One World Archaeology

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World Archaeo-Geophysics

Integrated minimally invasive approaches using country-based examples

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This book is dedicated to the memory of our colleagues Oliver O'Grady (22.05.2020) and Stanislav (Stas) Ţerna (29.12.2020). Gone too soon.

Preface

Welcome to the pages of *World Archaeo-Geophysics*, a volume that illustrates the fascinating intersections of geophysics and archaeology across five continents. Our book offers a unique lens into the evolution of geophysics' role in archaeological research and cultural heritage management. Hailing from 18 diverse countries, our contributors have united their knowledge and experiences to craft an exceptional collection of overviews spanning 24 different countries.

This book stands out as it unites 74 experts from around the world to explore the significance and development of archaeo-geophysical applications. The focus of this evolutionary journey is on near-surface (and ground-based) geophysical methods, and it is dissected from multiple perspectives. This comprehensive examination includes their potential when integrated with complementary methods, with a specific emphasis on the combination of geophysics with soil analyses. Notably, this book is the fruit of collaborative efforts by members of the European Cooperation in Science and Technology (COST) Action SAGA 'The Soil Science and Archaeo-Geophysics Alliance: Going Beyond Prospection' (Cuenca-Garcia et al., 2018), and their extended network.

While this book certainly presents successful experiences, it also critically examines common pitfalls and challenges that have delayed the adoption of these methods in some countries. It provides a glimpse into regions where the applications and use of archaeo-geophysics exhibit significant variations, influenced by unique material cultures. These diverse outcomes underscore the importance and diversity of geophysical applications in archaeology, extending beyond the mere confirmation of the presence or absence of buried remains and contributing to knowledge, practices, and advancements in digital applications.

From the early surveys in France and the USA during the 1930s to the cutting-edge technological advancements shaping our present, archaeo-geophysics has emerged as a pivotal force in uncovering, investigating, and digitally documenting buried archaeological remains (Fig. 1). Central to its significance is the capability of diverse geophysical methods to unveil these remains in a non-intrusive manner since the investigations of sites is conducted above the earth's surface and no

Fig. 1 Evolution of (ground-based) geophysical instrumentation, taking ground-penetrating radar (GPR) systems as an example. From left to right: (1) One of the first GPR surveys in archaeology carried out at the Bronze Age site of Dromolaxia-Vyzakia, near Hala Sultan Tekke mosque in Larnaca, Cyprus (Courtesy Peter M. Fischer, University of Gothenburg, Sweden); (2) First Finnish archaeological GPR survey using a multi-channel system at Iron Age sites of the Karjaa Lepinjärvi area (Courtesy Arne A. Stamnes, NTNU, Norway); (3) First autonomous archaeo-geophysical survey at the Viking age burial site of Rygg in Frosta, Trøndelag, Norway

excavation is strictly necessary. These methods have evolved to meet the distinctive needs of archaeological inquiries, offering faster field efficiency, heightened resolution, and increasingly refined interpretation capabilities. Overall, this has developed a novel perspective on the exploration of archaeological sites and landscapes as illustrated in the chapters in this book.

Yet, the utilisation of archaeo-geophysics, whether in research or cultural heritage management, varies widely across different nations. Acknowledging this global diversity in experiences is a crucial exercise—one that paves the way for wider integration in countries with less exposure and fosters collaborative efforts towards a shared agenda of progress. To reflect on these varied experiences, a dedicated session was organised as part of the World Archaeological Conference in Prague (WAC-9) by members of the COST Action SAGA. It was during this event that the concept of creating this book first took shape.

This book offers a comprehensive exploration of the application of archaeo-geophysics on a global scale. It delves into its historical progression, current status, and promising future prospects. As we continue to advance technologically, leveraging cutting-edge geophysical instruments, and methodologically, through the synergistic integration of complementary approaches like remote sensing and soil analyses, our understanding of the human past has reached unprecedented depths. This holistic approach prioritises non-destructive methodologies, ensuring the safeguarding of the archaeological record for generations to come and paving the way for novel scientific breakthroughs.

The first chapter by Lowe and Moffat (2023) describes how, despite an initial slow uptake, there has been a positive shift in the use of geophysics in Australian archaeology. They discuss the various factors that have driven this change, such as an increase in equipment availability, training efforts, and very importantly, the Indigenous community involvement. Studies highlight how the complex nature of the continent's geology for detecting burial sites makes interpretation challenging.

