurface structure. But it is essential to derive a one-dimensional model from the dispersion curve by modeling of inversion. Unfortunately, this invers problem is ambiguous. The dispersion curve can be explained by different one-dimensional models. Therefore, additional constraints have to be considered. Those constraints could be achieved by active refraction seismic tomography, cone penetration depths or in situ measurements through a direct push equipment.

This method is applied in several ongoing investigations. The methods shows that the tell at Chiselet (Romania) is located next to a silted lake or river which may was the reason to settle there in the first place and then to abandon it again. We find also indication for former lagoons in the Hebros plain close Greek-Turkish border and in the Chora plain on Samos (Greece). A possible application would be the mapping of the Xerxes Canal in Greece.

Conclusion

We are able to determine efficiently the Rayleigh wave dispersion curve for a frequency range between 2 Hz and 80 Hz by analyzing the seismic noise recorded on mini-arrays. Due to the short recording time we are able to cover an area up to 6 ha per day. The dispersion curve gives us a first qualitative image of the subsurface.

Acknowledgments

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Geophysical surveys at the former camp site in Berlin-Blankenfelde

Marlene Tielmann[1*], Georg Kaufmann[1], Ronald Freibothe[2], Rudolf Kniess[2], Jessica Meyer[2], Burkart Ullrich[2], Henning Zöllner[2]

1 Institute of Geological Sciences, Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany
2 Eastern Atlas GmbH & Co. KG, Berlin, Germany
* Corresponding author: E-mail: marlenet@zedat.fu-berlin.de

Abstract
The study investigates a site of a former camp from the time of National Socialism in Berlin (Germany). After the second world war, the study area was also part of the former Berlin Wall complex. Two different radar array systems, an impulse and a step-frequency radar, were applied to the area and compared. Both radar arrays complement each other in their results and allow a differentiated data view. In connection with other sources, the former camp site Blankenfelde could be reconstructed in great detail.

Keywords
archaeogeophysics; archaeological prospection; Berlin-Blankenfelde; impulse radar; step-frequency radar

Introduction

For the archaeological prospection of structures hidden beneath the subsurface, geophysical methods are essential. Besides the broadly applied magnetics systems, especially the ground penetrating radar (GPR) methodology offers an extensive three-dimensional view into the depth. In this study, two different GPR techniques, impulse radar and step-frequency radar, are applied and compared on an area of about three hectares for the investigation of archaeological structures from the time of National Socialism.

The area under investigation is a site of a former camp in Blankenfelde, an urban quarter in the district of Pankow of the city Berlin (Fig. 1). From 1941 to 1945, it was used as a camp for sick forced laborers from Eastern Europe, who were unable to work (Runder Tisch 2012).

The local authorities initiated the erection of a memorial at the former camp site. The project is promoted and scientifically accompanied by the “Museum Pankow”.

Materials and methods

To detect the foundations and remains that are still hidden in the subsurface, a magnetometer survey was conducted first, followed by GPR surveys using both an impulse radar and a step-frequency radar.

A distinction is made between different GPR systems, which differ in signal form and, therefore, in data acquisition in general. The most widely used GPR methodology is the impulse radar. Another approach is the step-frequency radar, which is also called a continuous-wave radar (Jol 2009).

In contrast to an impulse radar, which transmits short impulses into the subsurface and records reflections in the time domain, a step-frequency radar transmits sine waves with increasing frequency. Thus, phases and amplitudes of various frequencies can be recorded in the frequency domain. Fast Fourier Transformation displays these in the time domain (3D-Radar 2018).

For the impulse radar measurements, the pulseEKKO system from the manufacturer Sensors & Software Inc. from Canada with 250 MHz antennas consisting of four transmitting and receiving antennas was used (Meyer et al. 2021).

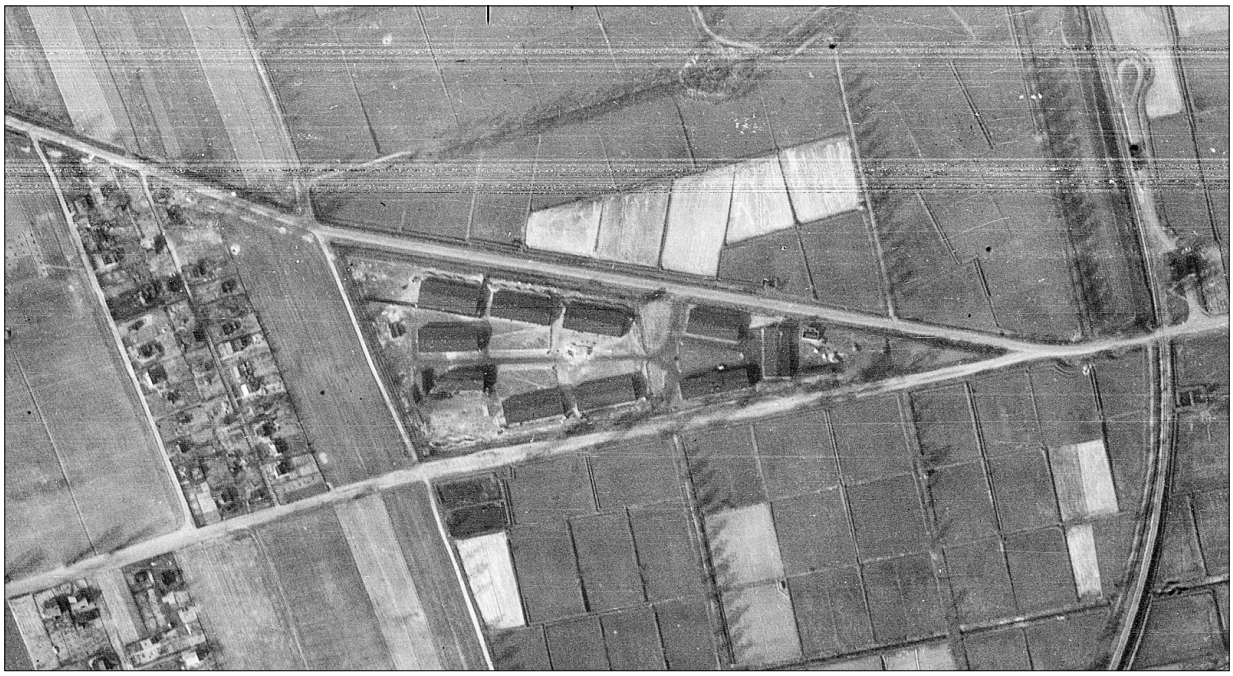

Fig. 1: Aerial photo from April 1945 of the former camp site in Berlin-Blankenfelde (Berliner Luftbildarchiv 1945).



Fig. 2: Results of the GPR measurements with a depth of 2.00 – 2.25 m for the impulse radar (left) and about 2.12 m for the step-frequency radar (right). Timeslices are shown as general view (bottom) and detail section (top). Low reflection amplitudes are shown in white, high ones in black.

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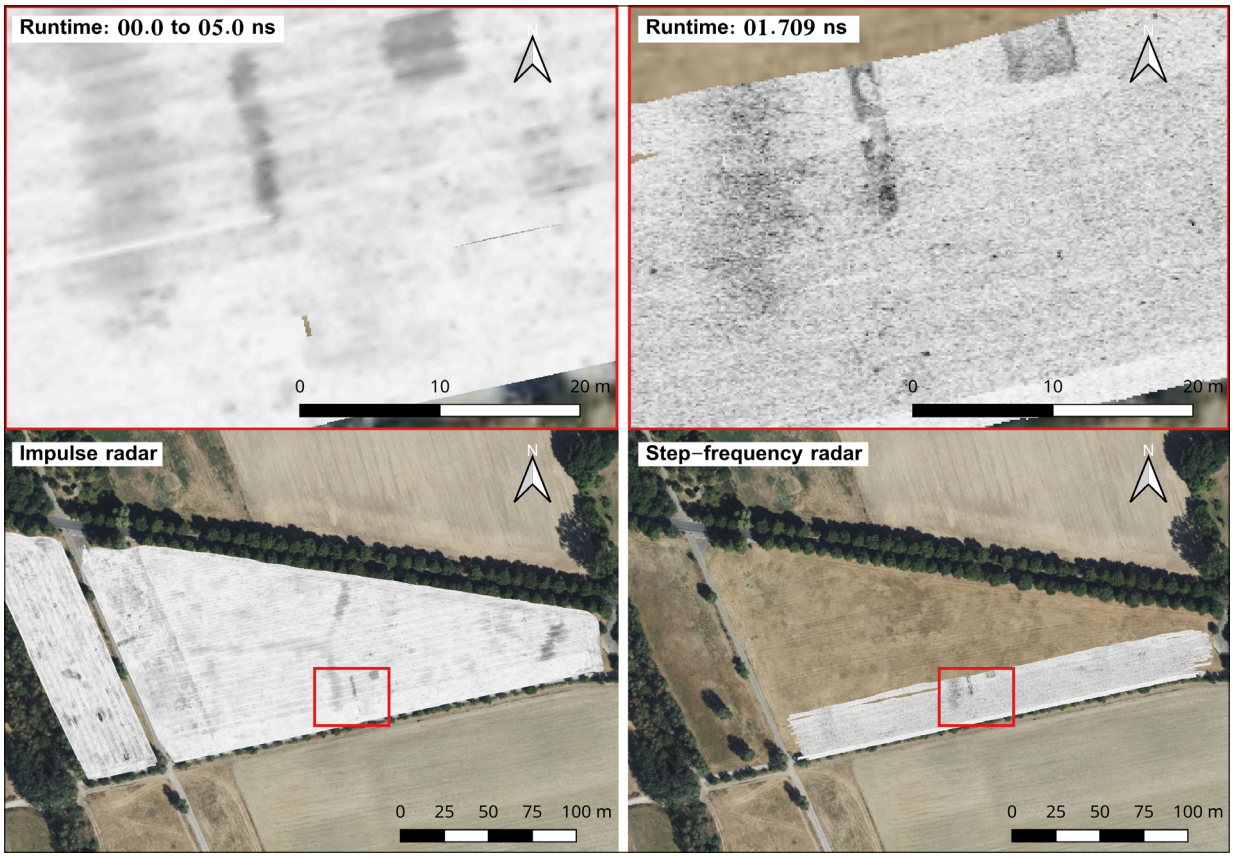

Fig. 3: Results of the GPR measurements with a depth of 0.00 - 0.25 m for the impulse radar (left) and about 0.09 m for the step-frequency radar (right). Timeslices are shown as general view (bottom) and detail section (top). Low reflection amplitudes are shown in white, high ones in black.

In contrast, the step-frequency radar array from the manufacturer Kontur (formerly 3D-Radar, Norway) covers low-frequency ranges from 200 MHz to high-frequency ranges of 3 GHz (3D-Radar 2018).

Results

Due to the low-frequency antennas of the impulse radar, larger structures can be resolved very well down to depths of 2.25 meters (Fig. 2). On the one hand, smaller remains in the near-surface area can be resolved only poorly if at all with such low frequencies. On the other hand, the step-frequency radar can more clearly resolve this depth range of 0-0.5 meters in some details since much higher frequencies are used (Meyer et al. 2021) (Fig. 3).

Discussion

Based on historical sources and several aerial photographs, various structures can be referred to as the former camp. Among them are remains of walls or foundations, traces of paths, pits, cellars, and pipes. However, a clear attribution is problematic since, presumably, relicts from the time before and after the camp and from the time of the Berlin Wall complex remain and overlap (Meyer and Ullrich 2022).

Conclusion

The radar-data processing provides a large leeway, especially for the step-frequency radar, due to the different frequencies. Both radar arrays complement each other in their results and allow a differentiated data view. In connection with other sources, the former camp site Blankenfelde can be reconstructed in great detail.

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Geophysical archaeological prospection, the road ahead ...

Immo Trinks [1*], **Klaus Löcker** [2], **Erich Nau** [3], **Alois Hinterleitner** [2]

1 Vienna Institute for Archaeological Science, University of Vienna, Vienna, Austria
2 Near Surface Geophysics, GeoSphere Austria, Vienna, Austria
3 Norwegian Institute for Cultural Heritage Research, Oslo, Norway
* Corresponding author: E-mail: immo.trinks@univie.ac.at

Abstract
We provide an overview of challenges and possible promising developments that lie ahead in the field of archaeological geophysics. The presented ideas can serve as blueprints for exciting new developments.

Keywords
archaeological prospection; future perspectives; technological and methodological innovations

Introduction

Having seen a dramatic increase in coverage rates in the field of geophysical archaeological prospection as well as data density through the introduction of motorised prospection array systems (magnetometer, GPR, EMI) over the past decade (Trinks et al. 2018), the question arises, what will be the next exiting and promising challenges for research and development? In line with the three "S" stated by Helmut Becker at a workshop in Grossetto in 2006 regarding possible advancements in the field of magnetometry (Becker 2009), i.e. increased Speed, Sampling density, and Sensitivity, there exists still ample space for methodological and technological advancements of geoarchaeological prospection. While application case studies with increasingly larger survey areas – and thus greater chances of detecting interesting buried anthropogenic or natural anomalies – are becoming more common, the methodological and technological advancements of the discipline, with few exceptions, still seems to be mainly driven by the industry and geophysical prospection system manufacturers, through availability of new sensors and survey devices. Particularly in exploration or rescue archaeology, but as well in archaeological research projects, geophysical prospection still suffers from the inherent drawback that the relationship between archaeological structures buried in the subsurface and their expression in form of anomalies in geophysical prospection data is still not fully understood. Geophysical archaeologists are still mostly confronted with the situation that they would need to – and mostly want to – survey larger areas than time and funding normally permits, in order to properly understand the archaeological situation, site or problem. Even the ability to gather five hectares of high-resolution ground-penetrating radar data over the course of two days, at not insignificant cost, will not reveal the structure of a 50-60 ha large settlement, and thus inhibit a comprehensive understanding of a site. There exists still an urge to be able to collect ever more data across huge areas. At the same time, technological advancements in unrelated fields offer exciting new opportunities for collecting data of greater quality, and the survey of challenging archaeological sites that still are difficult to tackle with traditional means. Some important developments that lend themselves to the advancement of our discipline are outlined below.

Increasing data quantity

Closer channel spacing and wider sensor arrays and the use of affordable precise positioning systems – RTK-GNSS receivers in base-rover or network/NTRIP configuration –

offer increased data quantity in equal time spend. Partly, higher data sampling speed permits increased survey velocities and thus larger coverage rates. This is valid not only concerning motorised prospection systems, but similarly regarding for instance manually pushed single-wheel four-channel magnetometer carts equipped with an RTK-GNSS rover antenna for efficient mapping of ancient building terraces in challenging terrain. Multichannel EMI arrays as developed by the experts from Ghent University will lead to an increase in data quantity (Hanssens et al. 2021). The advent of semi-autonomous all-terrain or agricultural vehicles will permit continuous, driverless data acquisition following well defined survey patterns (Nau et al. 2023). While magnetometer sensors deployed from drones for UXO detection may be of interest for archaeological prospection, endurance and flight altitude is still a major issue when it comes to the coverage of large areas. While increasing sampling density and the size of the survey areas are important, data quality should always have highest priority.

Enhancing data quality

New hyper-stacking, real-time and high-dynamic-range GPR antennae and miniaturised optically pumped magnetometers permit prospection data with greater penetrating depth, respectively sensors with increased sensitivity. Step-frequency single channel and array GPR promise wider frequency bandwidths and thus optimized depth-imaging. Precise data positioning is of paramount importance for great data quality. The availability of precise RTK-GNSS receivers at considerably reduced cost, having seen a drop in price of a factor of 10-20 in recent years, offers the possibility to mount more than one satellite receiver on the same survey system (dual-head RTK-GNSS solutions), which in case of sensor arrays offers greater control over system orientation, heading and tilt. Through utilisation of inbuilt inertial measurement units (IMU), the movement of the geophysical system can be recorded more realistically, opening up for new data processing approaches for more precise imaging. For instance, this could be used to detect and remove variable unwanted systematic noise (e.g. caused by swinging of sensor carts) from the data, through locally adaptive frequency filtering (Schmidt et al. 2020).

3D surface and subsurface imaging

Laser scanning and photogrammetric image based modelling allows for the efficient 3D recording of the surface of investigation areas. The combined 3D surface and subsurface imaging approach can be handled separately or simultaneously, by either 3D scanning/imaging the surface prior to or after the geophysical prospection survey (Merkle et al. 2021), or alternatively through integration of affordable mobile LiDAR sensors and cameras on the geophysical survey systems. The combined visualisation of surface and subsurface data permits not only the generation of a more realistic virtual scene of the encountered situation – and thus the possibility to detect causes for disturbances in the data – but offers the viewer immediate recognizable scales for enhanced understanding of the size of anomalies and structures in the data. Recording the micro-topography of the survey area will allow for more precise data positioning and enhanced data imaging. Combining multibeam sonar bathymetry data with subsurface sediment sonar data for enhanced 3D imaging of underwater archaeological sites is to be seen equivalent.

Prospecting challenging environments

While large, open, unobstructed areas already can be prospected efficiently, sites located in obstructed environments such as forests, plantations or high-rise built-up areas can be very challenging to explore due to insufficient availability of efficient data positioning solutions. The concept of visual simultaneous localization and mapping (visual SLAM) and LiDAR based odometry and mapping (LOAM) is a highly promising development (Shan et al. 2020), utilising small LiDAR sensors or stereo-cameras to provide local relative position information by recording the movement of the system through the obstructed, RTK-GNSS-denied environment (woods, urban areas, indoor, caves). By linking the geophysical prospection data with the position information through precise PPS time stamps, a link for merging position and prospection data during processing can be made. When continuously mapping spatially extent areas, challenges are loop-closure detections and SLAM/LOAM data management to achieve sufficient operation durability due to the large amount of laser scanning or feature point data recorded for position determination. The integration of IMUs as well as of RTK-GNSS sensors for the recording of supporting points with global position infor-

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mation enhances the approach, wherever available. By copying the successful large-scale high-resolution terrestrial geoarchaeological prospection approach to shallow underwater environments, similar successes regarding discovery and exploration of underwater archaeological cultural heritage, alongside natural wonders, will be possible. Tidal flats, streams and bogs are as challenging as promising environments.

Extracting more information from prospection data

The development of new data formats, fully describing the acquired prospection data, comprising all available information, such as measured amplitude, system speed, sensor orientation and distance to the ground, voltage, quality of position data, distance to nearest neighbour, permit the generation of maps illustrating data quality and variations therein, as well as the development of new data processing algorithms. Such maps will be fundamental for the identification of and differentiation between systematic noise/errors and subsurface anomalies, rendering data interpretation more reliable. Automatic and semi-automatic data segmentation facilitate the generation of interpretation maps (Trinks et al. 2020). The adaptation of the successful, efficient feature extraction from magnetic prospection data to full 3D GPR data segmentation remains on the to-do list. While GPR amplitude maps are useful for the identification of anomalous regions in the data, we need to be able to quickly, interactively query large data sets to extract freely spaced full-trace profile sections and individual GPR traces for enhanced understanding of the data. Adapting and applying algorithms developed by the geophysical prospection industry, such as seismic attribute processing for innovative GPR data analysis (Trinks and Hinterleitner 2020), or potential field continuation and routine reduction-to-the-pole magnetic map generation, has the potential to substantially enhance data imaging and thus data interpretation possibilities. The possibilities offered by GPR (Warren et al. 2016) and magnetic data simulations remain unutilized and could substantially help to improve the understanding of prospection data, and to investigate the physical boundaries of detectability and imaging potential for specific scenarios. The quest for joint data inversions, e.g. by linking magnetic and GPR data through EMI data, remains the holy grail.

Advancing the understanding of prospection data

Through immediate routine geoarchaeological minimum-invasive coring/sampling of the soil at selected anomalies and areas of interest, using augers and direct-push sensors (Völlmer et al. 2018), it will become possible to gain an improved understanding of the causative structures in the ground, without destroying them through excavation. The measurement of physical soil parameters is necessary to understand the cause of observed anomalies. The nature of our discipline is inherently highly interdisciplinary. A major challenge will be to get funding bodies to accept that the evaluation of related research and development proposals has to reflect that fact. The potential to generate better prospection results is great. Exciting archaeological discoveries are waiting to be made and endangered cultural heritage is in need of documentation. Let's do it!

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Developing a geophysical framework for Neolithic land-use studies: in situ monitoring and forward modelling of electrical properties at "Valther-Tweeling" (NL)

Jeroen Verhegge [1,2*], Gaston Mendoza Veirana [1], Wim Cornelis [1], Philippe Crombé [2], Hana Grison [3], Jan-Willem De Kort [4], Eelco Rensink [4], Philippe De Smedt [1]

1 Department of Environment, Ghent University, Ghent, Belgium
2 Department of Archaeology, Ghent University, Ghent, Belgium
3 Institute of Geophysics, Czech Academy of Sciences, Prague, Czech Republic
4 Archaeology section, Cultural Heritage Agency of the Netherlands, Amersfoort, the Netherlands
* Corresponding author: E-mail: Jeroen.Verhegge@UGent.be

Abstract
Boosting Neolithic land-use studies in the Low Countries requires optimal geophysical survey. Hereby, forward modeling such subtle soil features in a sandy soil could support survey design. The models are parametrized through soil sample analyses and in situ data collection over a feature. Supplemented by long term in situ monitoring, these results reveal variable detectability. This approach enables a quantitative approach for geophysical survey design.