Verhegge et al. (2023) define how geophysical survey techniques have become increasingly significant in Belgian archaeology since the 1970s, with a particular rise in their use in Flanders over the past decade. Local expertise development in ground-penetrating radar (GPR) and electromagnetic induction (EMI) has contributed to this growth. However, Brussels and Wallonia are slower in adopting geophysical techniques, with invasive methods still prevalent. While integrated geophysical surveys are widely used in academic research, in development-led archaeology, geophysical survey adoption remains limited and often depends on individual decisions.

The chapter by Jordanova et al. (2023) moves from the consideration of near surface geophysical survey and provides an overview that explores the combined use of archaeomagnetic and environmental magnetic research in Bulgaria, showcasing its application in archaeology. Case studies illustrate how magnetic properties of iron oxides in fired archaeological materials provide valuable insights into various aspects, including paleoenvironmental conditions and technology-related aspects. The advanced archaeomagnetic database for Bulgaria supports accurate dating and synchronisation of archaeological sites.

Through numerous case studies, Wenke and Bangbing (2023) provide an historical perspective of how geophysical survey methods have played a crucial role in identifying and mapping archaeological features and site changes in China, with a history dating back to the 1950s during the survey for the Mausoleum of Emperor Wanli of the Ming Dynasty. These methods are now routinely employed in a wide range of archaeological contexts in China, including ancient city sites, tombs, urban remains, and underwater archaeology. However, visual inspections through excavation and drilling cores remain common due to a lack of awareness among traditional field archaeologists.

The chapter by Vella et al. (2023) discusses various geophysical methods, including remote sensing and soil analyses of cores used for mapping archaeological sites, reconstructing the archaeo-environment and assessing the risk to sites and monuments in Cyprus. They draw attention to the sporadic use of these methods in landscape archaeology and cultural heritage management. The chapter highlights the variable success of these techniques, influenced by the island's geological diversity and distinctive characteristics, such as metamorphic formations and iron-rich soils.

The chapter about Scandinavia (Stamnes et al., 2023) offers a comprehensive overview of the use of near-surface geophysical methods across Finland, Sweden, Norway, Denmark, and Iceland. It assesses the current status, role, and acceptance of these techniques in each of these countries. The chapter considers academic, curatorial, and commercial aspects of geophysics and discusses the reasons behind varying levels of acceptance and integration of these methods in each nation. It emphasises the need for sharing knowledge and experiences across Scandinavia and highlights the discrepancy in practical experience, application, and general acceptance of geophysical methods among the different countries. The case studies presented illustrate various archaeological applications of geophysics in the region and emphasise the importance of recognising these methods as neither "new" nor "untested".

Herbich (2023) underscores the crucial role of geophysical methods, especially magnetometry, in Egyptian archaeological research. Over the past 30 years, these methods have been employed at approximately 150–180 archaeological sites, often followed by excavations, offering valuable opportunities for method validation. The primary objective of surveys in Egypt is the identification and characterisation of settlements, production areas, and cemeteries to understand site development and plan research excavations, rather than heritage management. He argues that the success of magnetometry is attributed to the magnetic properties of the Nile River's mud, the key material for sun-dried bricks, a fundamental building material in the Nile Valley. Other methods have yielded less convincing results, but GPR is gaining importance, especially for desert sites and areas with low iron oxide content in the soil.

Parker et al. (2023) focus on the development of commercial archaeo-geophysics in England. It describes the long history of the use of these methods, dating back to over 75 years. For the past 30 years, it has been integral to developer-funded archaeology, and there are likely hundreds of active archaeo-geophysicists in the country, making it one of the world's largest communities. While standards and guidance support the profession, staying up-to-date with evolving technology and methods remains a challenge. The profession seeks to balance cost-effective field data acquisition with increasing the depth of information gained from investigations.

France has a rich history in archaeo-geophysics, as Thiesson et al. (2023) extensively detail. Their chapter deepens into the multifaceted landscape of practices in France, showcasing concrete examples of geophysical surveys across rural and urban settings, as well as other contexts. The authors recognise that preventive archaeology represents a significant portion of the surveys carried out in France. Furthermore, they underscore the potential for archaeology to catalyse advancements in geosciences. This potential lies in the collaborative efforts that transcend traditional boundaries between scientific disciplines, spanning geology, soil science, geotechnics, geochemistry, and geophysics. This interdisciplinary synergy serves to refine and elevate geophysical techniques, propelling the field forward. The authors specifically spotlight the ongoing development of geochemistry in archaeo-geophysics, including the adoption of x-ray fluorescence (XRF) analysers. In doing so, they discuss the challenges and potential of this approach.