Keywords
geophysical forward modelling; geophysical survey strategy; in situ monitoring; Neolithic land-use; soil physics

Introduction

Although many Neolithic settlements, consisting of artefact scatters, have been revealed on the sandy and loamy soils of Belgium and the Netherlands over the past decades, little is known about their structural layout and spatial organization. Redressing this current understanding of Neolithic land use requires the development of a framework to map related land-use traces with minimal intrusiveness. Hence, the "Working the land, searching the soil" project (Verhegge et al. 2021) was established to optimize the use of geophysical techniques to map and characterize Neolithic features along with existing prospection approaches.

Geophysical surveys of Neolithic feature sites, particularly those employing magnetometers on loess soils, have been satisfactory. However, more subtly contrasting features are not investigated geophysically in the sandy soils of the Low Countries, partially because a lacking quantitative basis for survey strategization. Furthermore, geophysical studies into the geometry and composition of archaeological features and temporal variations in (di)electrical contrast could contribute to such a framework, but are still uncommon. We aim to develop a widely applicable framework embedded in archaeological practice and rooted in geophysical theory.

Materials and methods

Methodological approach

The potential (changing) contrasts between natural soil profiles and Neolithic archaeological soil features of the Low Countries are characterized by excavating vertical profiles on a range of natural (i.e. non-archaeological) and archaeological soil sequences. On these sections, in situ geophysical data are registered following De Smedt et al.

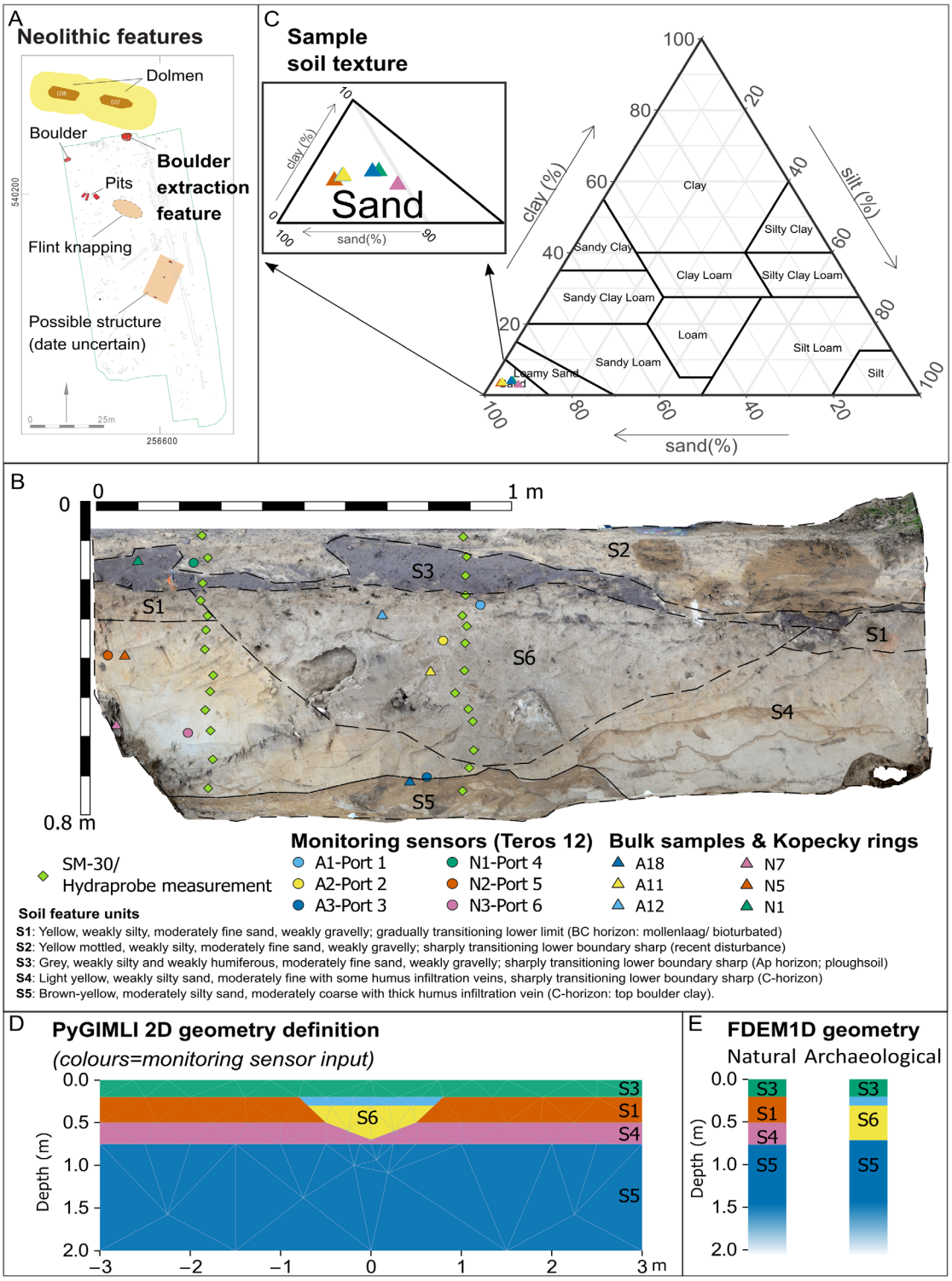

Fig. 1: a) Site map with the excavated soil features and dolmen (adapted from Fens et al. 2016). The feature under investigation is marked in bold, b) Orthophoto of the section wall of the excavated profile pit at Valther-Tweeling with the observed soil feature units, positions of profile measurements, samples and monitoring sensors. Macroscopic descriptions of the delineated natural and archaeological soil feature units at the bottom, c) results of the soil texture analysis on the USDA soil triangle. Colours according to sample locations (see Fig. 1b), d) simplified 2D profile geometry used in PyGIMLI. Colours represent monitoring sensors (see Fig. 1b) used as input, e) simplified 1D geometry used in FDEM1D. Colours represent monitoring sensors (see Fig. 1b) used as input.

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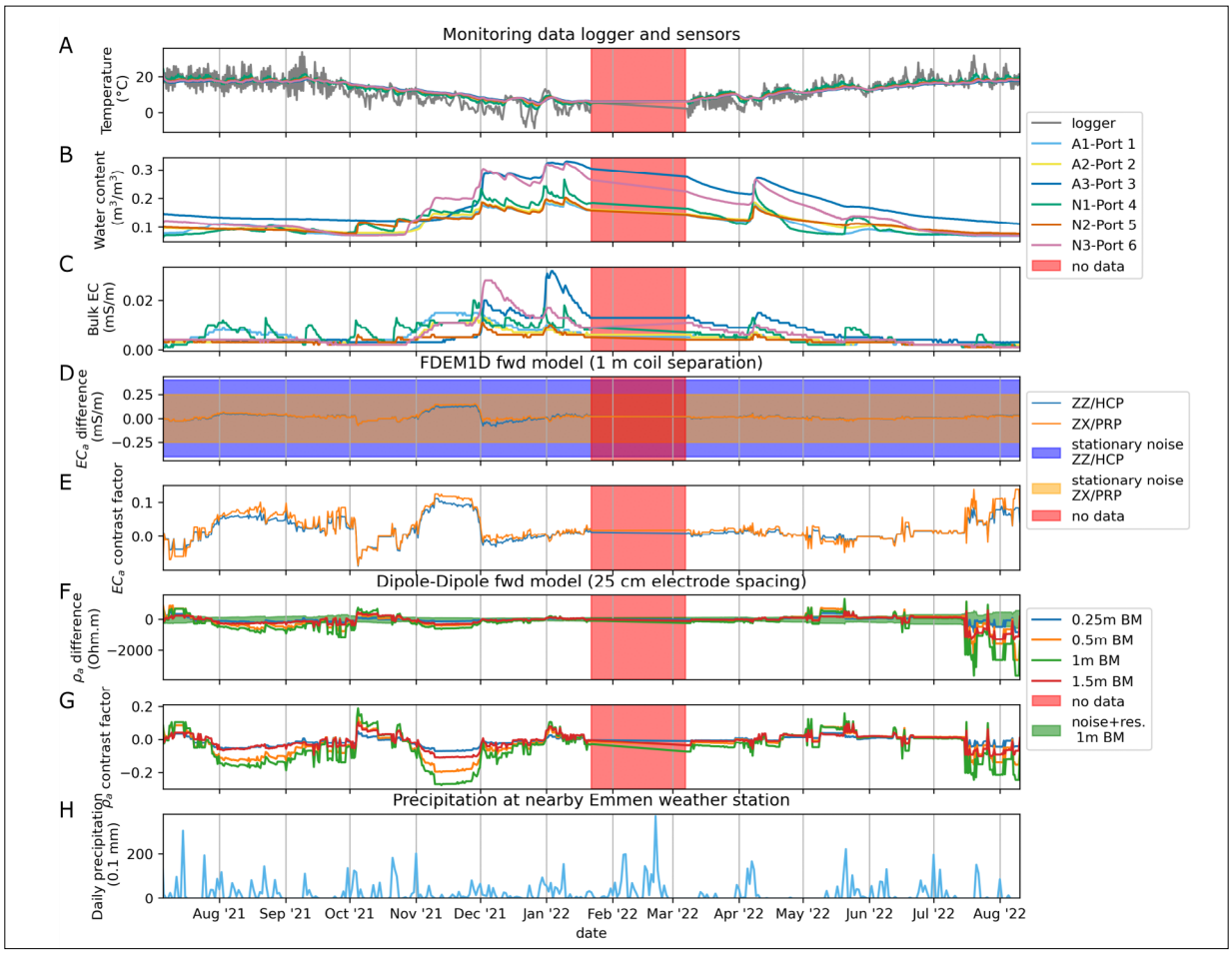

Fig. 2: a) Temperature monitoring data of the ZL6 data logger and Teros 12 soil sensors, b) Soil moisture content monitoring data of the Teros 12 soil sensors, c) Bulk electrical conductivity data of the Teros 12 soil sensors (corrected to 25°C), d) Difference of the FDEM1D models (1 m coil separation in horizontal coplanar (ZZ/HCP) and perpendicular (ZX/PRP) configuration) of the archaeological and natural sequence, expressed as LIN approximated ECa. Colour shading indicates stationary noise in comparable Dualem sensors (Delefortrie et al. 2014), b) Contrast factor (Schmidt et al. 2017) of the FDEM1D ECa, c) Difference of the PyGIMLI ρ_a model within and outside the feature. Colour shading indicates the instrument resolution and noise, approximated for a Geoscan RM85 (Geoscan Research 2019), d) Contrast factor of the PyGIMLI ρ_a, e) Daily precipitation data of the nearest weather station (333-Emmen, Royal Netherlands Meteorological Institute).

(2019) with a magnetic susceptibility meter (SM-30, ZH-Instruments) and a coaxial impedance dielectric reflectometer probe (Hydraprobe, Stevens Water), registering real dielectric permittivity (ε) and bulk electrical conductivity (EC). Furthermore, Kopecky ring and mixed bulk samples are gathered from every observed soil horizon or archaeological layer to determine bulk density, porosity, water- and organic matter content, texture and cation exchange capacity. At selected sites, monitoring stations (Teros 12 with ZL6, Meter Group) are installed to examine temporal changes in temperature, bulk EC (corrected to 25 °C), ε and moisture content (derived). Once geophysical properties and soil feature geometry are established, and at least year-long monitoring data is collected, geophysical forward modelling allows evaluating cross-temporal geophysical signals to strategize surveys. In tandem with this novel archaeological fieldwork and survey strategization approach, pedophysical models are developed to predict EC and ε (phases) requiring only basic soil properties of bulk samples by removing fitting parameters (Mendoza Veirana et al. 2021).

Case study: Valther-Tweeling

While investigations of several natural soil sequences assist in developing pedophysical models, the results of one archaeological site, next to dolmen D36 and D37 at

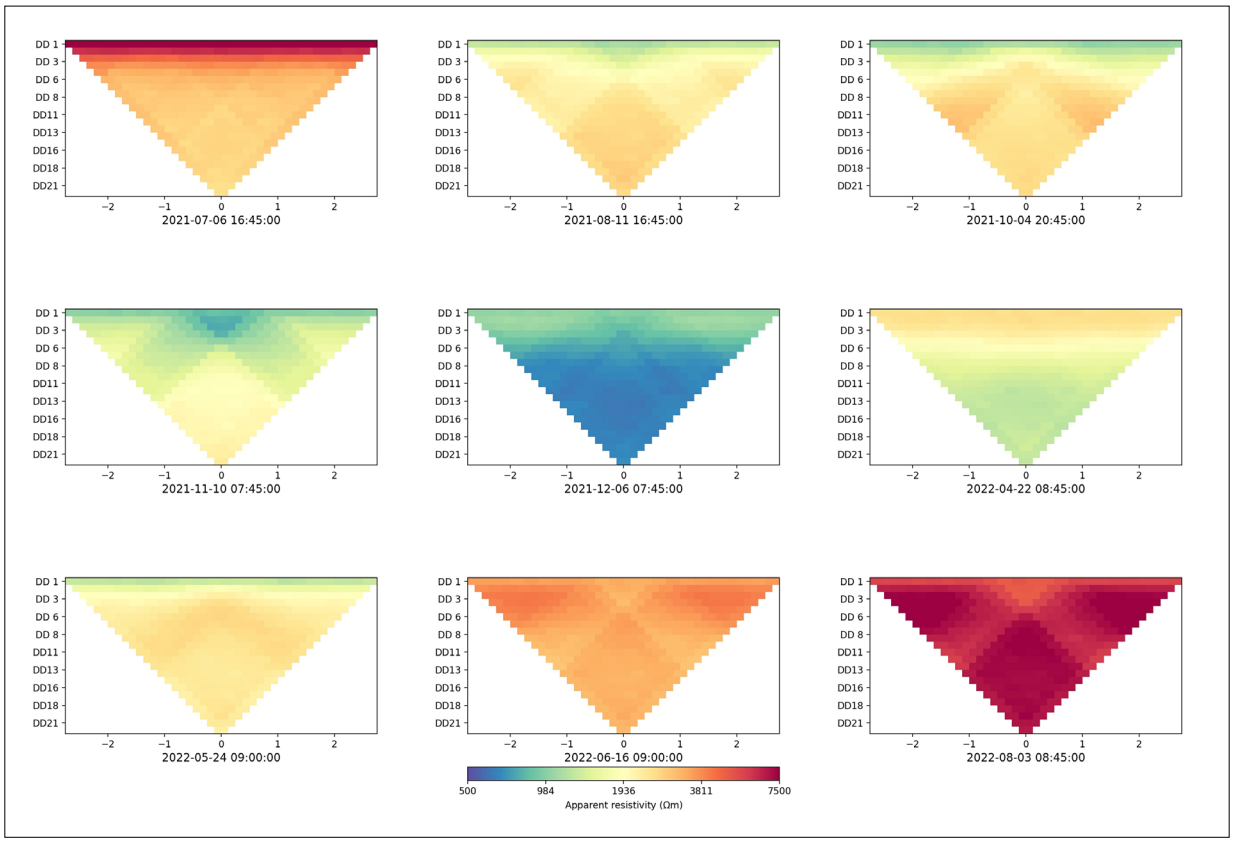

Fig. 3: Mosaic of divergent PyGIMLI ρ_a section models throughout the monitoring timespan.

Valther-Tweeling (NL), are addressed here. Here, the soil consists of coversand with a Gley-Podzol, of which the top was later disturbed by ploughing. A nearby, partially excavated, soil feature, interpreted as a boulder extraction pit (Fens et al. 2016) (Fig. 1a), was re-excavated and investigated following before mentioned methodology.

To plan upcoming surveys in the surrounding landscape, possibly holding Neolithic features, monitoring data are used to forward model the response of common electromagnetic induction instruments of both sequences using FDEM1D (Hanssens et al. 2019) (Fig. 1e). A 2D apparent resistivity (ρ_a) section with a dipole dipole array and 25 cm electrode separation was forward modelled using PyGIMLI (Rücker et al. 2017) (Fig. 1d).

Results

The profile description and photo (Fig. 1b) reveal the feature with greyish fill color. Despite the topsoil (S3) and backfill (S2) disturbance, sufficient feature fill (S6) was preserved for measuring and sampling. EC, ε, magnetic susceptibility measurements of the natural and archaeological sequence during the excavation were very low and nearly indistinguishable (Verhegge et al. 2021 – Fig. 3). The analyzed soil samples consisted of sand with low clay and silt content ($<10\%$), barely exhibiting texture contrast (Fig. 1c) as do the volumetric water content and porosity (Verhegge et al. 2021 – Fig. 3).

Last year's monitoring data expose significant bulk EC variability (Fig. 2c) and soil moisture (Fig. 2b) between the natural soil and archaeological feature fill. Temperature (Fig. 2a) change across the year is significantly larger than between the natural soil and archaeological feature fill but this is not reflected in the bulk EC due to the temperature correction. The difference of the modelled FDEM1D quadrature phase between archaeological and natural sequence, expressed as LIN approximated apparent conductivity (EC_a), increases mostly in November 2021, maximizing to 0.15 mS/m and a 0.12 contrast factor in ZX/PRP (Fig. 2a, 2b). The largest negative differences, down to -0.08 mS/m (contrast factor: -0.03), were modelled in early December 2021. However, these differences are below observed stationary sensor noise levels.

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In the ρ_a models, the feature appears differently throughout the year. When recognizable on Figure 3, it appears mostly as a lower ρ_a anomaly, but e.g. on October 4th, 2021, a more resistive anomaly is detectable (Fig. 3 – top right). Comparison of various distances between the B and M electrodes (Fig. 2c, 2d) illustrate that a 1m separation generates the highest ρ_a difference and contrast factor throughout the year. In November 2021, the ERT model indicates a negative contrast factor (-0.27) and anomaly (590 Ohmm), which is beyond estimated RM85 noise. However, compared to the EMI EC_a model, larger differences and contrast factors are present more frequently throughout the year, markedly in resistive summer conditions.

Discussion and conclusion

Despite diachronic variation under the influence of soil moisture and temperature, the modelled ECa signals of the monitored feature at "Valther-Tweeling" are too subtle to be measurable with current EMI sensors, while the ERT models do indicate a measurable signal. However, noise due to instrument use, external interference or natural soil variability was not included in the models yet. Nevertheless, electrical resistance survey also seems applicable across a larger timespan than EMI. Therefore, an electrical resistance survey is planned in late 2022-early 2023 to corroborate these findings. Correlation with precipitation data ratios (Fig. 2e) is still required to pinpoint suitable precipitation conditions preceding a survey.

Indeed, compared to initiating an electrical resistance survey at the site uninformed, executing it in established, optimally contrasting conditions at feature s6 and its surrounding soil should benefit survey results of the surrounding site and landscape as well. Importantly, the results illustrate the starting development of a quantitative framework for developing geophysical survey strategies for subtle (Neolithic) soil features, and complex archaeological features more broadly, without requiring repeated surveys. The presented approach is applicable to other sites and features by using pedophysical models to convert traditional soil properties into geophysical properties, such as EC or ε, to parametrize forward models if in situ geophysical data are unavailable. However, soil monitoring is still required to include soil moisture and temperature variations across time but this becomes more practical as affordability and user-friendliness of monitoring sensors is increasing.

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7

PROCESSING AND VISUALIZATION OF DATA

Merging scalar magnetometer and fluxgate gradiometer data – an alternative method

Sandra Hahn[1*], **Jörg W. E. Fassbinder**[1]

1 Department for Earth and Environmental Sciences - Geophysics, Ludwig-Maximilians-Universität (LMU), Munich, Germany
* Corresponding author: E-mail: sandra.hahn@geophysik.uni-muenchen.de

Abstract
Combining the records of different types of magnetometers to one magnetogram can be onerous. We introduce an alternative way to merge magnetograms of diverse magnetometers. The application of a high-pass filter on scalar magnetometer data resembles gradiometer data. This can be a fast and easy way to merge scalar magnetometer and fluxgate gradiometer data.

Keywords
fluxgate gradiometer; high-pass filter; magnetogram; scalar magnetometer

Introduction

The circumstances of campaigns or field work may require the use of a scalar magnetometer and a gradiometer on the same survey area in adjacent segments, for example, when a large survey area is to be investigated in a short time, as was the case with our project in Fara (Hahn et al. 2022). However, the different designs of the magnetometers measure different components or quantities of the magnetic flux density of an anomaly. Specifically, a scalar magnetometer measures the total-field anomaly, the projection of the anomalous anomaly onto the geomagnetic field vector, while a single axis gradiometer measures the difference of the anomaly's component at the lower and upper fluxgate sensor. Therefore, the instruments produce different visual outputs. This can be disturbing or distracting during archaeo-geophysical interpretation. To obtain comparable readings of both instruments, the correct physical approach involves

- a transformation of the scalar magnetometer data from the total-field anomaly to the vertical component of the anomaly
- adjusting these data to one fluxgate gradiometer sensor height and computing a signal for a virtual second sensor through upwards or downward continuation
- calculating the difference between these two data sets

In the following, we discuss a more simple way to combine scalar magnetometer and fluxgate gradiometer output to a visually uniform magnetogram.

Materials and methods

The magnetometer survey from the 2018 Fara campaign, the results of which we show here, was conducted with scalar magnetometers in duo-sensor configuration, a Scintrex Smartmag SM4G-special magnetometer and a Geometrics G-858 magnetometer, and with a fluxgate gradiometer, a Foerster Ferex instrument. For the total-field anomaly data, the data processing involves the correction of the diurnal variation including the subtraction of a reference value. Knowing that a fluxgate gradiometer measurement has an intrinsic high-pass filter (HPF) effect (Schmidt 2008) inspired the approach to merge the high-pass filtered scalar magnetometer data with the fluxgate data as a quick, time-efficient and simple method in comparison to the above-mentioned exact method. The mean value of the individual data sets of the segments is set to zero before the merging. We used the "Geoplot" (Geoscan Research) "HPF" command on the total-field anomaly data with different radii for the image HPF.

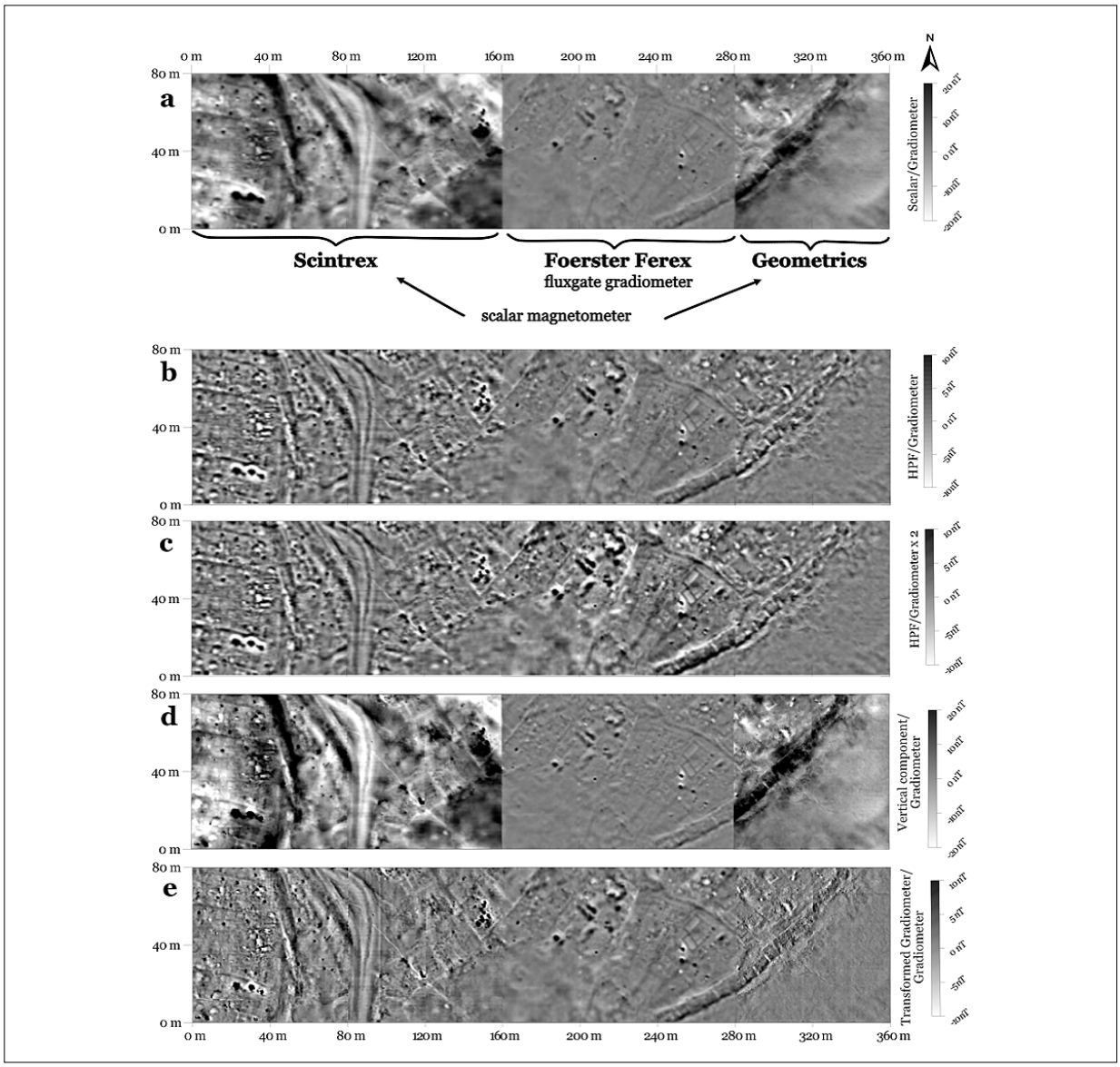

Fig. 1: a) Combination of the scalar magnetometer and the vertical gradiometer data sets. b) ... of the high-pass filtered scalar magnetometer and the fluxgate gradiometer data sets. c) ... of the high-pass filtered scalar magnetometer data sets and the gradiometer data sets multiplied by 2. d) ... of the vertical component computed from the scalar magnetometer data sets and gradiometer data sets. e) ... of vertical upwards continuation (0.65 m) of the vertical component of the scalar magnetometer data set minus the original data set (transformed gradiometer data) and fluxgate gradiometer data sets.

Results

Combining the segments measured by the two scalar magnetometers and the fluxgate gradiometer directly after data processing (Fig. 1a) the difference is distinct. Through trial-and-error, a visual match works best when an image HPF (Gaussian) with a radius of 10 is applied to the scalar magnetometer data. This visual result is shown in Figure 1b. Comparing the standard deviation for all three magnetometer data sets, the high-pass filtered scalar magnetometers' data sets have the same value, while the fluxgate gradiometer data sets show only half of the high-pass filtered scalar magnetometers' data sets for all magnetograms of this case study. Therefore, we multiplied the gradiometer data set by factor of two to achieve a better match of the data sets in terms of their data values as well as their optical output. The resultant magnetogram (Fig. 1c) appears visually uniform.

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Discussion

Scalar magnetometers and fluxgate gradiometers measure different components of the magnetic flux density. If these different components are now displayed in a combined magnetogram, these physical differences also become visually apparent. The application of a HPF on the segments of scalar data, corrected for diurnal variations, effectively filters out larger spatial wavelengths as illustrated by Scollar (1969). Theoretically, this, together with the correction for diurnal variations, is akin to the idea of gradiometer measurements. As Figures 1b and 1c show, this strongly resembles the visual appearance of the gradiometer data set of the adjacent segments. By multiplying the data set of the gradiometer by a factor of two, the lack of signal strength in comparison to the scalar magnetometer data can be compensated for (Fig. 1c). The lack of signal strength results from measuring only one component of the magnetic flux density and the subtraction of the two readings of the upper and lower fluxgate sensor. This factor is expected to be dependent on the inclination of Earth's magnetic field in the survey area (higher for lower inclinations) and the distance between the two fluxgate sensors of the gradiometer (higher for shorter distances). Exactly how they affect the multiplication factor and whether the inclination affects the settings of the image HPF still needs to be investigated.

To compare our method with the physical correct approach, we transformed the total-field anomaly data with a self-written MATLAB script based on Gerovska and Araúzo-Bravo (2006), Figure 1d, and used the „MagPick" program (Geometrics) to obtain the upward continuation (Blakely 1996) for a second sensor at height of 0.65 m and subtracted these values from each other. The result can be seen in Fig. 1e. The high-pass filtered and the transformed gradiometer data of the scalar magnetometer data show good visual agreement (see Fig. 1c and d).

Conclusion

Our method of applying an image HPF (Gaussian, R = 10) on the total field data sets and multiplying the gradiometer data sets by a factor of two can provide a combined magnetogram of all three survey segments which appears uniform regardless of the instruments used and the boundaries of the survey segments. The findings in the case study of Fara highlight the benefit of combing both data sets into one magnetogram. Our method enabled faster visual interpretation of the magnetograms and made it easier to trace and compare features across the different segments. In our inplementation, the use of a high-pass filter is quicker and more convenient, since all visual data processing is then carried out by one software.

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Multi-antenna GPR data processing of the garrison of the governor's guard in Carnuntum/Austria

Alois Hinterleitner[1*], **Mario Wallner**[1], **Ingrid Schlögel**[1], **Immo Trinks**[2]

1 Near Surface Geophysics, Geosphere Austria, Vienna, Austria
2 Vienna Institute for Archaeological Science, University of Vienna, Vienna, Austria
* Corresponding author: E-mail: Alois.Hinterleitner@geosphere.at

Abstract
Multiple antenna GPR data provide excellent results when using 3d migration. 3d migration must be performed without erroneous measurements. 3d migration must be sensitive to the different channels. Wall structures along the measurement lines can then be visualized.

Keywords
archaeological prospection; ground penetrating radar; GPR data processing; GPR multi-antenna systems

Introduction

The recorded data of (motorized) GPR multi-antenna systems are different in several respects from those of GPR single-antenna systems and therefore require additional and more differentiated processing steps. Using single antenna systems every trace recorded is immediately visualized on the measuring device, thus enabling continuous quality control. Problems with the GPR antennas become visible and faulty measurement lines can be repeated immediately. The entire GPR data set is generated with one physical pair of antennas, so it has always the exact same transmission signal, the same influences of the measuring device setup and always an optimal ground coupling due to the smaller size of the antenna box. A single channel data set therefore usually has few errors and is very consistent in wave form and data quality.

The data quality of all channels of multi-antenna systems with 16 parallel channels, such as the Malå MIRA System available to ZAMG, on the other hand, cannot be constantly checked by the operator during the measurement. The individual antenna pairs are separate units and therefore behave slightly differently. They are mounted in different places in the measurement system and are therefore subject to different external influences due to the antenna box suspension and the towing vehicle. They sometimes have different ground clearance on uneven ground and sometimes a different, less than optimal ground coupling. In addition, the overall system is more complex and so more prone to errors. Therefore, the radar waveform is less consistent with multi-channel data sets and the data quality is sometimes lower because it contains more error values. This leads to increased demands on the processing software for multi-antenna systems, because the amount of data is much larger, the error correction is very sensitive, must happen automatically and the individual processing algorithms must be able to adapt to the different waveform and quality of the channels. If, in addition, a three-dimensional migration is to be carried out, disturbances in one channel affect several other channels, so that automatic error detection is of great importance. All processing algorithms must be implemented in such a way that they do not use single erroneous measurement points.

Data processing

Error detection

Error detection is carried out in several steps to detect different types of errors in the sequence of the severity of the possible error. First, traces without (reasonable) measured values and traces that show strong deviations in the first 2 ns

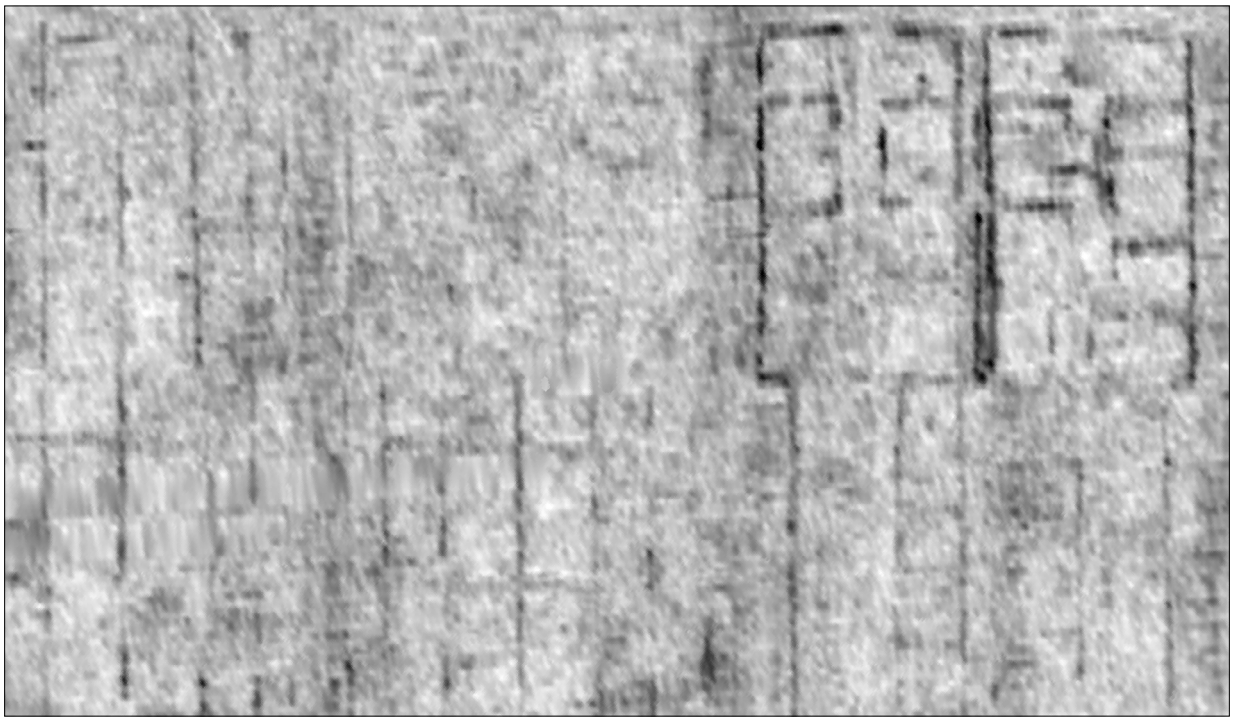

Fig. 1: GPR depth slice (80-140 cm) of an area of the garrison of the governor's guard; simulated single-channel survey with 50 cm line spacing; two-dimensional migration; area 43 m x 76 m. High amplitude reflections are shown in darker tones towards black and the survey data is orientated with north to the top of the page.

are detected. Both types of errors usually provide no measurement data, so these traces were completely removed. Then individual spikes are filtered out. Then the entire trace is divided into three sections and examined separately, because the ranges of possible error-free values differ greatly in these three sections. These three sections are, firstly, the direct wave section (around time zero), secondly, the mid-depth section with moderate energy loss, and thirdly, the section in the deeper areas from which very little energy returns. For the first section, the correlation is calculated with the same section of a mean trace determined by median calculation, since this section is dominated by the direct wave. Traces with low correlation are classified as faulty. For the other two sections, the envelope of the mean trace is calculated and used to set a limit for possible erroneous values. The limit of these two sections is usually higher for the second section than for the third. The samples of each trace are compared with these limit values and classified as faulty if exceeded. All faulty traces and readings are marked to be removed from further processing.

Time zero calculation

True time zero is not only very crucial for the depth estimation, but also very essential for the three-dimensional migration, which takes several channels into account. The first wave in turn is strongly dependent on the position of the antenna within the measurement system and can therefore vary greatly between the channels. In order to be as robust as possible here, the zero time is first calculated at an average trace calculated by median calculation. Then the zero time is calculated for each trace of this channel by correlation with the averaged trace.

Energy balance of the individual channels

The total energy of the individual channels can vary by up to 50%. An equalization by multiplication is carried out so that the energy of all channels is equal afterwards. This is absolutely necessary if several channels are used for one processing (three-dimensional migration).

Image processing

Due to the different ground coupling of the antennas in multi-antenna systems on survey areas with agricultural cultivation traces, there are often stripe-like patterns in the depth slices which, in addition, sometimes run exactly along archaeological structures. These patterns are eliminated or at least suppressed by a small-scale adaptation of the absolute amplitude values of an antenna channel to

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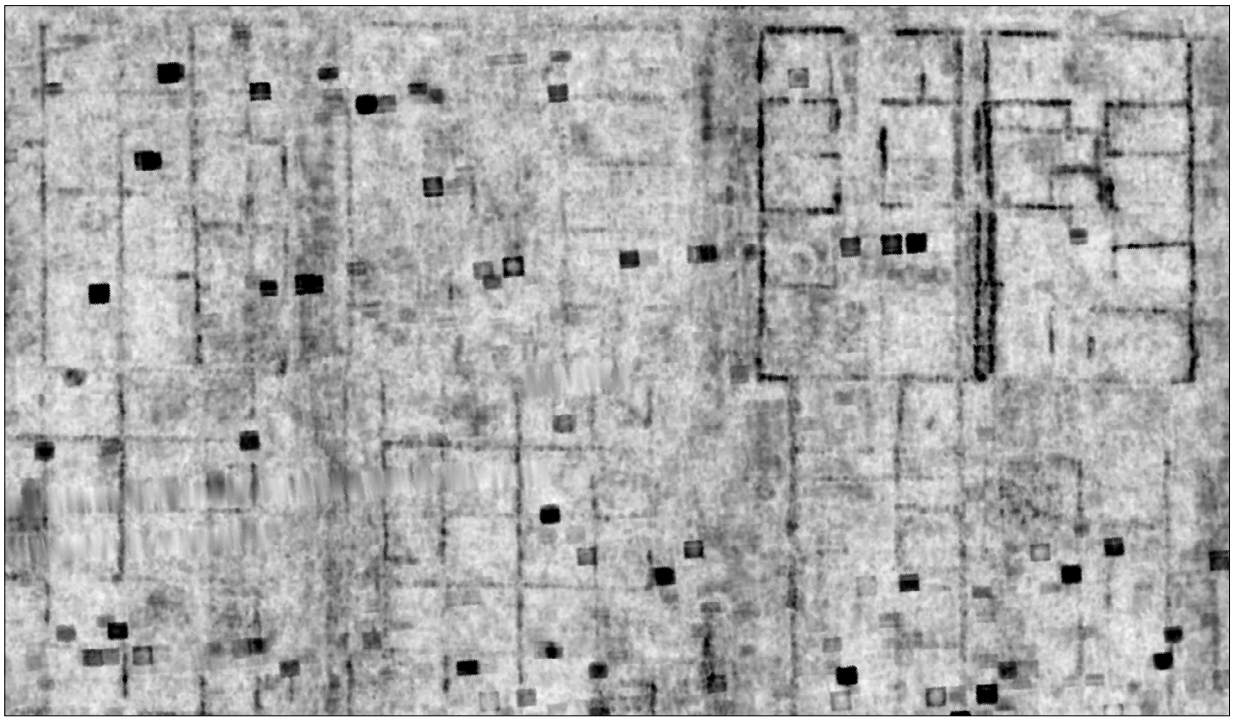

Fig. 2: GPR depth slice (80-140 cm) of an area of the garrison of the governor's guard; Malå MIRA survey with 10 cm line spacing; 3d migration without error detection; area 43 m x 76 m.

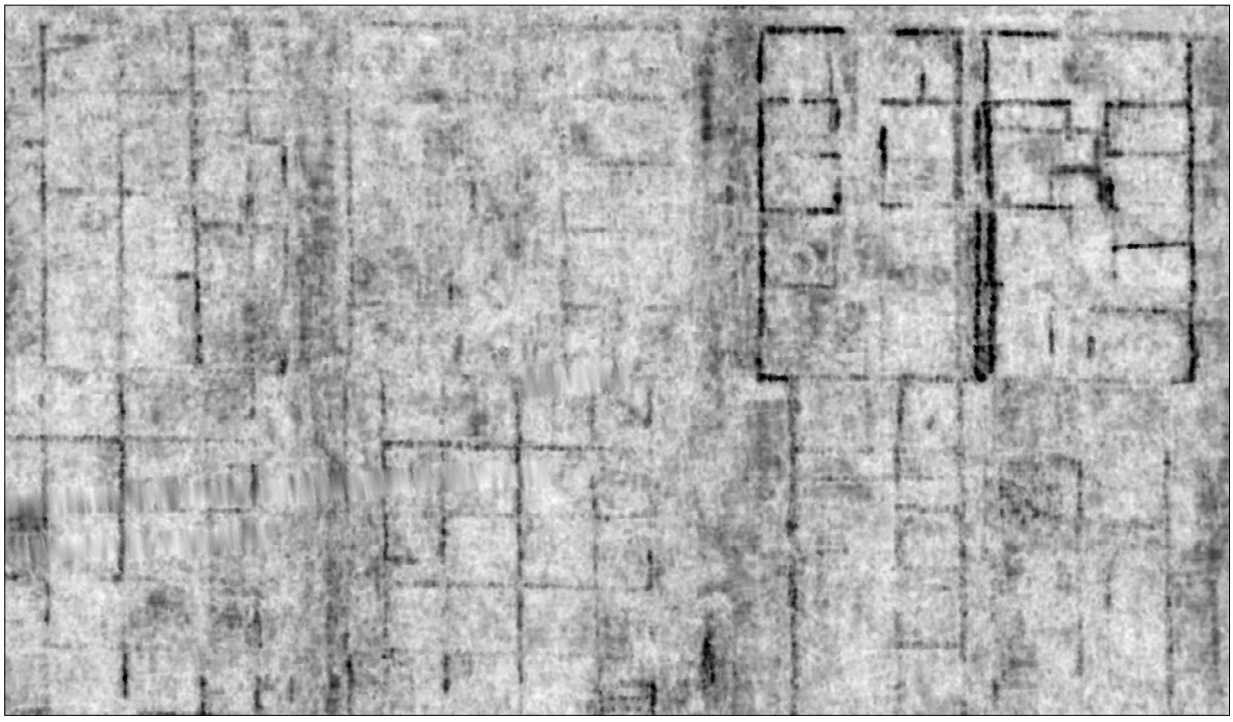

Fig. 3: GPR depth slice (80-140 cm) of an area of the garrison of the governor's guard; Malå MIRA survey with 10 cm line spacing; 3d migration with error detection; area 43 m x 76 m.

the neighboring channels in the direction of travel. Individual faulty values in the depth slices are also removed by a selective median filter in this last processing step.