In the Near East, as observed by Fassbinder et al. (2023), the role of pedogenic enrichment of magnetic minerals in the topsoil in magnetic prospecting on archaeological sites seems to differ from regions in Europe. The authors describe their findings conducting magnetometers surveys and complementary soil/rock magnetic analyses at sites located in wetland and marsh areas of southern Iraq and certain mountain regions of Kurdistan. In southern Iraq, the research points to the significance of induced magnetisation and variations in mudstone composition as prominent factors influencing magnetic anomalies. In contrast, their case study in Iraqi Kurdistan highlights the predominant impact of natural remanent magnetisation originating from rocks.

Bonsall (2023) addresses the underappreciated role of soil studies in archaeological prospection strategies in Ireland. The author highlights the challenges posed by archaeological prospection, particularly in a landscape dominated by carboniferous limestones, tills, and peats. He argues that soil studies can significantly improve archaeological interpretations. The chapter features six case studies that showcase how soil studies can be effectively integrated into archaeological prospection.

The chapter by Blancas et al. (2023) illustrates their long tradition of archaeological investigations combining geophysical and soil analysis in Mexico since 1983. To illustrate this, their chapter highlights key case studies and their achievements towards an enhanced interpretation and understanding of archaeological sites.

Băț et al. (2023) discuss the increasing significance of geophysical investigations in Moldova, with a notable focus on magnetometer surveys since the early 2000s, revealing significant insights into Neo-Eneolithic, Iron Age, Roman Imperial, and mediaeval sites. They describe how these surveys have provided valuable insights into settlement organisation, archaeological structures, and the complexities of Getic fortifications' defensive systems. Furthermore, the authors highlight the growing collaboration between archaeologists and soil scientists, particularly in determining element concentrations within archaeological deposits. The authors express optimism regarding the expanding utilisation of soil analysis and geophysical techniques among Moldovan archaeologists, signalling a promising future for minimally invasive research in the region.

In their chapter, Jrad et al. (2023) offer insights into the development of archaeo-geophysical surveys in Tunisia and Morocco. While these practices took root in the 1970s, they have seen increased adoption in recent decades, primarily within ancient and mediaeval contexts. Despite this progress, the authors stress the importance of further promoting geophysical methods as an integral part of archaeological fieldwork, particularly in the context of rescue archaeology.

Asăndulesei et al. (2023) discuss the significant role of geophysical surveys and soil analyses in assessing, re-evaluating, and documenting buried archaeological heritage in Romania. They provide an overview of the research background, highlighting key moments in promoting these methods in Romanian archaeology. Then, they focus on the Cetățuie site, a well-known prehistoric archaeological site in Romania associated with the Cucuteni Culture. Despite extensive past research, recent magnetometer surveys and soil investigations have uncovered previously unknown aspects about the site's extent and function, suggesting a much larger and more complex settlement than previously believed. This discovery has opened the door for further research into this significant archaeological site in the context of the European Chalcolithic period.

The chapter by Jones (2023) provides a review of geophysics in Scottish archaeology. It covers the scope of surveys, targets investigated, techniques used, and the individuals involved in conducting and commissioning surveys. Case studies from various locations, including mainland Scotland, Orkney, and the Isle of Lewis, are utilised to exemplify methodological and interpretative challenges. One case study highlights the challenges posed by poor magnetic and earth resistance responses when dealing with ditch and pit features, primarily due to drift geology and soil conditions. Efforts to explain these responses in terms of soil properties are discussed, leading to a recommendation for increased collaboration between archaeo-geophysics and geoarchaeology, given their areas of study often intersect more than commonly acknowledged. Another recommendation emphasised by the author is the need for better dissemination of graphical survey outputs and access to raw data. This would encourage a more critical evaluation of how interpretations of individual geophysical responses are made, promoting transparency and advancing the field of archaeo-geophysics.

Drahor and Berge (2023) discuss the historical development of archaeo-geophysics in Turkey since the early surveys in the 1960s. They emphasise the importance of considering soil variations and the complexity of interpreting geophysical results, especially in the context of ancient earthquakes. Despite the crucial role of geophysical survey methods in Turkish archaeology, they stress the need for enhanced integration with soil prospecting, which is currently limited. The authors also anticipate that the growing interest in archaeo-geophysics from universities, the private sector, and the public sector will stimulate sectoral growth and foster scientific development.