Results of the Garrison of the Governor's Guard

The area of the garrison of the governor's guard at the Roman town of Carnuntum was prospected using a Malå MIRA multichannel system with 16 channels of 400 MHz antennas with 10 cm channel spacing. The measuring point distance is 2-5 cm depending on the surveying speed. This area includes a large military camp with rows of houses representing the barracks of the Roman soldiers. This unique military camp is part of the newly discovered administrative complex of the Roman province of Pannonia superior (Gugl et al. 2021).

A simulated 50 cm single antenna prospecting using only one fifth of the Mira channels is not able to show the walls along the measurement lines running east-west because the three-dimensional Kirchhoff migration is not better than the two-dimensional Kirchhoff migration (Moran et al. 2000) due to the large line spacing (Fig. 1).

The multichannel measurement with three-dimensional Kirchhoff migration, on the other hand, also shows the walls running along the measurement direction (east-west) very well. But without sufficient error detection, the individual erroneous readings appear through the three-dimensional migration as large interfering squares whose size corresponds exactly to the migration window (Fig. 2). Only processing with sufficient error detection and subsequent exclusion of the erroneous measured values during migration enables optimal visualization for detailed archaeological interpretation (Fig. 3).

Conclusion

In order to optimally visualize the data of multi-antenna systems, a three-dimensional migration must be performed. An optimal result can only be achieved if this processing can take into account the properties of the individual channels and exclude erroneous values.

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Determination of the subsurface structure of the Chora Plain (Samos) by seismic noise analysis

Nina Kallinich[1*], Martin Thorwart[1], Wolfgang Rabbel[1]

1 Institute of Geosciences, Kiel University, Kiel, Germany
* Corresponding author: E-mail: stu223269@mail.uni-kiel.de

Abstract
Seismic noise was passively recorded with mini-arrays, allowing shear wave velocities of individual layers to be estimated. A statistical analysis by beamforming was performed. A 1D underground model of the Chora plain was derived. Three dominant structures were found: coastal barrier, siltated lagoon and the interior of the Chora plain.

Keywords
archaeological prospection; forward modelling; landscape reconstruction; mini-arrays; passive seismic

Introduction

The area studied is located in the Chora Plain, a coastal depression in the southeast of the eastern Aegean island of Samos (Fig. 1a). Samos played a major role as a trading centre in ancient Greece. Since large parts of the island were not suitable as arable land, the fertile soil of the Chora Plain had great importance for the food and water supply of the Samian population.

In spring 2023, a drilling and direct push campaign will be carried out in cooperation between Kiel University and the German Archaeological Society for landscape reconstruction of the plain over the last 5000 years, to gain knowledge about the water and food supply of the Samian population, and for an estimate of the population size on Samos over time.

As preliminary work, passive seismic data were collected with mini-arrays in May 2022 to find suitable study sites. For this purpose, the sedimentary structure of the plain was to be roughly determined. The project is funded by the ROOTS Cluster of Excellence.

Methods

The methods commonly used in geophysical prospection, such as electromagnetic induction (EMI), ground penetrating radar (GPR) or electrical resistivity tomography (ERT), have a penetration depth of only a few meters, which is too shallow for landscape reconstruction. Therefore, seismic was used as a measurement method for this task. For seismic depth sounding and estimation of shear wave velocities of individual layers, seismic noise was passively recorded on 84 mini-arrays along three profiles (Fig. 1b), and the dispersion of the Rayleigh wave was determined. The two-dimensional geophone arrangement shown in Figure 1c was used. The configuration is composed of an outer square (2.5 m x 2.5 m) and an inner square (0.7 m x 0.7 m), so it has a relatively small footprint.

A statistical array analysis is performed in the frequency range from 2 Hz to 80 Hz. The data of each mini-array is narrowband filtered and divided into short, overlapping time windows. For each time window a slowness value, the propagation direction (backazimuth) and a coherence value are determined by beamforming. To minimize statistical errors, the slowness values of the 20 data points with the highest coherence are averaged to obtain the dispersion velocity.

From this, dispersion curves for all arrays can be derived by plotting the phase velocity versus frequency. A dispersion spectrum can then be generated using the qseisfk algorithm (Wang 1999) based on a defined 1D background model. This model must be adjusted until the dispersion curve of the fundamental mode of the spectrum resembles

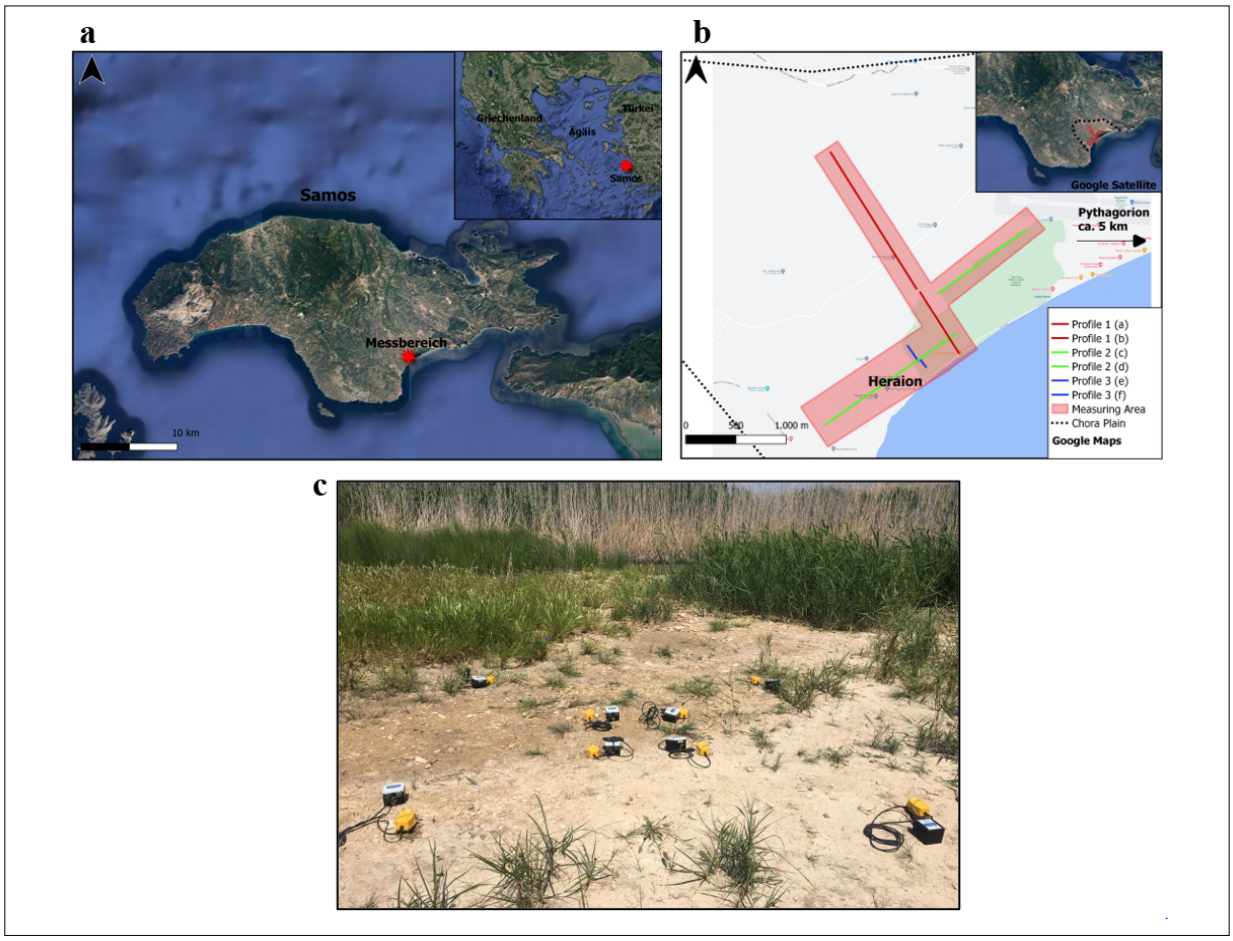

Fig. 1: a) Location of Samos and of the study area in the Chora Plain in the Southeast of Samos. b) Study area with the profiles. c) One mini-array with eight geophones as an example. We used the shown configuration for the measurements.

the previously calculated dispersion curve. Since there are ambiguities in the models, it is important to compare the models of neighbouring arrays and adjust them if necessary. From this, velocity distribution plots as a function of depth can be generated.

Results and discussion

Figure 2a shows an example of the subsurface model of profile 1 which runs vertically to the coastline. From 300 m to 600 m a depression can be seen in the boundary of the layers with 300 m/s and 500 m/s shear wave velocity, which extends to a maximum depth of 30 m. Relatively high velocities of 1000 m/s to 1200 m/s emerge from about 800 m inland at a depth of 20 m. Overall, high velocities dip from the west towards the east. Between 350 m and 750 m, a low-velocity region is visible at depths of about 3 m to 6 m with velocities below 100 m/s, vertically surrounded by velocities slightly above 200 m/s.

The lateral velocity distribution (Fig. 2b) shows a deep velocity region with shear wave velocities of below 100 m/s parallel to the shoreline. The velocity of this region contrasts sharply with the surrounding higher velocities, especially at depths of 4 m. From a depth of about 9 m, it is hardly discernible.

Figure 3a shows the petrophysical interpretation of the front part of profile 1. The shear wave velocities of the layers are assigned to different sediment and rock types (Hızlar et al. 2012).

The approximately 1.6 km long and 450 m wide area parallel to the coastline, with velocities below 100 m/s, which is particularly evident at a depth of 4 m, could be interpreted as part of an oversedimented lagoon. A lagoon is a shallow body of water separated from the sea by a landform, with sediments largely composed of clay, sand,

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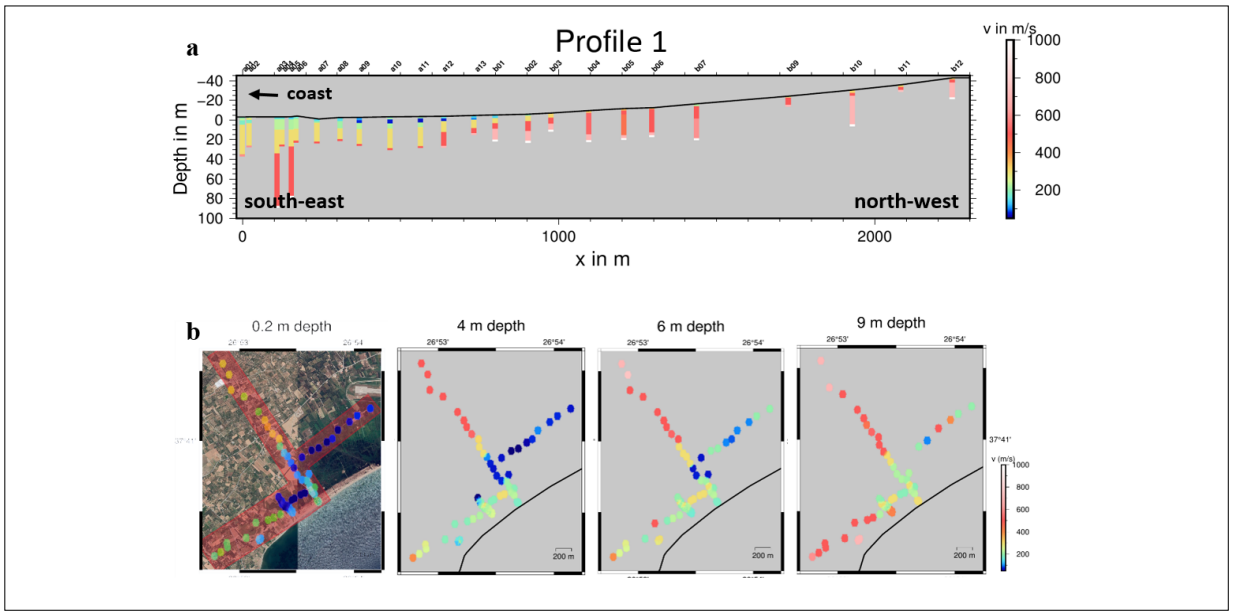

Fig. 2: a) Subsurface models of the 2300 m long profile 1. The black line represents the height of the earth's surface. b) Lateral velocity distribution plots according to 0.2 m, 4 m, 6 m, and 9 m depth. The black line represents the coastline.

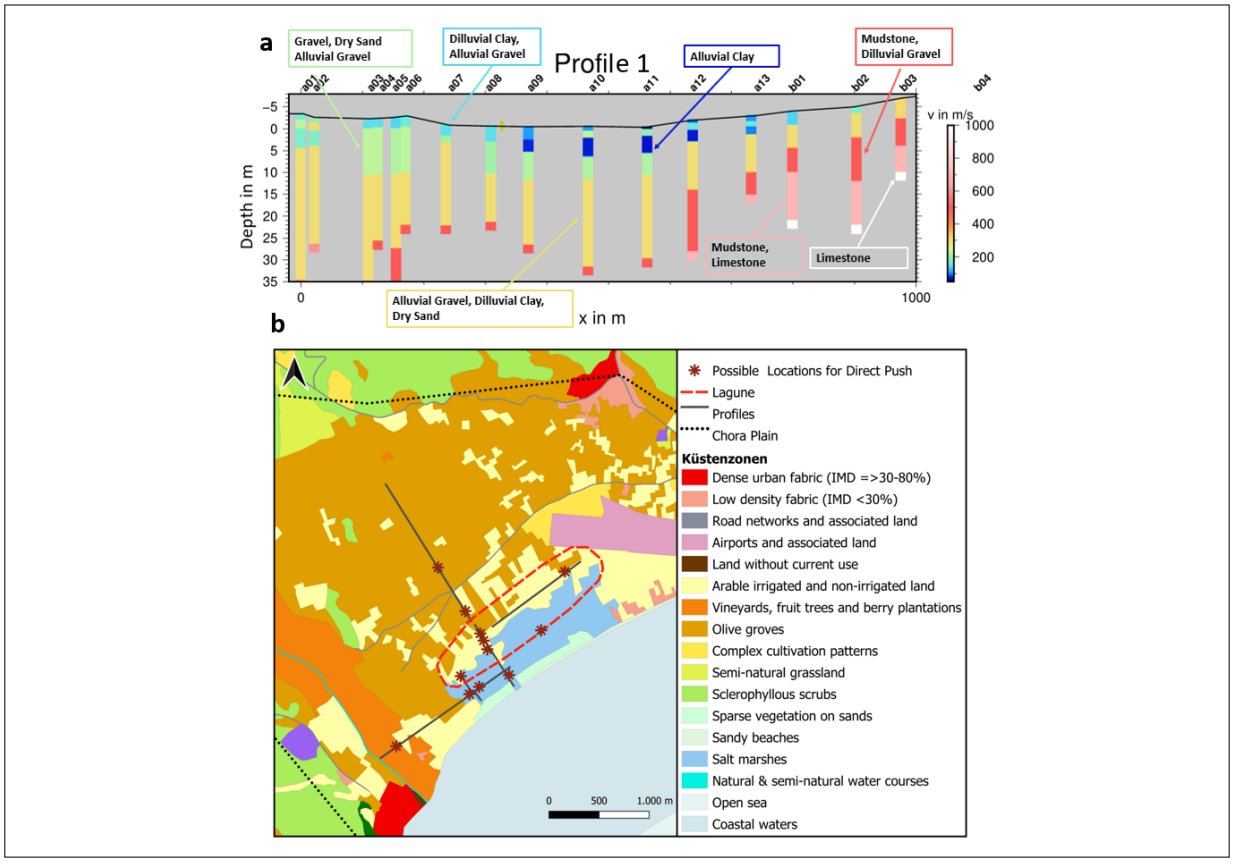

Fig. 3: a) Petrophysical interpretation of the results. Shear wave velocities of the front part of profile 1 assigned to different sediment and rock types (Hızlar et al. 2012). b) Coastal Zones map of Copernicus with possible locations of the Direct Push campaign in 2023. © European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA), Coastal Zones.

and biogenic material (Omoregbe et al. 2020). This area is shown along with a coastal zone map of *Copernicus* (Fig. 3b). The map shows an area classified as a salt marsh (blue) which runs parallel to it with a slight offset to the southeast. Since salt marshes are often contained within lagoons, this would reinforce the assumption that lagoonal material may be involved.

Also shown on the map are possible locations for the drilling and direct push campaign in spring 2023. These were placed so that the course of the individual layers of the sedimentary basin can be traced and, in particular, so that the area interpreted as a lagoon/salt marsh can be studied in more detail.

Conclusion

The results of this work can be used as a basis for planning the 2023 Direct Push campaign. The array method is generally well suited for preliminary investigations in geophysical prospecting and gives the opportunity to obtain a rough overview of the subsurface structure with relatively little effort. Especially if, as in this case, it is known that the material is clayey and very soft, which strongly attenuates electromagnetic waves, passive seismic can be considered as a prospecting method.

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Identification of buried archaeological features using the curvelet transform

Alexandra Karamitrou [1,2*], **Gregory N. Tsokas** [1]

1 Laboratory of Exploration Geophysics, Aristotle University of Thessaloniki, Greece
2 Department of Archaeology, University of Southampton, United Kingdom
* Corresponding author: E-mail: karamitrou@geophysics.gr

Abstract
We present an application of the curvelet transform fusion method between geophysical and remote sensing data. The method was tested in two different archaeological areas in Greece with different historical, archaeological, and environmental characteristics. The final fused images combined all available information reducing the noise and enhancing the interesting features.

Keywords
archaeology; curvelet transform; fusion; geophysics; remote sensing

Introduction

Over the last decades geophysical methods have become a crucial part of the archaeological field exploration. All involved parts have recognized the importance of employing overlapping geophysical measurements with different methods as they deliver sensitivity to dissimilar subsurface properties, allowing a more robust and complete representation of the targets (Ernenwein and Hargrave 2007; Gaffney 2008). One common combination is the electrical resistivity with the geomagnetic gradiometry method. This is mainly to integrate the advantages of the resistivity in mapping targets such as building footings and other structural remains, with the sensitivity of the geomagnetic method to targets with substantial magnetic susceptibility e.g., ferrous metals, ceramic objects, and hearths (Kvamme et al. 2018). Additionally, remote sensing data have nowadays became a useful tool in archaeological research complimenting with data that provide easy access to even remote areas. Towards this direction, image fusion and in particular the curvelet-based fusion method (Karamitrou et al. 2019) allows the automatic integration of multiple overlapping datasets from various remote sensing methods, (e.g. Karamitrou et al. 2021) that delineate surface signatures of subsurface structures. In this work we demonstrate the advantages of this approach using data from two archaeological areas in Greece.

Method

Once the remote sensing images are acquired some basic processing is applied (e.g. arctan function, interpolation, dynamic range compression, high-pass filter, Wallis filter). While the data cover that same area of examination an additional fine co-registration is applied that further adjusts fine-scale discrepancies associated with inaccuracies mainly since the geophysical measurements are taken using hand-held devices as well as from errors in the relative positioning of the grids (Karamitrou et al. 2017). The next step is to apply the curvelet transform (CT) method where each image is decomposed (Candès and Donoho 2000) into discrete coefficients. These coefficients are functions of the spatial coordinates, scale (i.e. size), and azimuth of the imaged features. The CT is fully reversable and sparse. The main advantage of curvelet transform is that objects can effectively be represented as a series of smaller linear segments. The ability of the CT to distinguish the importance of imaged features according to their location, size, and orientation provides the means for an objective integration of different remote sensing images. The final fused image is created directly in the curvelet domain by comparing the corresponding CT coefficients of the initial input images and choosing the one with the maximum amplitude ("the maximum frequency rule").

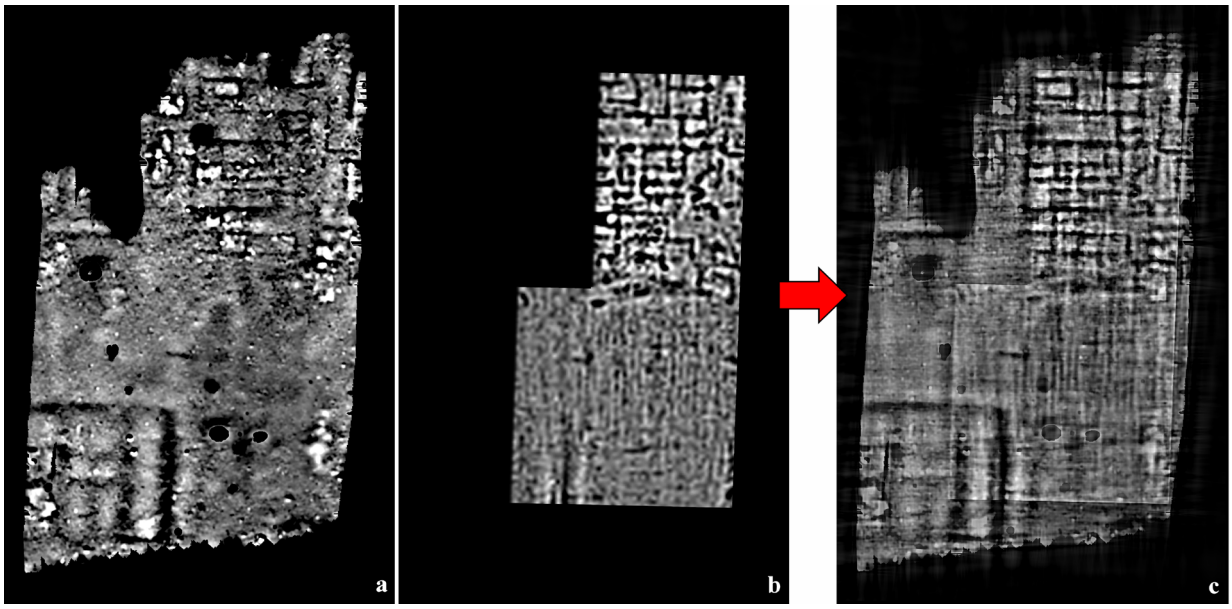

Fig. 1: Geophysical images from the area of Phillipi in N. Greece a) Magnetic gradiometry, b) electrical resistance and c) final fused image using the curvelet method.

Data

We applied the curvelet transform in two archaeological areas in Greece, the archaeological area of Philippi, located in Central Macedonia Region and the archaeological area of Stryme in Thrace. Each archaeological area represents a different era with different environmental and historical conditions. For the archaeological area of Philippi, we examined two geophysical methods (magnetic gradiometry and the electrical resistance) and one aerial image taken using a drone. On the other hand, for the archaeological area of Stryme, we have examined an image depicting the electrical resistance of the area and a GeoEye-1 panchromatic image with a resolution of 0.45 m.

Results

In both cases the final fused images represent the examined area in more details by enhancing the interesting features and suppressing the noise. From historical information and from excavations in the nearby locations of both areas of investigation we knew the orientation of the expected features. Therefore, during the fusion process we enhanced the images along these specific angles. Figure 1 shows an example from the archaeological area of Phillipi.

A visual inspection reveals that at the N-NE region where there are fine scale structures the resistivity image contributes more while at the SW region where longer wavelength features exist the magnetic image prevail. A further statistical analysis of the final fussed images allows the evaluation in more details. This analysis can be done efficiently on-the-fly during the fusion by keeping track of the number of non-zero coefficients that each image contributes to the fused product across different levels of the decomposition (i.e. scales) and angles (i.e. azimuths) (Fig. 2). This analysis reveals that the contribution of each image varies significantly over different scales and different orientations.

Conclusion

Image fusion is a powerful tool that enables the visualization of all available overlapping imagery into one single image. Archaeological images include complex features of various sizes and shapes and curvelet transform has proven to be a reliable method that manage to process these features as it can elevates a 2-dimensional image into a 4-dimensional space where instead of the two spatial coordinates the image can be expressed as a function of space, scale and orientation. In the final fused images, the noise is suppressed while the interesting features appear enhanced and, in many cases, more complete.

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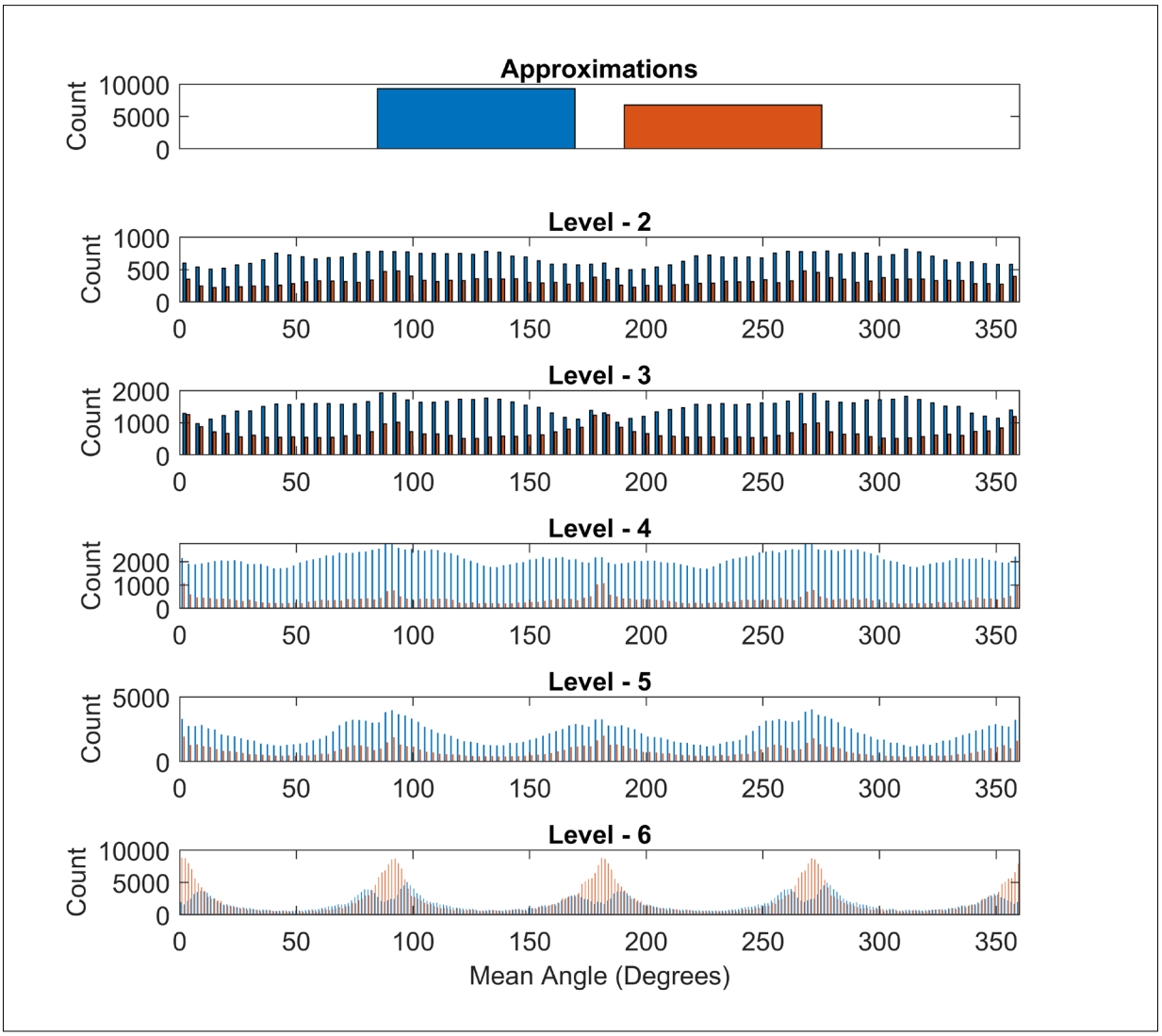

Fig. 2: Comparison of the contribution of the magnetic (blue) versus the resistivity (red) image to the fused product, along different levels and angles (azimuths). Vertical axes count the number of coefficients each image contributed. Top row shows the approximations, where no angular information is available.

Acknowledgments

This work has been accomplished on behalf of the project EKATY: Innovative imaging of the subsurface of archaeological sites and the interior of structural elements of monuments in 3 and 4 Dimensions. The project is running under the framework of the Operational Programme Competitiveness, Entrepreneurship and Innovation 2014-2020 (EPAnEK), Special Actions "Aquaculture" – "Industrial Materials" – "Open Innovation in Culture", T6YBΠ-00211.

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The gradient structure tensor (GST): an efficient tool to analyze 3D GPR data for archaeological prospection

Philipp Koyan[1*], **Jens Tronicke**[1]

1 Institute of Geosciences, University of Potsdam, Potsdam, Germany
* Corresponding author: E-mail: koyan@uni-potsdam.de

Abstract
We present GPR data across remains in a Palace Garden at Paretz (Germany). We use the GST to highlight archaeological structures in the GPR data. We outline the flexibility and time-efficiency of a GST-based analysis strategy.

Keywords
archaeological prospection; attribute analysis; gradient structure tensor; ground penetrating radar; 3D imaging

Introduction

Ground penetrating radar (GPR) is a well-established near-surface geophysical tool commonly applied in archaeological prospection. Thanks to steady developments in system design and surveying strategies, the acquisition of 3D GPR datasets densely covering thousands of square meters has become common practice. However, developing GPR interpretation strategies has not kept pace with technological advances. Today, the ever-growing amount of GPR data is still typically interpreted in a manual fashion which makes interpretation a time-consuming and rather subjective process.

Amongst other techniques, the application of 3D attributes has shown to be a helpful strategy in GPR data analysis to concise the interpretation processes and make interpretation a less subjective and more reproducible task. Attributes enhancing and quantifying structure information such as dip and continuity are able to deliver reliable results when incorporated into the interpretation process (Koyan et al. 2021). The gradient structure tensor (GST) is well known as a tool to describe structure in 2D/3D/4D image and video processing including medical applications. GST-based strategies have also been successfully used to interpret reflection seismic data (e.g. Bakker 2002) but to our knowledge no examples for the application to 3D GPR datasets can be found in the literature.

Theory and method

In 3D, the gradient structure tensor N of an image I is defined by smoothed outer products of the image gradients:

$$\mathrm{N}(x,y,z) = \begin{pmatrix} \langle I_x^2 \rangle & \langle I_x I_y \rangle & \langle I_x I_z \rangle \\ \langle I_y I_x \rangle & \langle I_y^2 \rangle & \langle I_y I_z \rangle \\ \langle I_z I_x \rangle & \langle I_z I_y \rangle & \langle I_z^2 \rangle \end{pmatrix}. \quad (1)$$

Here, the indices x, y, z denote the derivatives with respect to the three spatial dimensions and $\langle \cdot \rangle$ denotes a Gaussian smoothing operation applied to produce stable results at the target spatial scale characterized by a standard deviation σ_T (x,y,z). Relevant information from this tensor can be obtained by calculating its three eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$) and the corresponding eigenvectors $\hat{e}_i$ with $i = 1, 2, 3$. From the orientation of the eigenvectors, local structure, for example, within locally stratified environments can be quantified by calculating the dip angle and dip azimuth. In contrast, to detect and map archaeological targets, we analyze the tensor eigenvalues in terms of planarity C_{plane} calculated by

$$C_{plane} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}. \quad (2)$$

In general, planarity describes the local structure in terms of continuous regions ($C_{plane} \approx 1$) such as layers in stratified sediments and discontinuous regions ($C_{plane} \ll 1$) such as

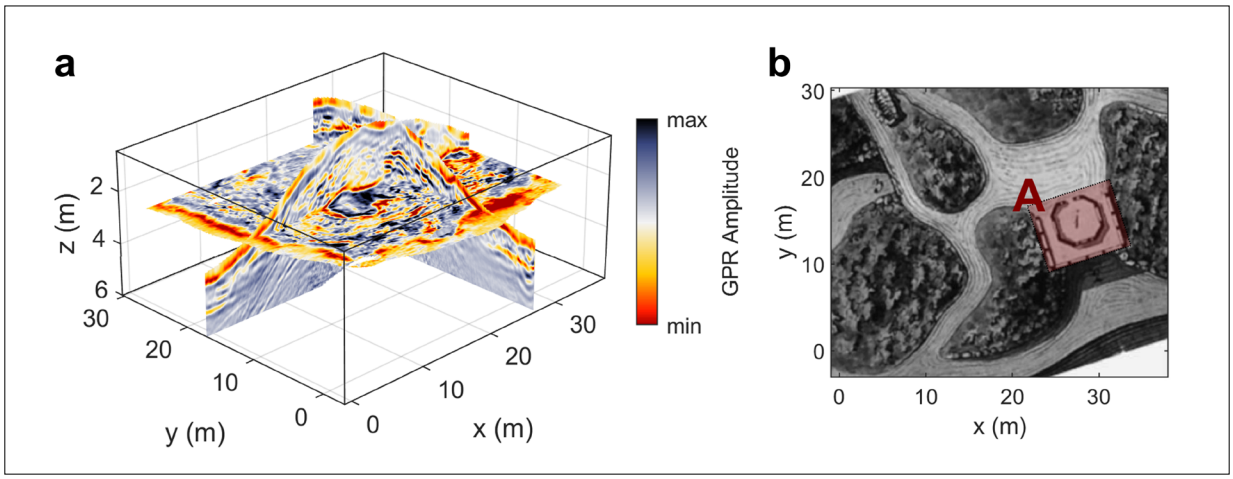

Fig. 1: a) Example slices of the processed dataset in terms of GPR amplitude (vertical exaggeration is 3). b) Historical sketch of the Paretz Palace Garden highlighting structure A, a historical grotto located beneath a teahouse (redrawn after Böniger and Tronicke 2010).

debris. Compared to other relevant attribute calculation strategies, the GST procedure (1) can be considered as computationally efficient (calculation times in the order of seconds for typical 3D datasets consisting of several 100.000 traces and more), (2) delivers a wide range of diverse attributes highlighting different structural characteristics, and (3) enables an intuitive parameter selection because its output mainly depends on the target-specific parameter $\sigma_T\,(x, y, z)$.

Results and discussion

To detect the remains of ancient architectural elements in the Palace Garden of Paretz, Brandenburg (Germany), Böniger and Tronicke (2010) collected densely-sampled 3D GPR data (with an in- and crossline spacing of approximately 0.05 m and 0.25 m, respectively) using a common-offset pair of unshielded 200 MHz antennas covering an area of approximately 35 m x 40 m. In Figure 1a, we show selected slices of the GPR amplitude volume after applying a typical 3D processing sequence including migration, topographic correction, and time-to-depth conversion. By performing extensive attribute-based analyses of this GPR volume also considering collocated magnetic and topographic surveys, the authors identified several anomalies that they interpret using a historical sketch of the garden from the early 19th century (Fig. 1b). To demonstrate the potential of our GST-based method, we focus on structure A, where the historical sketch reports an ancient grotto with rectangular walls underneath a teahouse.

To calculate the GST, we set $\sigma_T\,(x, y, z)$ to 0.35 m such that the Gaussian smoothing kernels operate in the order of a dominant GPR wavelength. In Figure 2a, we show a selected x-y slice of the GPR amplitude volume shown in Figure 1a at a depth of approximately 3 m. We observe mainly chaotic reflection patterns appearing to lack a preferential direction which makes it hard to interpret the GPR data alone in terms of archaeologically relevant structures. Mainly the same holds for GPR energy (here calculated as the averaged sum of squared amplitudes over a depth window of 0.35 m), a common attribute in archaeological GPR prospection, that we show along the same slice in Figure 2b. Here, we calculate planarity across the GPR amplitude volume following Equations 1 and 2, and show the result as transparent overlay on the corresponding GPR data slice shown in Figure 2a. Comparing Figures 1b and 2c reveals that discontinuous areas (highlighted by lower planarity values) nearly perfectly trace the apparently well-preserved walls of the grotto. Additionally, we calculate planarity for the GPR energy volume and show the result in Figure 2d as transparent overlay on the corresponding GPR energy slice shown in Figure 2b. Comparing Figure 2b and 2d shows that the energy-based planarity highlights the inner part of structure A and thus indirectly images the outer boundaries of the grotto. Taking also Figure 1b into consideration implies that the low energy-based planarity values in the central part of structure A are caused by discontinuous energy patterns that, in turn, indicate debris originating from the formerly overlying teahouse.

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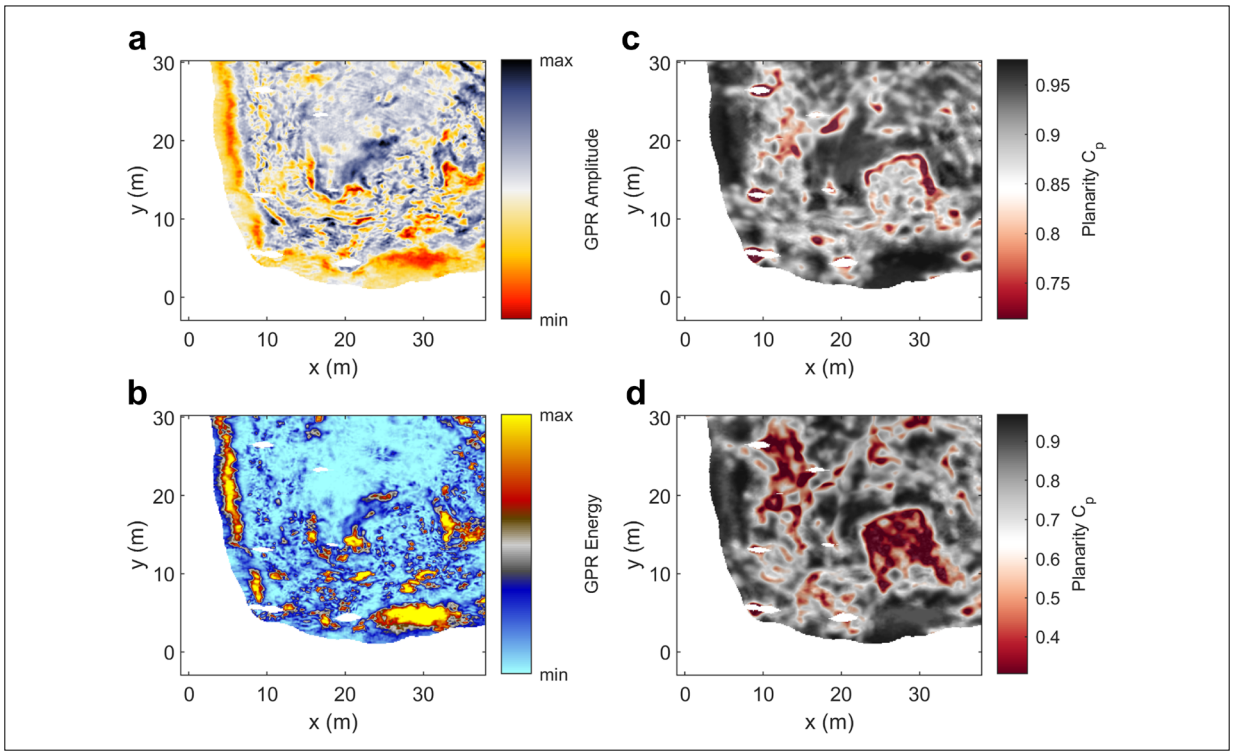

Fig 2: Example *x*-*y* slices at a depth of approximately 3 m of a) GPR amplitude, b) GPR energy, c) GST-based planarity calculated across GPR amplitude, and d) GST-based planarity calculated across GPR energy.

Conclusion

Analyzing GPR attributes aids the interpretation of the underlying datasets. However, calculating and selecting an appropriate set of attributes can be a cumbersome procedure. We apply the 3D gradient structure tensor (GST), a time-efficient, flexible, and comparatively objective tool that runs with only a few (target-specific) parameters. Additionally, applying the GST strategy delivers a selection of attributes to outline diverse structures in the underlying 3D datasets. Here, by calculating the planarity attribute based on the GST across a GPR amplitude and a GPR energy volume, we show that GST-based analysis is a useful means to detect and highlight a grotto and remains of an associated teahouse in the ancient Palace Garden in Paretz, Brandenburg (Germany).

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Structure aware noise reduction of multi-channel ground penetrating radar data using Principal Component Analysis

Neil Linford[1*]

1 Geophysics Team, Historic England, Portsmouth, Hampshire, United Kingdom
* Corresponding author: E-mail: neil.linford@historicengland.org.uk

Abstract
Multi-channel ground penetrating radar (GPR) may contain interference and decoupling noise. Principal Components Analysis (PCA) is applied to adjacent GPR data channels to reduce noise. Structure aware image fusion only replaces areas of isolated noise.

Keywords
ground penetrating radar; noise reduction; Principal Component Analysis; structure aware image fusion

Introduction

Ground penetrating radar (GPR) data can be adversely influenced by sources of radio frequency (RF) noise or when a ground coupled antenna loses coupling with the ground surface. This can be a particular issue for multi-channel antenna when acquiring data over uneven ground surfaces where, due to the ~2 m width of the array, it may become levered off the ground as it passes over surface irregularities. The noise is often most prominent in the outer channels of the array as these are more likely to be lifted away from ground surface and may also have reduced shielding from RF noise compared to the inboard antenna elements. While this may be largely cosmetic, suppressing the influence of this noise within densely sampled data sets can improve both the presentation and interpretation of time slices derived from the data.

Principal Components Analysis (PCA) has been demonstrated to be effective for the suppression of pixels attributed to noise when no correlation occurs between adjacent GPR time slices created from a single channel data set (Linford 2004). Multi-channel data provides a greater cross-line sample density allowing PCA analysis for noise suppression between both adjacent vertical profiles across the array and horizontal slices through the swath. The greater sample density allows for a more confident identification of random noise and will not, necessarily, be influenced by the positioning errors or the vertical integration of the data into aggregated 'thick' time slices. In addition, structure aware image fusion (Li et al. 2018) between the original and PCA noise suppressed data has been applied to preserve areas of detail where no excessive noise has been identified.

Methods

Data was collected with a 3d-Radar (Kontur) MkIV GeoScope Continuous Wave Step Frequency (CWSF) GPR system with a 20 channel DXG1820 vehicle-towed, ground-coupled antenna array at a 0.075 m by 0.075 m sample interval. PCA analysis is performed between adjacent profiles from the individual channels across the array, replacing the central profile with the maximum correlation profile defined by the highest eigen-value (Gonzalez and Wintz 1987, pp. 122-125). This should preserve the greatest degree of correlation between the adjacent profiles and, hopefully, suppress random noise present only in a single channel.