The final chapter focuses on Ukrainian archaeo-geophysics, as presented by Bondar et al. (2023). It offers a compelling case study that exemplifies their growing collection of case studies, showcasing how geophysics becomes a vital tool for detecting some of their distinctive monuments, known as kurgans (burial mounds) and other Bronze and Early Iron Age settlements. The work involved integrated geophysical surveys, which include magnetometry, electrical resistivity tomography (ERT), and GPR, conducted on sites in the Dnieper River floodplain under the threat of mining development. Their findings not only confirmed the presence of nine sites but also unveiled later remains. Moreover, they categorise three specific geophysical responses linked to kurgan presence. Additionally, the chapter addresses methodological challenges tied to magnetic interference caused by enriched topsoil and ploughing, the limited applicability of GPR in sandy soils, and the efficacy of ERT in stratigraphical analysis for extensive kurgans.

Across different countries, we see a common thread of the need for protocol optimisation and broader knowledge dissemination in archaeo-geophysics, transcending the boundaries of practitioners. This emphasis is crucial for the further adoption and sustainable use of these methods in archaeological research and cultural heritage management. Collaboration and interdisciplinary efforts are recurring themes in many chapters and a major outcome of this field. The interaction between archaeo-geophysicists and other scientific disciplines, notably soil science and geochemistry in particular, is viewed as an area of interest with potential to contribute to better interpretation of data.

Additionally, several chapters highlight the need for greater funding for easing infrastructure constraints but also for fostering the development of training programmes aimed at nurturing the next generation of archaeo-geophysicists. One of the biggest issues seen globally is the lack of programmes offered for students and other interested communities to learn these applications.

In summary, the collective insights from these chapters illuminate the escalating significance of archaeo-geophysics. It emerges not only as a cost-effective and minimally invasive tool for archaeological prospection but also as a vital means of preserving and comprehending our buried cultural heritage. The future holds promise for the further development and integration of geophysical and other complementary methods into archaeological practices, provided that the challenges are addressed, awareness is raised, and interdisciplinary collaboration continues to thrive.

By reading all the above, readers should be aware that this book does not provide descriptions of each geophysical method. The constraints of this volume, coupled with the abundance of existing literature on the subject, precluded such an exhaustive treatment. Those in search of detailed methodological information are encouraged to explore the SAGA's database (https://www.saga-cost.eu/SAGA_DB/user-db.php). Within this database, readers can easily navigate to the 'Methods' section, offering comprehensive descriptions and an extensive repository of relevant bibliography accessible through the Zotero SAGA library. Moreover, the SAGA database includes a dedicated 'Instruments' section, thoughtfully connecting each method with the geophysical equipment available at various research institutions. This resource serves as a valuable asset to facilitate a deeper comprehension of the tools and technologies associated with each method. Overall, this is a tool that aims to facilitate exploration and collaboration within the field of archaeo-geophysics.

The work on this book commenced during the challenging period of the pandemic. The effects of this extraordinary time impacted our workload, leading to the realisation that some of the initially proposed chapters could not come to fruition. Nevertheless, we are confident that the contributions we have received from a diverse range of countries substantiate the book's title, inspired by the global audience of the World Archaeological Congress (WAC).

Our aspiration is that this book will stand as a valuable resource, catering to the needs of practitioners, curators, students, and educators worldwide who seek insights into the evolution of archaeo-geophysics. Moreover, we aim for this retrospective perspective to pique the interest of our colleagues, encouraging similar publications from countries not represented within these pages. It is our sincere hope that this book will not only shed light on the past but also illuminate the path for future endeavours in the field of archaeo-geophysics, fostering continued growth and global collaboration.

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About the Editors

Carmen Cuenca-García is a Distinguished Researcher (CIDEGENT) at the University of Valencia (UV) and holds a research affiliation with the Norwegian University of Science and Technology (NTNU). Her career in archaeology began at the UV (Spain, 1993–1998), followed by seven years dedicated to rescue archaeology in Spain and the UK. Her commitment to geophysical prospection began with an MSc from Bradford University (England, 2007–2008), followed by a PhD from the University of Glasgow (Scotland, 2009–2013). Her professional pathway has been marked by research and consultancy positions in Greece (FORTH-IMS, Rethymno-Crete, 2013–2015), Austria (Comprehensive Nuclear-Test-Ban Treaty Organization-CTBTO, Vienna, 2015–2016), and Norway (NTNU, Trondheim, 2017–2023). Her interdisciplinary research, spanning archaeology, applied geophysics, and geosciences, underscores the critical role of geophysical methods in archaeology and heritage management. She specialises in using geophysical techniques for the non-invasive discovery, mapping, and characterisation of archaeological sites and paleo-environments. A particular focus of her work has been on the development of field methods, incorporating soil/deposits characterisation into archaeo-geophysical investigations to yield more detailed interpretations. Her extensive fieldwork encompasses a variety of archaeological sites from different eras across Scotland, Greece, Cyprus, Spain, Norway, and Estonia, contributing to the development of a rich portfolio of scientific publications, reports, and dissemination materials. Dr. Cuenca-García has successfully led several projects won through national and international competitive calls, notably coordinating the COST Action SAGA. Actively engaged in the academic and research community, she serves on scientific panels and conference committees, performs reviews and editorial work for international journals, and dedicates herself to teaching and mentoring.