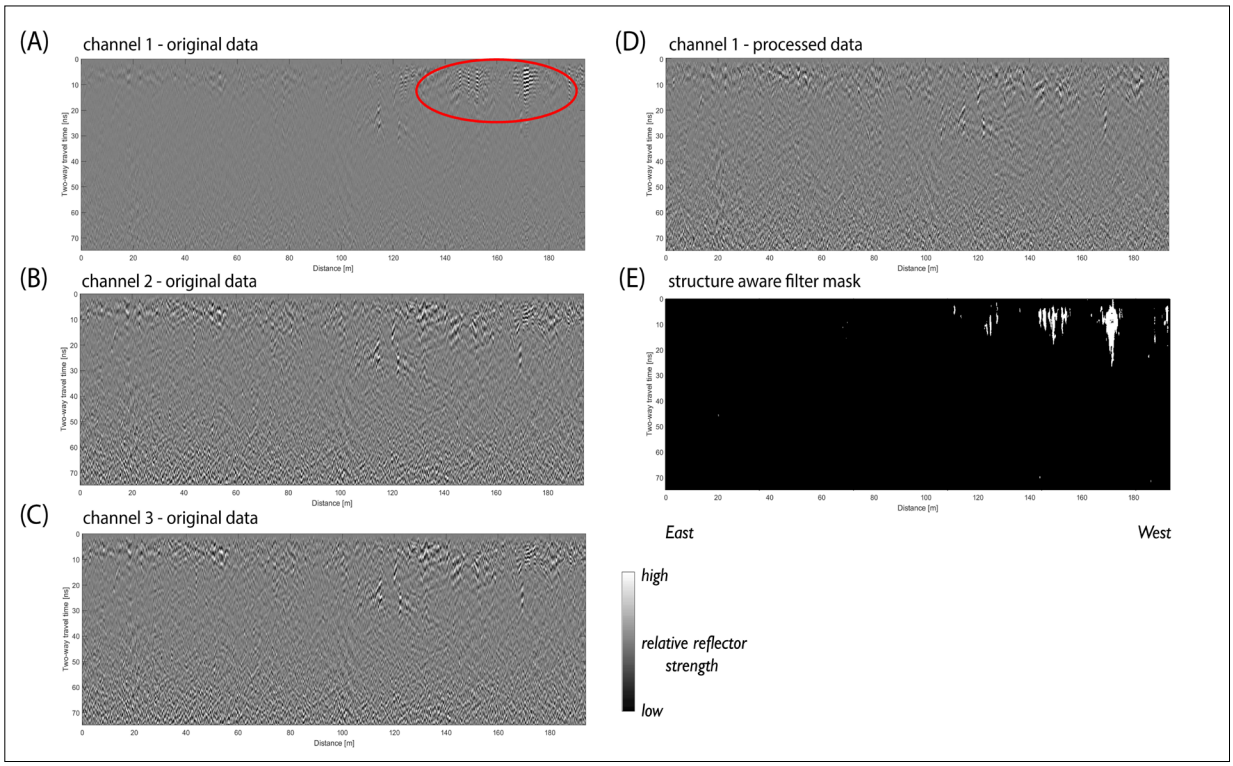

Fig. 1: GPR profiles from the first three adjacent channels from an array based antenna (A), (B) and (C). The outer most channel 1 shown in (A) contains acquisition noise due to the uneven nature of the ground surface between approximately 120 m to 180 m (red circle). The noise in channel 1 has been successfully suppressed through the application of PCA analysis performed between adjacent channels (D) in regions identified by a structure aware image fusion mask (E).

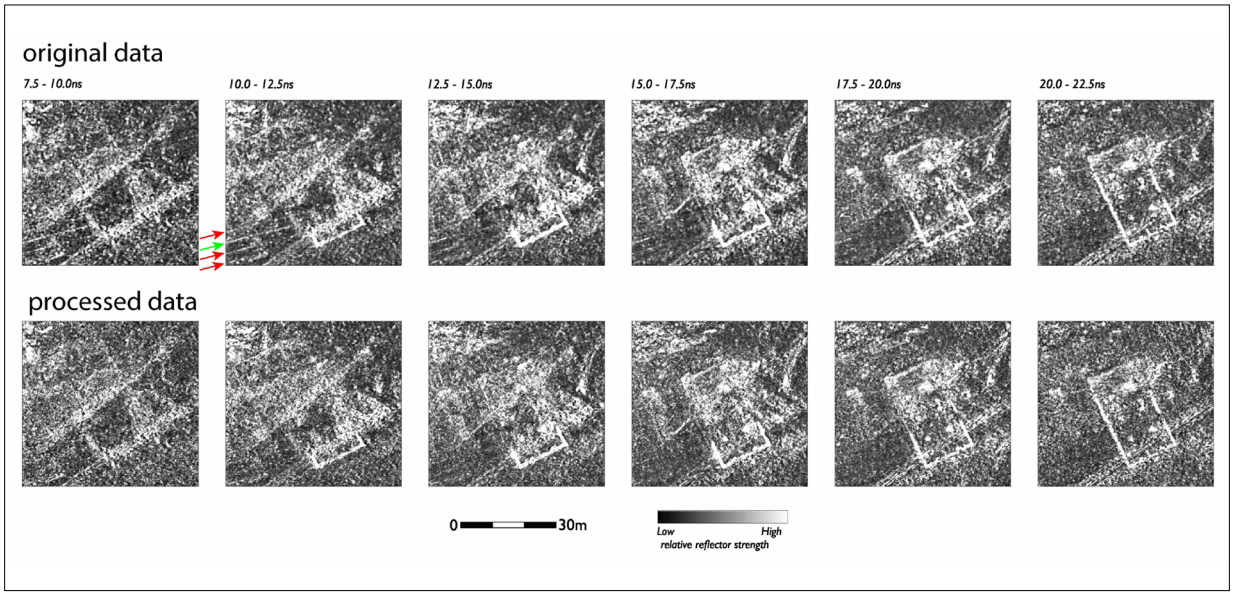

Fig. 2: Extracted amplitude time slices from the GPR survey at Sibton Abbey, Suffolk. The upper row shows the original data containing the profiles shown in Figure 1 (green arrow) together with adjacent instrument swaths showing measurement noise in the outer channel (red arrows). The lower row shows processed data where the measurement noise has been suppressed.

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Data from the central profile and maximum correlation profile are subsequently combined using a structure aware image fusion algorithm (Li et al. 2018). This method has been modified to recover small-scale details of the maximum correlation profile in the neighborhood of large-scale noise structures of the input profile, only applying image fusion to the areas affected by noise. A structure-preserving filter is determined by a 2D convolution of the input profile with an edge detecting structural element h = [1,-1] in both a horizontal and vertical orientation. Subtracting a convolved input profile containing noise from the convolved maximum correlation profile of adjacent channels creates a mask to isolate the image fusion to the localized noise degraded areas (Fig. 1, (E)).

Results

Figure 1 shows the GPR profiles from the first 3 channels from a multi-channel array where the first channel contains isolated noise (Fig. 1, (A), (B) and (C)), between approximately 120 m and 180 m, due to the uneven nature of the site terrain. The area of high-amplitude noise has been isolated by the structure preserving filter (Fig. 1, (E)) allowing the noise to be successfully suppressed following image fusion with the PCA maximum correlation profile (Fig. 1, (D)). In this case the noise occurred in a number of adjacent instrument swaths and is visible as distracting linear artefacts in time slices created from the data (Fig. 2). Processing all of the instrument swaths with the method described above has successfully suppressed the linear artefacts within the time slices with minimal adverse impact on more significant anomalies.

Conclusion

The application of PCA based analysis can be successfully used to suppress isolated noise through the analysis of both adjacent GPR profiles and horizontal time slices. This works particularly well with multi-channel array based GPR antennas where the sample density within each instrument swath allows for the successful suppression of noise in the outer most channels. Structure aware image fusion helps preserve original data in the profile where it appears that no noise has been detected.

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Love your polygons: powerful processing of vectorised geophysics data

Armin Schmidt [1*]

1 Dr Armin Schmidt - GeodataWIZ, Remagen, Germany
* Corresponding author: E-mail: A.Schmidt@GeodataWIZ.com

Abstract
By converting raster data to vectors several spatial attributes become readily available. For non-gridded data the vectorisation can happen after creating a raster, from a Triangulated Irregular Network (TIN) , or directly from the xyz data using an efficient spatial index. Classification, clustering and envelop creation is simple from vectorised data. Examples of aggregation and analysis of results are provided using different data sources.

Keywords
anomaly; classification; data envelope; processing; vector

Introduction

While most processing algorithms for archaeological geophysics data rely on raster representations it was shown that the use of vectorised forms opens up new avenues for spatial processing and classification through powerful vector manipulation and filtering engines (Schmidt and Tsetskhladze 2012, 2013; Schmidt 2016, 2019; Schmidt et al. 2019). The popular vector processing database PostGIS, for example, uses the OpenGIS Consortium (OGC) compatible GEOS library and the examples provided in this contribution refer to this specific implementation. The main advantage of vector-based methods is the immediate and fast availability of spatial characteristics for data areas (e.g. size, shape, elongation) and their mutual spatial relationships. The availability of powerful Machine Learning/ Deep Learning (ML/DL) algorithms (Verdonck 2019; Küçükdemirci and Sarris 2022) has made some of these spatial classification schemes available to raster data (Sevara et al. 2016; Cornett and Ernenwein 2020). It hence seems timely to provide an overview of the different processing tasks that can be undertaken with vectorised data.

Overview

Vectorisation

To convert archaeological geophysical data into a vectorised form there are three main approaches available: (a) a data raster can be created first (either by combining individual data grids or by interpolation) from which vectors are then derived; (b) an intermediate Triangulated Irregular Network (TIN) is calculated; or (c) a spatial database is used with a spatial index that allows for very fast filtering to support the creation of vector representations. The latter two methods are well suited for data that were collected irregularly and tagged with their individual GPS/GNSS location, requiring interpolation if a raster representation were used.

The simplest vectorisation is the creation of polygons that enclose data points above a threshold value (e.g. based on a statistical analysis, using ST_Reclass and ST_Polygon (Schmidt and Tsetskhladze 2013)). For ground penetrating radar (GPR) data with strong contrast it was found that the resulting polygons only depended weakly on the exact choice of such a threshold.

In another approach the range of data values is represented by contour polygons, which can be created with various algorithms (ST_Contour or gdal_contour from the Geospatial Data Abstraction Library (GDAL)). Most contouring algorithms create contour lines and if their start and end points coincide they can easily be closed to form polygons.

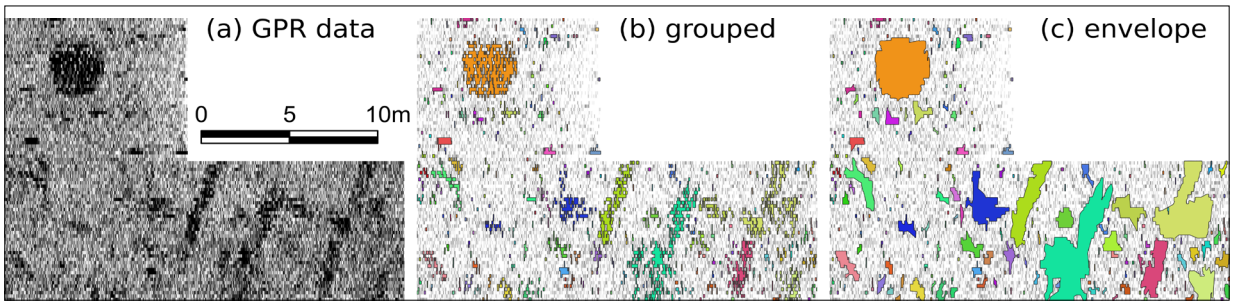

Fig. 1: GPR data from the Dutch Fort in Jaffna, Sri Lanka. (a) GPR data, strong reflections are black; (b) extracted anomalies grouped based on spatial vicinity; (c) envelopes of concave hulls around the grouped anomalies.

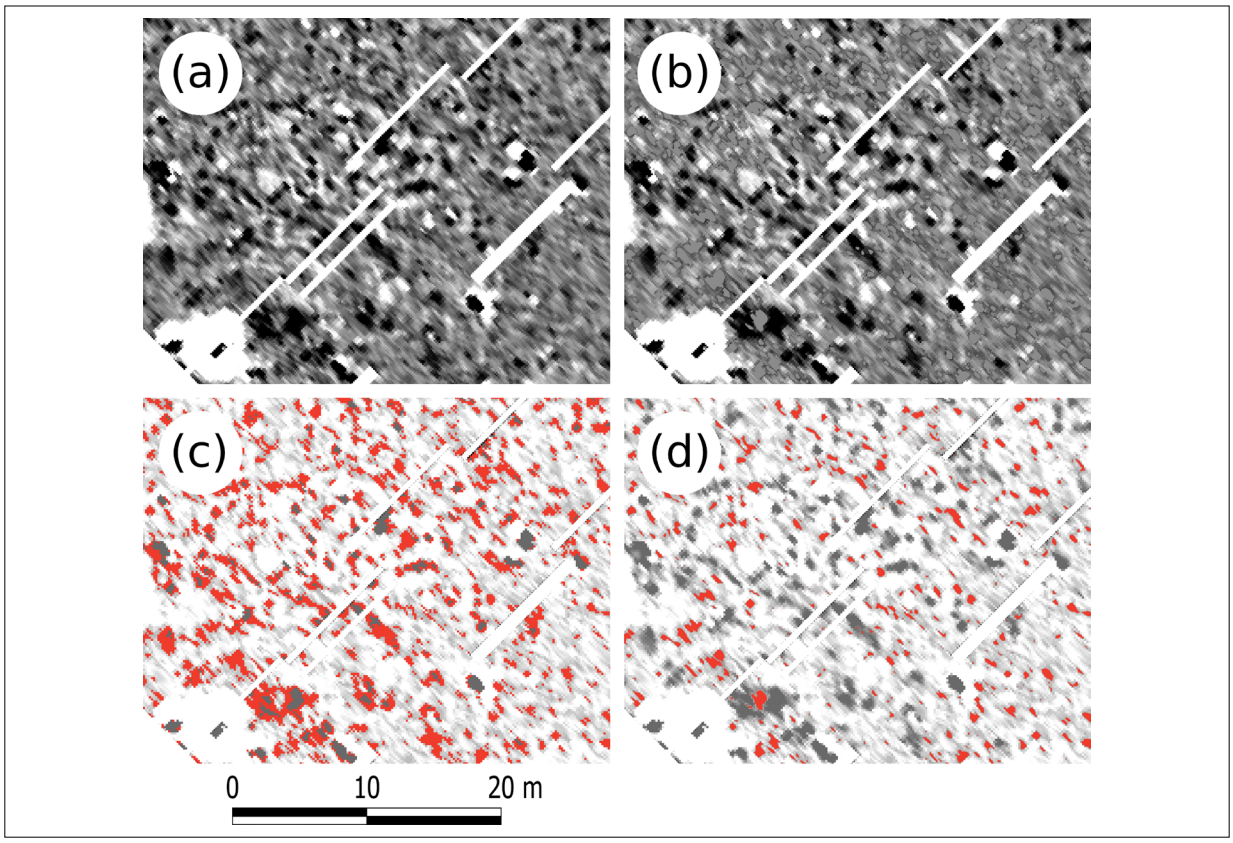

Fig. 2: Magnetometer data from the Iron Age enclosure in Eisenach, Rhineland-Palatinate, Germany. (a) magnetometer data with a greyscale range of -2.5 to +3.0 nT, white to black; (b) data with those anomalies masked that had a maximum between 1 and 3 nT; (c) all raster cells marked in red that have a data range between 1 and 3 nT; (d) only anomalies marked in red whose maximum is between 1 and 3 nT.

Aggregation

Especially in GPR time slices that were created from single-channel surveys, buried features sometimes manifest as disjoint small anomalies. While a human interpreter may be able to join them together, this is more difficult for computer-based classification schemes (Sevara et al. 2016). Using threshold derived polygons for all individual parts of such a 'dispersed anomaly' it is possible for vector processing engines to create automatically combined anomalies based on spatial attributes of the constituent parts (Schmidt and Tsetskhladze 2013). For example, anomalies with a very small extent can first be discarded and then all remaining anomalies that are a certain distance apart are combined into a single larger anomaly (Fig. 1).

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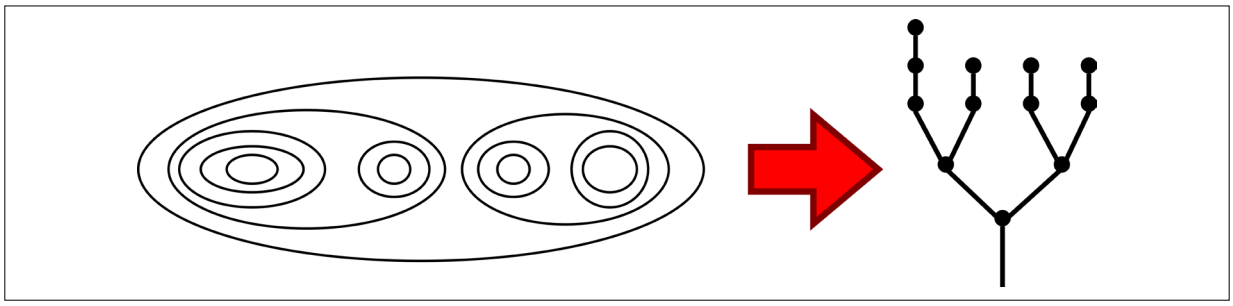

Fig. 3: The topological nesting structure of contour lines (left) can be represented by a tree structure (right).

Analysis

A useful method for the analysis and subsequent interpretation of magnetometer data is the identification of those anomalies that have a certain range of magnitudes, for example from 1-3 nT. A magnetometer survey inside an Iron Age enclosure ('Keltenschanze'), located in a wooded area in Germany, showed many small-size and small-value anomalies, which obliterated the majority of the site (Fig. 2a). They were due to ferrous remnants of shooting exercises after the end of the Second World War. Masking these small anomalies allowed a far easier evaluation of the site overall (Fig. 2b). This task cannot be accomplished easily with raster data alone, as masking a middle-range of data also affects anomalies from stronger features (Fig. 2c). If instead a topological classification of data-contours is undertaken it is possible to relate each contour to the maximum value of its anomaly and then select only those that belong to chosen range (Fig. 2d). Hinterleitner et al. (2019) achieved similar results with a raster method that descended from each raster peak to its base.

A topological tree structure can be built to represent how data-contours nest inside each other (Fig. 3) and by traversing this tree the minimum/maximum of each anomaly can easily be found.

This method was used to identify the contours that represents the magnetic anomalies' "full width at half maximum" (FWHM), which are reasonable proxies for the shape of buried features that are causing these anomalies (Schmidt 2019).

Using such classifications of anomalies it is also possible to identify positive and negative peaks that are within a given proximity to each other and that may jointly be the result of a bipolar anomaly. The data can subsequently be investigated further by fitting analytical bipole models to them (Norton and Witten 1998; Hinterleitner et al. 2019).

Conclusion

Vectorised geophysics data provide natively a variety of spatial attributes that would be far more difficult to derive from raster data. There are hence several vector-based classification schemes that allow for advanced analysis and visualisation of geophysics data using deterministic processing that can be engineered in accordance with the specific characteristics of the geophysical data types (e.g. magnetometer, GPR). The computing power provided by free vector processing engines like PostGIS makes such processing available to many researchers and practitioners, and the examples provided show what can be achieved with this approach.

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3DMCD/1DLCI inversion of an FD-EMI dataset: the case study of the paleolandscape of Bourbourg/Loon-Plage (France)

François-Xavier Simon[1,2*], **Benjamin Fores**[1], **Guillaume Hulin**[1,3], **Laurent Deschodt**[1,4], **Julien Guillemoteau**[5]

1 Inrap, Paris, France
2 Chrono-Environment UMR6249, Besançon, France
3 Metis UMR 7619, Paris, France
4 LGP, Laboratoire de Géographie Physique: Environnements Quaternaires et Actuels UMR 8591 CNRS, Meudon, France
5 Institute of Geosciences, University of Potsdam, Potsdam, Germany
*Corresponding author: E-mail: francois-xavier.simon@inrap.fr

Abstract
An electromagnetic survey supports the archaeological field evaluation. Data calibration with electric sounding is necessary before inversion. The 1D LCI inversion is accurate enough if the horizontal variation is smooth. The 3D MCD inversion considerably reduces lateral effects. To date, the 3D/pseudo-3D is not required in the field evaluation phase.

Keywords
conductivity; development-led archaeology; electromagnetic low-frequency; inversion; paleolandscape

Introduction

Since 2015, when the first geophysical survey was carried out on the Port of Dunkirk extension land planning project, more than 600 ha have been surveyed. The aim of this work was to support the conventional methods of investigation used in France: trial trenching with mechanical shovels. Here, loop-loop frequency domain electromagnetic induction (FD-EMI) surveying is used as a complementary tool to map sedimentary deposit variations at the scale of the construction scheme (Deschodt et al. 2021).

Initially, these FD-EMI prospections were carried out using a single-receiver instrument (Geonics EM31), in vertical co-planar (VCP) mode. This first campaign showed that the contrast of electrical conductivity between the fairly sandy surrounding soil and the filling of the paleochannels and old drainage ditches, can be well detected by the FD-EMI method. From 2019 onwards and in order to specify the nature of these variations, we decided to use a three-receiver instrument (GF Instruments CMD Explorer) that allows measurements at three different depths. In order to increase the depth of investigation, the configuration was switched to a horizontal co-planar (HCP) mode. The results were just as convincing but small-scale anomalies inversions related to the complexity of the response of the HCP configuration were observed on channels 2 and 3. Preliminary inversion tests showed very convincing results. This is why we decided in 2021 to continue this research and to carry out measurements with a six-receivers instrument (GF Instruments CMD6L) in preparation for both 1D and 3D inversion experiments. Beyond the inherent technical difficulties of EMI instruments (e.g., their calibration), a discussion has been initiated on the interest of a 3D characterization of the geomorphological shape of the soils and their impact on the land analysis by the archaeological teams.



Fig. 1: View of the acquisition system (GF Instruments CMD6L).

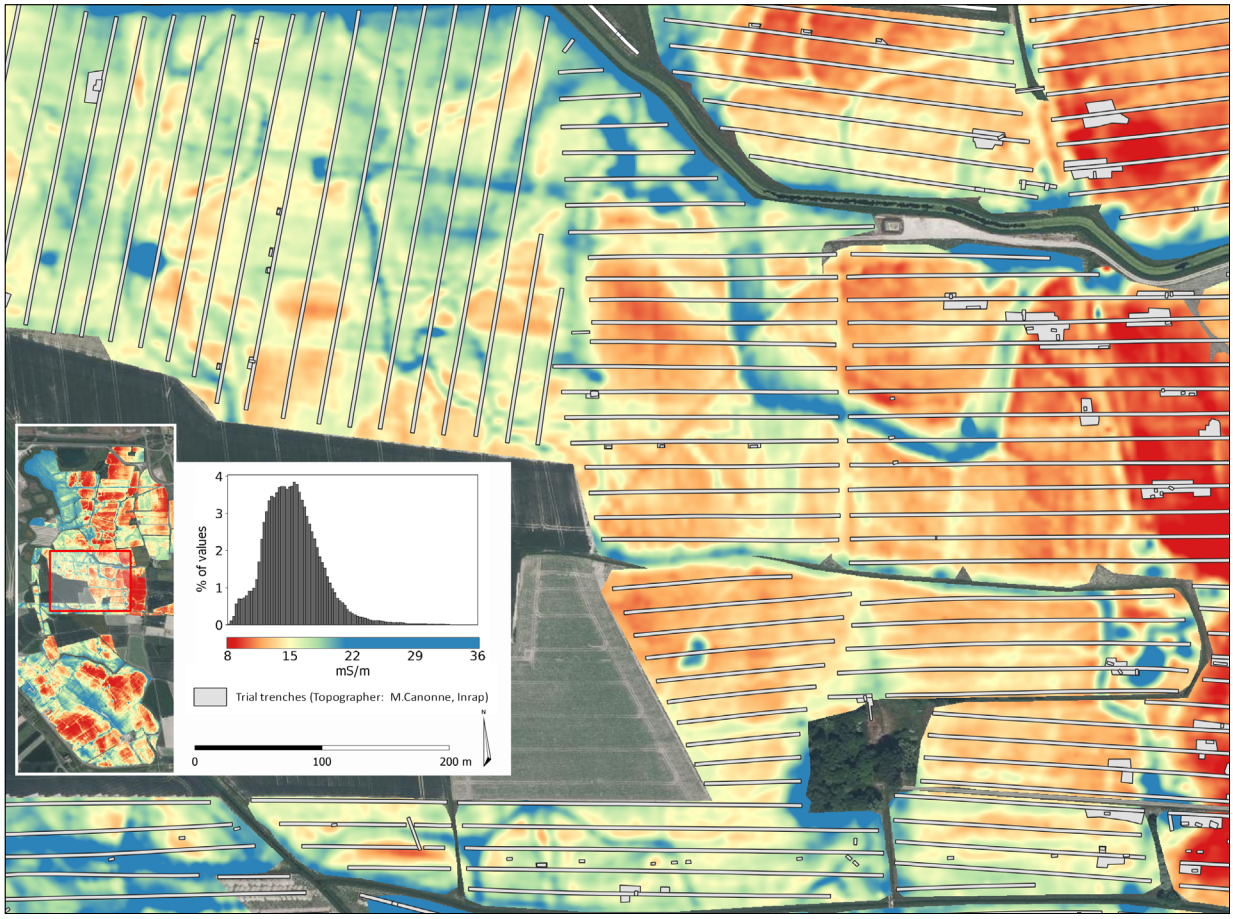

Fig. 2: Map of the apparent electrical conductivity (CMD6L, coil spacing = 1.05 m, HCP configuration) (background: ortho-photography IGN©).

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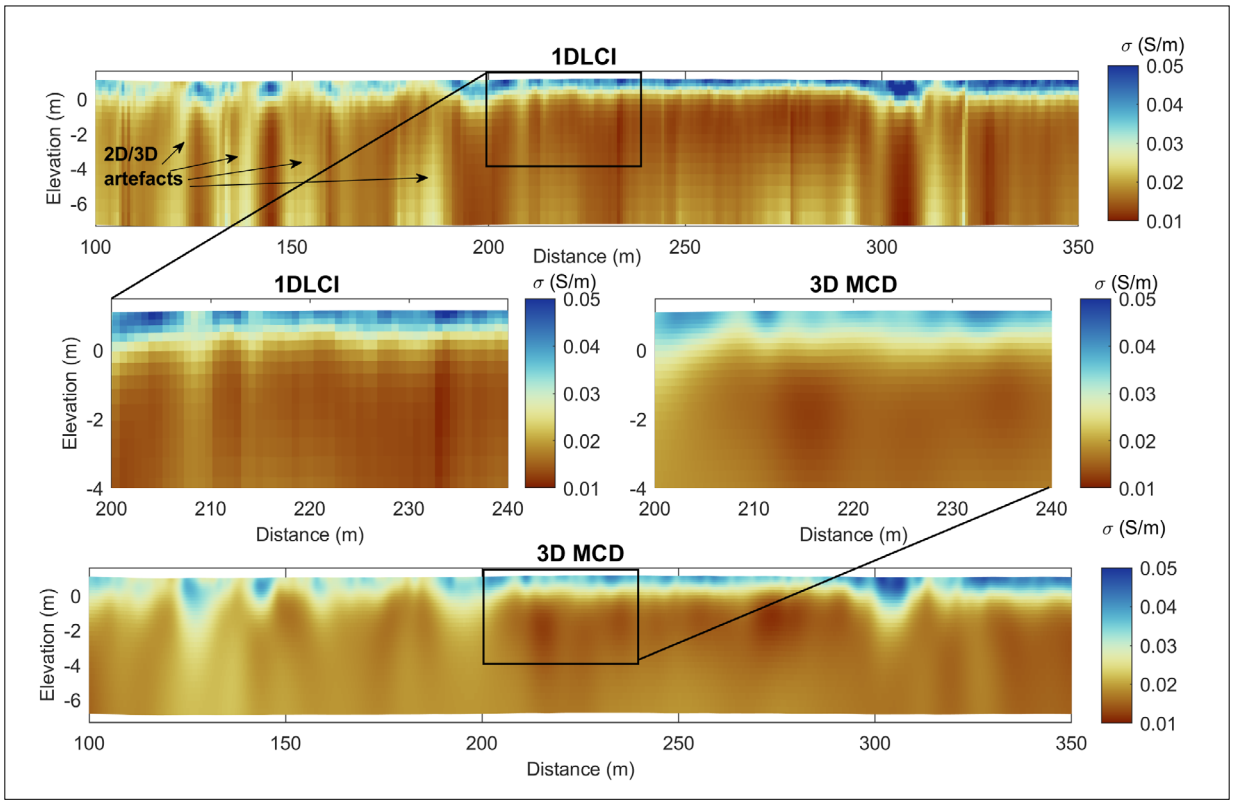

Fig. 3: Results of both inversion algorithms.

Materials and methods

The survey was carried out with the CMD Explorer 6L (GF Instruments). It includes a transmitting coil that emits an electromagnetic field at a frequency of 10 kHz and 6 receiving coils. These coils are separated by 0.6, 1.05, 1.6, 2.45, 3.30 and 4.23 m. The device was mounted on a sledge providing acquisition at a constant height of less than 30 cm above ground. The system was pulled with a 4x4 vehicle located at a distance of 6 m ahead (Fig. 1).

In order to carry out the calibration of the data, several vertical electrical soundings were repeated over the whole area of the project with the Lippmann 4 Point Light. These electrical soundings were inverted with Ipi2Win and the response of the CMD6L was modelled for each sounding point for comparison and calibration.

We then inverted a selected high-resolution dataset using two types of inversion: the non-linear 1D laterally constrained inversion (1D LCI) described in Klose et al. (2022), and the linear 3D inversion based on the multi-channel deconvolution (3D MCD) method (Guillemoteau et al. 2016; Guillemoteau et al. 2017; Guillemoteau et al. 2019).

Results

The results of both 1D LCI and 3D MCD inversion techniques can be used to determine the depth and shape of the detected features. They also allow archaeologists to visualize geophysical properties in vertical slices of soil rather than horizontal maps of apparent electrical conductivities, which, by definition, show less contrasted anomalies. Furthermore, in case of small-scale lateral variations (i.e., at the order of the coil distance), apparent conductivity anomalies have complex shapes due to 2D/3D effects and are difficult to interpret (e.g., three-peaks anomalies typically observed for the HCP configuration) (Fig. 2). By definition, the 1D or 3D inversion are able to correct the first effect or both effects, respectively and reconstruct a more realistic spatial distribution of the electrical conductivity (Fig. 3).

Discussion

This dataset allowed us to assess the contribution of such an approach for the study on Dunkirk port extension proj-

ect. The distortions linked to the shape of the anomalies are largely reduced thus the geomorphologist is able to predict the layout of the paleochannels at different depths. However, the latter information is partly redundant with his work. In order to clearly define and characterize the geomorphological features and sedimentary deposit process, direct inspection is essential. Despite inversion, the uncertainties on the depth estimation based on geophysical data remain significant and cannot be substituted for direct observation. Apparent conductivity maps would be sufficient to identify areas of interest for geomorphological test pits. However, once integrated with archaeological and geomorphological observations, the inversion provides a laterally continuous information, which can link the coarser grid of test-pit points.

Conclusion

After a proper calibration (e.g., based on few VES soundings), the loop-loop FD-EMI data collected by a CMD6L instrument can be inverted to reconstruct the true spatial distribution of subsurface conductivity within the first 5-6 m of the subsurface with a sub-meter lateral resolution. This inversion process reduces interpretation errors among archaeologists and geomorphologists and realistically characterizes conductivity variations of the soil.

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Multi-scale analysis and interpretation of multi-method geophysical data sets

Jens Tronicke [1*], **Erika Lück** [1]

1 Institute of Geosciences, University of Potsdam, Potsdam, Germany
* Corresponding author: E-mail: jens@geo.uni-potsdam.de

Abstract
Redundant wavelet transform is proposed to analyze multi-method databases. Multi-scale analyses are used to separate target features from noise and background. As a main result, we generate composite images optimized for complementary information.

Keywords
archaeological prospection; composite imaging; multi-method approaches; multi-scale analysis; wavelet transform

Introduction

In archaeological prospection, the benefit of multi-method geophysical exploration strategies is well known. The basic idea of collecting multiple geophysical datasets across the same field site is to sense different medium properties and, thus, to collect complementary information. To ease the analysis and interpretation of such multi-method databases different approaches have been proposed (e.g., Kvamme et al. 2019). One popular group of approaches relies on integrated visualizations using transparent overlays and color blending. Here, the individual datasets are typically pre-processed to suppress random and acquisition-related noise. Furthermore, we have to consider the resolution capabilities of the involved methods which depend on subsurface parameter contrasts, target depths, and sensor configurations. Thus, a typical multi-method database comprises datasets showing anomalies at multiple spatial scales with different noise, sensitivity, and resolution characteristics. To analyze such a database and to generate optimized composite images, we present a multi-scale approach based on a redundant wavelet transform. After briefly discussing the methodological basics, we present a case study where we use the proposed strategy to analyze magnetic, electromagnetic (EM), and topographic data in an integrated fashion.

Materials and methods

Our approach relies on a redundant wavelet transform (RWT) which allows for an undecimated multi-scale decomposition of a dataset. Using a series of low-pass filters, the selected RWT iteratively decomposes a given data set a0 into n wavelet planes w_j (j = 1, …, n) and an approximation an (Starck et al. 2015). Such redundant transforms (i.e., the size of all wj is equal to the size of a_0) are preferred in applications aiming at reconstructing an image. For example, for filtering we reconstruct a filtered dataset using selected w_j to highlight features at specific spatial scales (similar to a wavenumber-domain filtering). Following Tronicke et al. (2020), we may also use scaled and normalized w_j to balance the contributions of selected planes in the reconstruction (similar to spectral balancing approaches).

Here, we use the RWT to analyze magnetic and EM data collected in 2012 across a well-known Neolithic ring ditch system (Lück and Eisenreich 1999) using a cesium gradiometer and an EM38 device, respectively. Both datasets were kinematically recorded with an in- and cross-line point spacing of ~0.1 m and ~0.5 m, respectively, using an auto-tracking total-station for positioning. This also resulted in a digital terrain model (DTM) of the surveyed area. Figure 1 illustrates our raw database after interpolation to a grid with a regular node spacing of 0.2 m. We used the RWT to decompose our datasets up to n = 8 scale levels

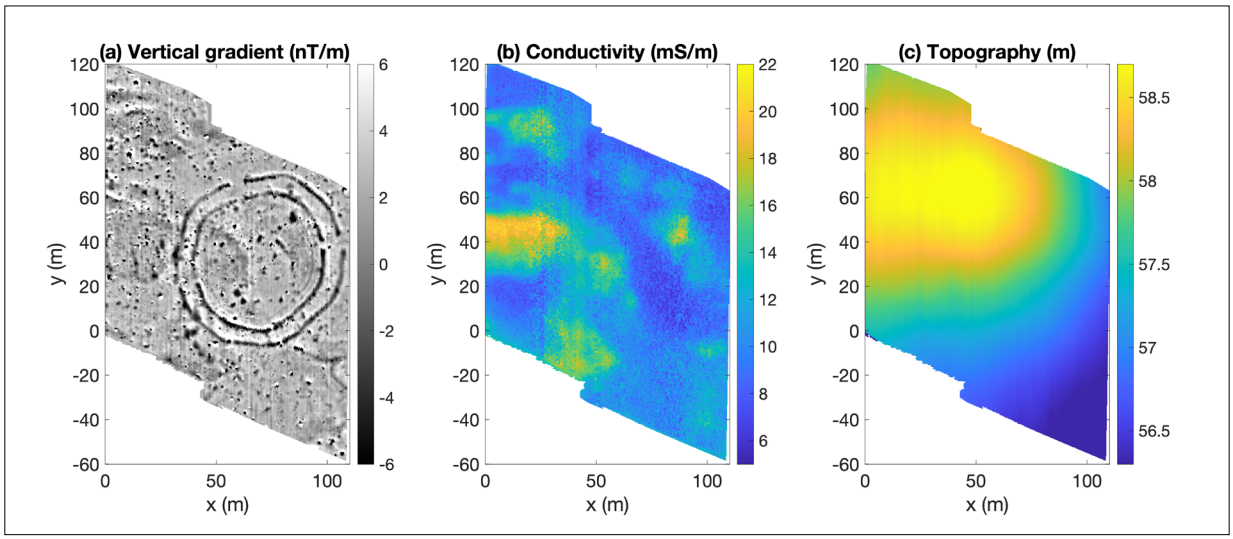

Fig. 1: Raw datasets consisting of a) vertical magnetic gradient, b) electrical conductivity, and c) DTM.

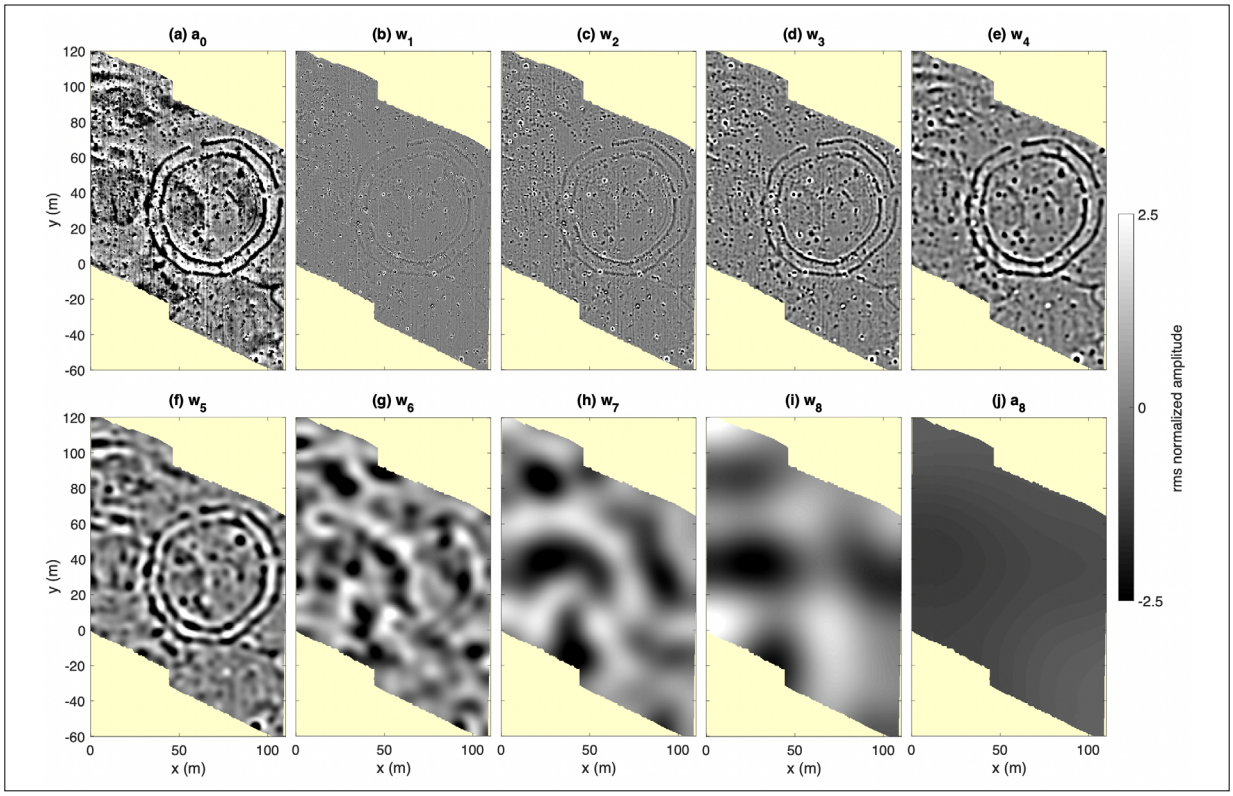

Fig. 2: Result of decomposing the magnetic dataset (Fig. 1) up to $n = 8$ scale levels. a) Input data a_0, b-i) the resulting wavelet planes w_1 to w_8, and j) the final approximation a_8.

for a scale-dependent analysis of noise and anomaly features. We also quantified similarities by calculating pairwise correlations coefficients r between the normalized images at all scales. Finally, the (dis-)similarities between the images were interpreted in terms of archaeological relevance to identify complementary information in our database and to create optimized composite images using selected scaled wavelet planes.

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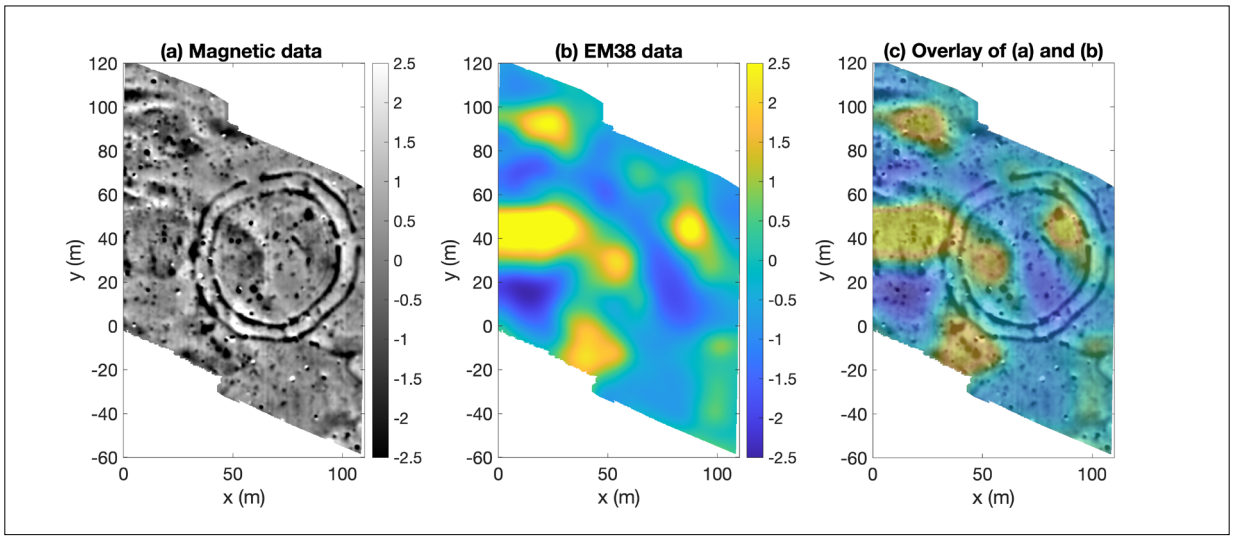

Fig. 3: a) Magnetic image reconstructed using wavelet planes w_3 to w_6, b) EM image reconstructed using wavelet planes w_6 to w_8, and c) composite image of a) and b).