Andrei Asăndulesei is a Senior Researcher/Archaeologist at the Institute of Interdisciplinary Research (ICI) with expertise in the area of prehistoric archaeology. His main responsibilities include non-invasive geophysical prospection, aerial photography, LiDAR/TLS interpretation, and GIS applications in archaeology. He is closely interested in the analysis of the ancient human settling patters and internal spatial organisations of settlements in order to better understand the interdependence relation between communities and the environment. He has received several scholarships abroad, as part of international multi-institutional research teams from Germany, Austria, France, and Australia, in which he had the possibility to conduct non-invasive field surveys in Kurdistan, Iraq, Azerbaijan, Georgia, Caucasus, Russia, Germany, and the R. Moldova. As project manager, he has coordinated two national grants: "Non-destructive approaches to complex archaeological sites. An integrated applied research model for cultural heritage management (2014–2017)" and "Settling Selection Patterns and Settlement Layout Development in the Chalcolithic Cucuteni Culture of Northeastern Romania (2020–2022)". His contributions are reflected in articles, studies, books and book chapters, participation and organisation of conferences, etc.

Kelsey M. Lowe is a Principal Heritage Consultant/Archaeologist in Brisbane, Australia. She is also affiliated as an Honorary Research Fellow at the University of Queensland. Dr. Lowe is recognised internationally as a leader in the fields of cultural heritage management (CHM), archaeology, archaeological geophysics, and geographic information systems (GIS) and is one of Australia's foremost archaeological geophysicist subject matter experts. She has over 30 journal publications on her research, 50 technical reports, and has presented her work nationally and internationally at conferences (+55) or guest lectures (39) throughout her career. She has also worked with several First Nations people in Australia, specifically using science (geophysical technologies) and oral histories to understand cultural significant events of the past as part of heritage management. Outside Australia, Dr Lowe has been involved in several international projects in Africa, the Caribbean, Europe, Indonesia, North and South America, Papua New Guinea, and Southeast Asia. She was also appointed as a Scientific Recovery Expert (2018–2022) for identifying World War II plane crash sites for the US Defence (POW/MIS) Accounting Agency in Papua New Guinea.

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Abbreviations

AD	Anno Domini
ALS	Airborne Laser Scanning (or LiDAR)
ARM	Anhysteretic Remanent Magnetisation
ARVI	Atmospheric Resistance Vegetation Index
BC	Before Christ
BP	Before Present
CA17131	COST Action SAGA
CHM	Cultural Heritage Management
COST	European Cooperation in Science and Technology
DEM	Digital Elevation Model
EAC	European Archaeological Council
EBA	Early Bronze Age
EEA	European Environment Agency
EIA	Early Iron Age
EM	Electromagnetic
EMI	Electromagnetic Induction
ER	Earth Resistance
ERT	Electrical Resistivity Tomography
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
HIRM	Hard Isothermal Remanence
ICP	Inductively Coupled Plasma
IRM	Isothermal Remanent Magnetisation
ISAP	International Society for Archaeological Prospection
LiDAR	Light Detection and Ranging
MAG	Magnetometry
MBA	Middle Bronze Age
MS	Magnetic Susceptibility
NDVI	Normalised Difference Vegetation Index

NIR	Near-Infrared
OM	Organic Matter
OSL	Optically Stimulated Luminescence
OSR	Optimal Spatial Resolution
PPN	Pre-Pottery Neolithic
RES	Electrical Resistance Survey
RGB	Red, Green, and Blue
RTK	Real-Time Kinematic
SAGA	Soil Science and Archaeo-Geophysics Alliance
SP	Self-potential
SR	Simple Ratio
SRT	Seismic Refraction Tomography
STSM	Short-Term Scientific Mission
UAV	Unmanned Aerial Vehicle
UXO	Unexploded Ordnance
VES	Vertical Electrical Sounding
VLF	Very Low Frequency
XRF	X-ray Fluorescence

Part I
Australia

Has Anything Changed? The Current Role of Archaeo-geophysics in Australian Archaeological Research and Cultural Heritage Management