Results and discussion

In Figure 2, we present the decomposition of our magnetic data. For balancing, all images are normalized by their individual root-mean-square (rms) amplitudes. Comparing these images illustrates that w_1 and w_2 are dominated by isolated and stripy patterns (interpreted as noise), while w_3 to w_6 show pronounced circular structures (interpreted as the Neolithic ditch system) and further curvilinear features (with potential archaeological relevance). Furthermore, w_7, w_8, and a_8 show anomalies with lateral extensions of >20 m (interpreted as geological background). To analyze these observations in more detail, we compare Figure 2 to our EM and topographic data (Fig. 1) including RWT-based decompositions of these datasets (not shown here) and calculate r between all datasets. These analyses demonstrate that our magnetic data are independent of topography ($r < 0.35$ for w_1 to w_8), while we observe some links between EM and topography ($r > 0.5$ for w_5 to w_8). At lower scales, where we expect archaeologically relevant structures, magnetic and EM data are uncorrelated ($r < 0.3$ up to w_6), while at higher scales, reflecting the geological background, we observe negative correlations ($r < -0.6$ for w_7 and w_8). Considering these observations, we generate denoised composite images optimized with respect to the complementary information. Figure 3a) shows a magnetic image reconstructed using the rms-normalized planes w_3 to w_6 (Fig. 2) to highlight archaeological structures, while Figure 3b) is reconstructed with the rms-normalized planes w_6 to w_8 from our EM data to characterize background structures. Because these images are not correlated ($r = -0.14$), the overlay image (Fig. 3c) represents an optimized starting point for further, more detailed interpretations.

Conclusion

Multi-method geophysical surveying is increasingly used in archaeological prospection. Typically, the gathered datasets show noise and anomalies at multiple spatial scales and are characterized by different resolutions and sensitivities. The proposed RWT-based strategy addresses these characteristics and, using a case study, we have shown that our approach results in composite images optimized in view of complementary information and, thus, detailed interpretations. Because our approach is computationally efficient and needs no parameter tuning, the presented strategy represents an efficient multi-scale approach for analyzing different combinations of geophysical datasets.

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Hyperbola detection with Retinanet: application to new sites and scalability

Tina Wunderlich [1,2*], **Annika Fediuk** [1], **Bente Sven Majchczack** [1,3], **Clemens Mohr** [1,3], **Natalie Pickartz** [4], **Dennis Wilken** [1,2]

1 Institute of Geosciences, Kiel University, Kiel, Germany
2 Collaborative Research Center 1266, Kiel University, Kiel, Germany
3 Cluster of Excellence ROOTS, Kiel University, Kiel, Germany
4 State Office for Cultural Heritage Baden-Württemberg, Ludwigsburg, Germany
* Corresponding author: E-mail: tina.wunderlich@ifg.uni-kiel.de

Abstract
The application of Retinanet to new datasets detected about half of the hyperbola present. Combining the detections from images with different aspect ratios results in better performance. The aspect ratio of the images is a crucial factor for detection.

Keywords
automatization; deep learning; diffraction hyperbola; GPR

Introduction

Machine learning methods became widely used in the last decades in geophysical applications and also in the context of ground penetrating radar (GPR) to automatically detect pipes and rebar or tree roots based on automatic hyperbola picking (e.g. Gamba & Lossani 2000; Shaw et al. 2005; Lei et al. 2019; Liu et al. 2021). From the hyperbolas' shape one can derive the velocity of the electromagnetic waves in the overlying material, which is needed for exact depth determination. Moreover, mapping all hyperbolas on a measured area can result in a map of small objects. In an archaeological context this might provide spatial information on e.g. settlement activity. Manual detection of all hyperbola in a dataset is time-consuming, especially for datasets from multichannel GPR systems containing radargrams up to thousands of kilometers length. In order to automatically detect hyperbolas in radargrams an artificial neural network, Retinanet (Lin et al. 2017a; Lin et al. 2017b), was trained on images from a dataset collected on the island of Föhr, Germany (Wunderlich et al. 2022). After training was completed the network achieved an average precision of 0.58 on data from the same site that was excluded from training. As we only tested data from the same site it was unclear how the network would perform on other data from (a) other sites and (b) collected with other GPR equipment/antenna.

Thus, our main aims of this paper are (1) to check if there is an influence of different aspect ratios of the input images on the detection result, (2) to apply the detection on data from new sites and see how it performs, and (3) to compare the detection results of data from different antenna and GPR systems.

Materials and methods

GPR data collection and processing

The data from Föhr (the training set) was collected with a Mala MIRA 16 channel system with 400 MHz antenna. Further information on processing these data can be found in Wunderlich et al. (2022). The other data in this paper were measured with GSSI systems and 200 and 400 MHz antennas. Processing was done with MultichannelGPR (Wunderlich 2021).

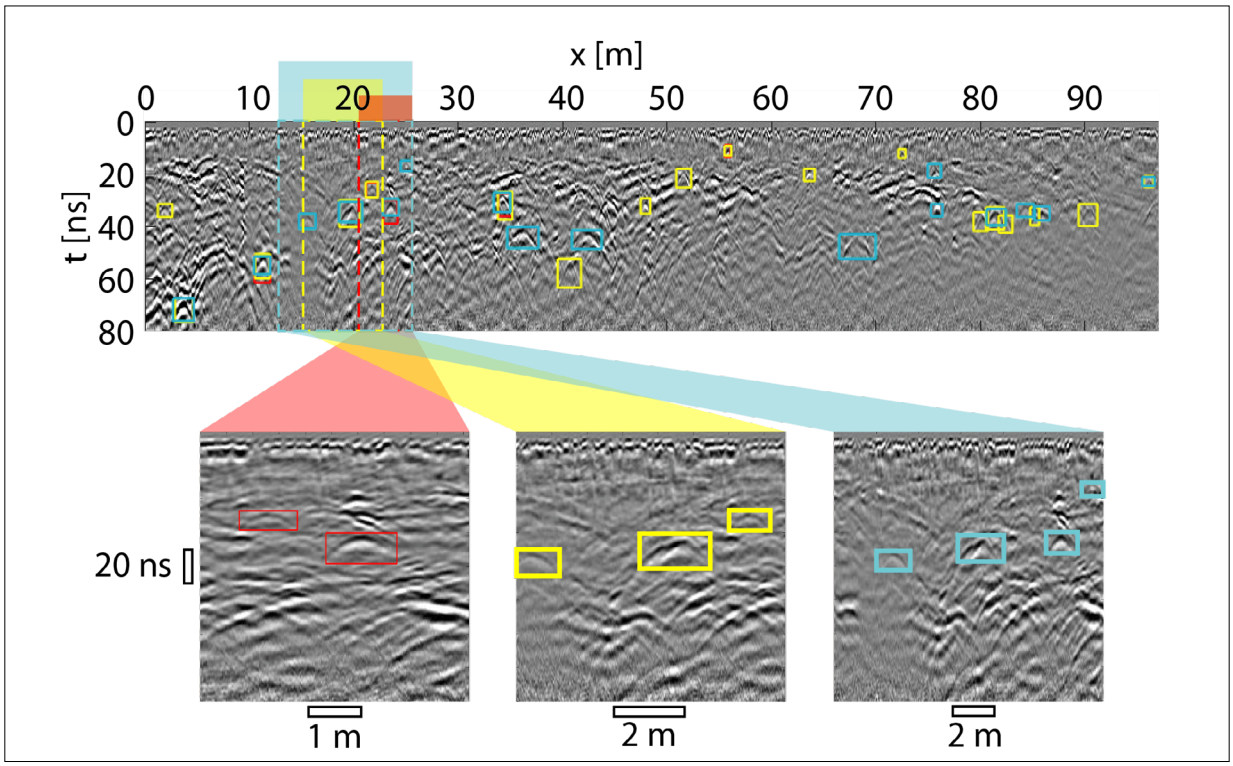

Fig. 1: Example radargram from Föhr with detection results of images with different trace spacings and thus aspect ratios: trace spacing 0.02 m (red), 0.03 m (yellow) and 0.05 m (cyan). The bottom row shows parts of the large radargram that were input images for the network with different aspect ratios.

Hyperbola detection with Retinanet

An existing architecture of Retinanet (Henon 2021) was used with a pretrained ResNet50 as backbone (He et al. 2016). Details can be found in Wunderlich et al. (2022).

Results

The original input images from Föhr for training and testing of our Retinanet had an aspect ratio of 256 * 0.03 m / 80 ns = 0.096 m/ns (with 256 being the number of traces per image and a trace spacing of 0.03m with a time range of 80 ns). Figure 1 shows the detection results on an example radargram for different trace spacings and thus different aspect ratios. The radargram was cut into smaller images of 256 traces using different trace spacings. The different trace spacings were achieved by linear interpolation between the original traces with 0.03 m spacing. This results in different lengths of the images and thus different apparent widths of hyperbola. The original images with 0.03 m trace spacing result in 16 detected hyperbolas in this radargram (Fig. 1, yellow boxes). Decreasing the trace spacing to 0.02 m also decreases the number of detection to 5 (red boxes). An increase of the trace spacing to 0.05 m has the same number of detections (cyan boxes) as for 0.03 m (16), but partly different ones. Thus, combining the detection results of trace spacing 0.03 and 0.05 m results in 27 hyperbolas.

The detection results for the Föhr dataset that was also partly used for training are satisfactory. But what happens for a completely new dataset? For a first test a dataset containing 58 profiles from another archaeological site was chosen, which was measured with a GSSI 200 MHz antenna. The subsurface structure is mainly peat and underneath sand with some timber structures inside the peat layer, which are the origin of the hyperbolas. To take different aspect ratios into account, the trace spacing was varied systematically from 0.01 m to 0.1 m and all images were input into Retinanet. In total 355 hyperbolas are present in all profiles (counted manually = ground truth). For the smallest trace spacing of 0.01 m only one hyperbola was detected (Fig. 2a). Increasing the trace spacing and thus the aspect ratio (Fig. 2b) results in more detections, with a maximum for 0.04 m trace spacing (109 hyperbolas).

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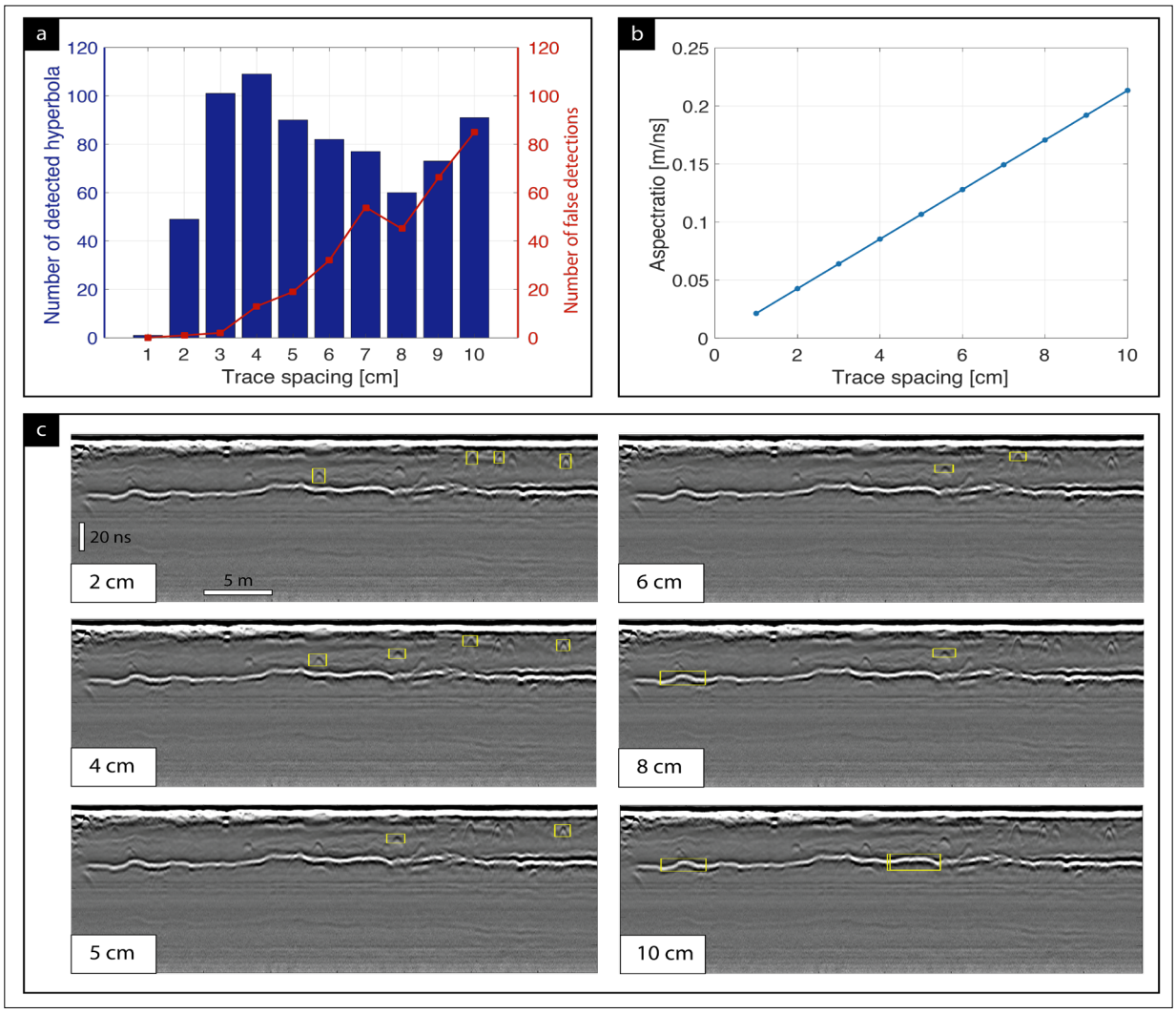

Fig. 2: Application of Retinanet for hyperbola detection on a new dataset from an archaeological site: a) The number of detected hyperbola for different trace spacings together with the number of false detections. b) Aspect ratio versus trace spacing. c) Example radargram and detection results for different trace spacings for the images.

For trace spacings 0.02, 0.04 and 0.05 m the number of detections is similar, but partly different hyperbolas are detected (Fig. 2c), which could be used for increasing the total number of detections when combining both results. For larger trace spacing the number of false detection increases rapidly. This in mainly due to slight curves in the interface reflection that bend upward and are appearing as hyperbolas when the images are compressed horizontally.

For application to other data we did not change the aspect ratio anymore, but chose a ratio similar to the one for the Föhr dataset. For the archaeological dataset measured with a 200 MHz antenna in Figure 3a) the detection resulted in only two hyperbolas. Some hyperbolas in the middle part of the profile with strong chaotic reflections are not detected. In the urban dataset in Figure 3b) again only two pipes are detected and other hyperbolic structures are missed. A special case is the dataset measured from the water surface on a pond with a 400 MHz antenna (Fig. 3c). While most of the image is relatively quiet, two stronger layered reflections are visible and two types of hyperbola: (1) narrow hyperbola in the water (branches and probably fish) and in the bottom of the pond, and (2) very wide hyperbola with long tails revealing a velocity of 30 cm/ns. The latter are caused by trees around the pond and rays travelling trough air. The isolated hyperbola of type 1 are all detected, whereas some below the pond bottom are missed. The wide hyperbola of type 2 are not detected.

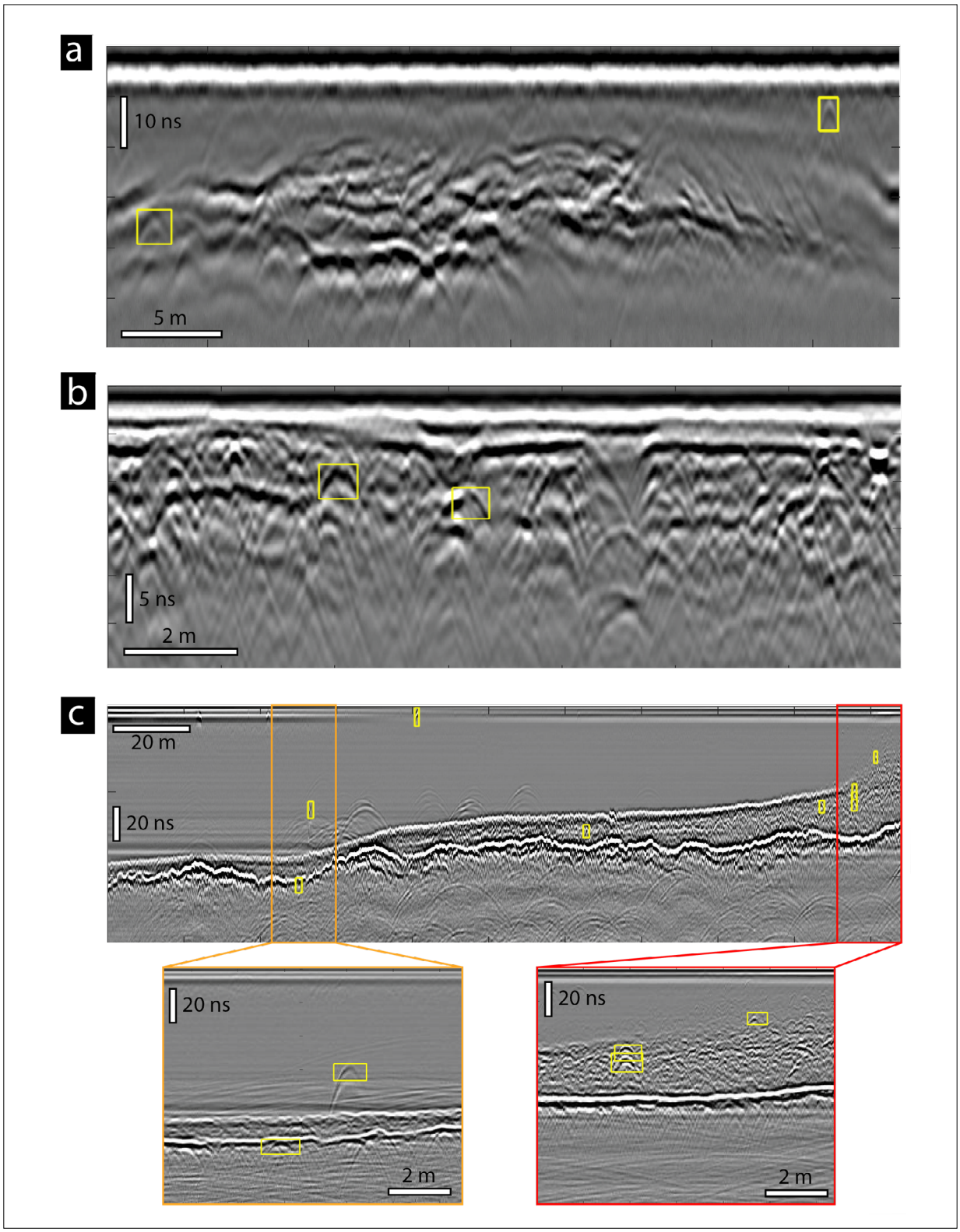

Fig. 3: Hyperbola detection on different example radargrams from new sites and with different equipment: a) Archaeological site, measured with GSSI 200 MHz antenna. b) Urban site, measured with GSSI 400 MHz antenna. c) Pond, measured from the water surface with a GSSI 400 MHz antenna.

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Discussion and conclusion

The success or failure of the hyperbola detection on new data can be seen in different ways depending on the aim: (1) If one wants to have an overview on all (!) hyperbola present in a dataset for e.g. inferring clusters of objects or counting of subsurface features, the detection performance definitely needs to be increased. (2) If one wants to get a quick automatic look on some hyperbolas and also derive the propagation velocity from them automatically to get a rough velocity model of the site, the detection capability is probably sufficient.

For further training of the network with new data care has to be taken to choose the best aspect ratio. A test should be conducted if it is helpful to include images with many different aspect ratios or to better train the network for one specific aspect ratio. The aspect ratio of new datasets can easily be adjusted by changing the trace spacing with respect to the time range.

With respect to the following automatic velocity determination it is helpful that very wide hyperbola originating from rays travelling through air and being reflected at objects above the surface, are not detected by the Retinanet as it is now.

For new datasets it is helpful to test different aspect ratios of the images in order to detect the 'correct' hyperbola. If the trace spacing gets too large, and thus the aspect ratio too, also slightly curved reflections are 'seen' as hyperbola. As hyperbola in different depths and with different velocities have different widths, it might be also good to infer hyperbolas from images with different aspect ratios and then combine the detection results in order to receive the best performance.

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