Kelsey M. Lowe and Ian Moffat

Abstract In 2012, *Australian Archaeology* published the paper entitled 'Review of Geophysical Applications in Australian Archaeology'. The goals of the article were to examine the history of archaeo-geophysics in Australian archaeological research and cultural heritage management (CHM) and consider what factors may have prevented these methods from being utilised in many archaeological investigations to date. It concluded that considerations such as cost, time, instrument availability and lack of theoretical knowledge contributed to the limited uptake of these techniques. This paper also offered suggestions on how geophysical applications were used internationally and whether there was potential for their more extensive use in Australian archaeology. Ten years have passed since this review. Since then, there has been a major increase in the uptake of geophysics in Australian archaeology and CHM. This paper discusses these changes and improvements, and what new opportunities have emerged since 2012. This includes a significant increase in the availability of training in archaeo-geophysics in Australian universities, a deeper engagement with Indigenous communities and the increased availability of equipment.

1 Introduction

The global development of archaeological prospection in Europe and North America has been documented in numerous publications (which are referenced in detail in this edited volume). The initial focus of archaeo-geophysics was primarily on locating material culture items over limited survey areas. Technological advances have allowed for faster data acquisition at the landscape-scale, making it useful for a

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wider range of research and cultural heritage management projects (Campana & Piro, 2009; Johnson, 2006). The discipline is now moving in a new direction, one that focuses on a more holistic understanding of archaeological sites which includes a consideration of landscape as well as archaeological features and their physical properties. This new approach demands a more nuanced approach to data interpretation and the development of a more rigorous understanding of the relationship between soil properties and geophysical measurements (Cuenca-Garcia et al., 2018). Geophysics is now universally recognised as a cost-effective way to examine the landscape's topographical, geological, and cultural characteristics. The standard geophysical methods commonly used in archaeological prospection are electrical resistance, electromagnetic conductivity, magnetometry, ground-penetrating radar (GPR) and magnetic susceptibility; all work as tools to map, locate and produce images of subsurface cultural and geological material (Clark, 1996; Gaffney & Gater, 2003; Johnson, 2006).

Despite the demonstrated potential of geophysical techniques to contribute to answering archaeological questions, the growth and development have been considerably slower in Australia than elsewhere. A detailed discussion of the history of geophysics in Australian archaeology has been provided by Lowe (2012) and the aim in this paper is to not present repeated information. Studies discussed therein demonstrated the effectiveness of geophysical methods in the Australian context and considered why these techniques have not been more widely adopted by the Australian archaeological community. In Australia, the most commonly used instruments are GPR and magnetic gradiometry due to their fast, practical nature in site mapping, their popularity with Indigenous communities and GPR's ability to map in three dimensions. The most common use of geophysical methods has historically been the location of unmarked graves, commonly in collaboration with community or Indigenous groups (Bladon et al., 2011; Brown et al., 2002; Kemp et al., 2014; Long & von Strokirch, 2003; Lowe et al., 2014; Marshallsay et al., 2012; Moffat et al., 2016, 2020a; Powell, 2010; Sutton & Conyers, 2013; Wallis et al., 2008).

In this paper, we consider how Australian archaeo-geophysics has changed over the last 10 years, highlighting a dramatic increase in the use of geophysical techniques and an increasing focus on the integration of geological information into data interpretation and closer collaboration with Indigenous communities. Several new geophysical applications have become popular including a range of techniques that have been applied to a variety of site types in both research and CHM contexts. This includes rockshelters (Barker et al., 2017; David et al., 2017a, b; James et al., 2017; Lowe et al., 2014, 2016, 2018b, 2020; Wesley et al., 2018), shell middens and shell mounds (Kenady et al., 2018a, b; Rosendahl et al., 2014), stone arrangements and rock quarries (Westaway et al., 2021), shipwrecks (Fowler & McKinnon, 2012; Roberts et al., 2017; Simyrdanis et al., 2018, 2019), submerged Indigenous sites (Benjamin et al., 2020; Wiseman et al., 2020), earth mounds (Ross et al., 2019) and historic sites (Lowe et al., 2018a, 2020; McKinnon et al., 2013), along with a continued interest in mapping cemeteries, both Indigenous and non-Indigenous (Bladon et al., 2011; Kurpiel et al., 2019; Lowe & Law, 2022; Lowe et al., 2014; Marshallsay et al., 2012; Moffat et al., 2016, 2020b; Roberts et al., 2021; Sutton & Conyers, 2013).

2 The Australian Context

As Lowe (2012) pointed out, several factors led to geophysical techniques being rarely used in Australian archaeology. Despite this, costs of instruments, time and adequate training are all issues that have seen improvement, as more universities and commercial companies are offering specialised teaching in this area, owning equipment, and providing geophysical services. However, as the practice has moved forward, other challenges have arisen (see Lowe et al., in press). Presently, one of the most significant issues is the nature of Australia's ancient landscape. Australia has some of the oldest rocks and soils in the world, has not been widely glaciated during the Pleistocene and has extensive areas of mobile sediments in the arid and semi-arid zones. This has several important implications for a geophysical survey; (1) soils that are present are often complex palimpsests having formed over long periods, often over mineralised bedrock and (2) in areas with mobile sediments, erosion is extensive and archaeological material is often conflated by deflation. Such erosional systems do not typically exist in other parts of the world, such as Europe's Palaeolithic or North America's Holocene, making it more challenging to understand spatial patterning, adaptation, fire use and occupation intensity of Australia's past (Holdaway et al., 2017). Therefore, preservation of the archaeological record can, in some cases, be ephemeral based on the geological location of sites and the local taphonomic processes. For example, combustion features—concentrations of heat-fractured rocks clustered together to form a campfire, are often found due to exposure from erosional processes and not in situ (Fanning et al., 2009; Moffat et al., 2008). Deflated landscapes such as this may serve as a detriment for adopting these techniques, particularly in areas that contain complex stratigraphy or depleted landscapes or where seasonal burning may have existed. Due to this, the distribution of many features within archaeological or culturally significant sites varies, making these features poorly understood in many environments.

Taphonomic processes also play a role in understanding sites and the early peopling of Australia and its associated environment. For example, the significant deep-time of continent-wide human occupation has been an ongoing debate in Australian archaeology. Most researchers now accept that Australia was first occupied at least 65,000 years ago (Clarkson et al., 2017). However, a major concern with the ages proposed for early human occupation of sites is based on luminescence dating of sediments rather than cultural materials directly, leaving many to question the association between dated sediments and human activity (e.g., Allen & O'Connell, 2003; Bowdler, 1990; O'Connell & Allen, 2004). In addition, high levels of weathering brought on by climatic changes, rain-splash erosion, bioturbation, and soil mixing are post-depositional disturbances that can contribute to the downward movement of artefacts and other preservation processes (Morley & Goldberg, 2016; O'Connell et al., 2018; Smith et al., 2020; Ward & Larcombe, 2021). Therefore, evaluating the structural integrity of old archaeological sites and the context in which these dated sediments is a critical step in the rigorous investigation of these sites.

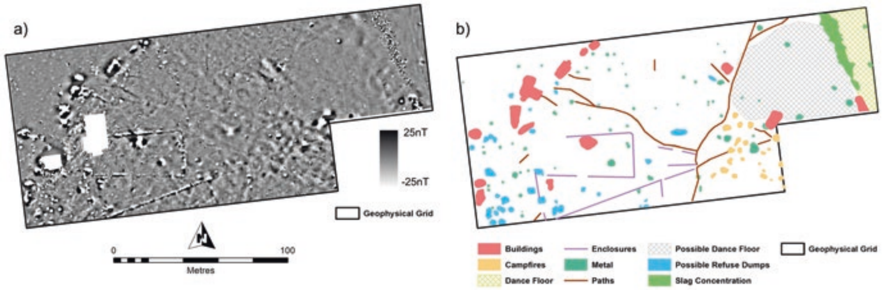

Fig. 1 Large-scale magnetic gradiometer survey of the Irish settlement, Baker's Flat in South Australia with black representing a positive magnetic gradient and white a negative gradient (**a**). Interpretations of Baker's Flat site based on geophysical data, excavation, and oral history (**b**). Note the total hectares surveyed was 2.4 ha; however, the size of the Irish settlement is 60 ha. (Modified from Lowe et al., 2020: Figs. 6 and 14)

Another challenge in Australian archaeo-geophysics is the lack of landscape-scale surveys that have become common in Europe due to the availability of multi-sensor instruments (i.e., Donati et al., 2017; Trinks et al., 2018). A notable exception to this is the detailed survey on an Irish mining settlement at Baker's Flat (see Lowe et al., 2020), which has demonstrated the important contribution that large scale survey can make to Australian archaeology by mapping a detailed landscape of occupation and confirmed that Baker's Flat was built in the style of a traditional Irish clachan (Fig. 1). Fortunately, a new National Facility for the 3D Imaging of the Near Surface has recently been funded at Flinders University that will make multi-sensor instruments available for free and provide training to Australian researchers, which we hope will lead to an increase in the use of geophysical techniques on a landscape scale.

Another possible reason for under-utilisation that has also come up in North America, is the language and communication used in geophysical interpretation and presentation (Sunseri & Byram, 2017: 1401). As Sunseri and Byram (2017) pointed out, practitioners need to adjust their ways of thinking and descriptions when delivering results to communities and researchers from other disciplines. For example, the variability of a site, such as texture, form or composition of sediments, should be considered first before making interpretations on likely features or strata, all of which comes from detailed data processing (Sunseri & Byram, 2017). When these variables are considered, one can create careful and methodical ways to disseminate the data to ensure a more meaningful understanding of the results. The 'shared languages' of description built around geophysics could complement cultural heritage preservation and the 'narrative building around archeological partnerships', which could promote more community engagement and collaboration (Sunseri & Byram, 2017: 1421).

Lastly, despite an increase in peer-reviewed literature and unpublished reports and the potential to inform CHM projects, there is still a limited number of archaeological sites studied (or even identified) for these methods to be applied to (Kurpiel et al., 2019). One reason for this is that the practice of archaeology is a relatively recent field in Australia. With the discipline only starting in the 1960s, the professionalism and expertise to identify and protect sites were low until about the 1980s (Smith & Burke, 2007: 5–8). Australia is also a very large continent, yet the population is relatively small for its size. This means that much of the continent has not been explored archaeologically since European colonisation, and areas that have been investigated today are primarily driven by infrastructure and mining development through CHM. Studies that are carried out in CHM are seldom reported outside peer-review literature or in social media, making it even more challenging to demonstrate its utility and, in some cases, test the methodology.

3 Changes in Geophysical Uptake in Australia

This increasing methodological breadth has been accompanied by a twofold change in approach; firstly, there has been an increased focus on using geophysical techniques to understand human behaviour rather than just locating archaeological sites as had initially been the primary goal (Lowe, 2012). Relevant to this is the increased deployment of laboratory techniques, such as magnetic susceptibility, to better understand features of geophysical anomalies. Meaningful interpretation of geophysical anomalies is currently a major limitation in archaeological prospection and why the Soil Science & Archaeo-Geophysics Alliance (SAGA) was developed (Cuenca-Garcia et al., 2018). The second change in approach has been an increased focus on assisting Indigenous communities with managing their cultural heritage, demonstrated by an increase in the use of minimally invasive studies undertaken with Indigenous community members as co-authors (see Lowe & Law, 2022; Lowe et al. 2018a, Moffat et al., 2008, 2016; Roberts et al., 2021; Ross et al., 2019; Westaway et al., 2021).

One significant development in Australian geophysical studies in the last decade is the foregrounding of hypotheses about human behaviour in research design, rather than focusing specifically on the mapping of geophysical anomalies. An example of this approach is including geophysical survey as an integral part of archaeological excavation of rockshelter sites. These studies use GPR or ERT to map the bedrock geometry and stratigraphic units allowing effective siting of excavation units and placing the excavation results within their broader geomorphic context. This work, which has been published for the Australian sites of Madjedbebe (Lowe et al., 2014), Gledswood (Lowe & Wallis, 2020), JSARN-124 site 3 (Barker et al., 2017), JSARN-113/23 (David et al., 2017a), Nawarla Gabarnmang (David et al., 2017b) and Dalakngalarr 1 (James et al., 2017). The use of geophysics in this context provides a much richer and more nuanced understanding of the archaeological record and facilitates the most effective investigation of these complex sites.

Recent laboratory advances see in Australian geophysical studies include sediment magnetic susceptibility and mineral magnetic characteristics supported by geochemistry and soil micromorphology Some of these studies have been used to determine human activity and the onset of human occupation via anthropogenic burning (Clarkson et al., 2017; Lowe et al., 2016, 2018b). Results show how magnetic enhancement in the shelter's sediments can assist in understanding initial occupation in deeply stratified sites as the enhancement becomes stronger once people come to the area. Other studies using sediment magnetic susceptibility, sediment analyses and geochronology have shown that shell mounds were repeatedly visited and constructed during multiple phases of occupation than as one single event (Lambrides et al., 2020; Rosendahl et al., 2014; Twaddle et al., 2017). Sediment analysis has also helped in creating volume estimates of buried shell deposits using GPR signatures (Kenady et al., 2018a, b).

Sediment magnetic susceptibility studies have been especially popular in understanding rock shelter stratigraphy (Lowe & Wallis, 2020; Wesley et al., 2018). They provide information on the site formation processes of the archaeological setting, particularly enhanced magnetic values which distinguish anthropogenic from natural site formation processes. Interpretation of the geophysical measurements and soil properties of earth floors at a historical camp revealed that they were made from ant beds or termite mounds, a locally sourced and highly compact material which were the cause of the high-amplitude GPR reflections (Lowe et al., 2018a) (Fig. 2).

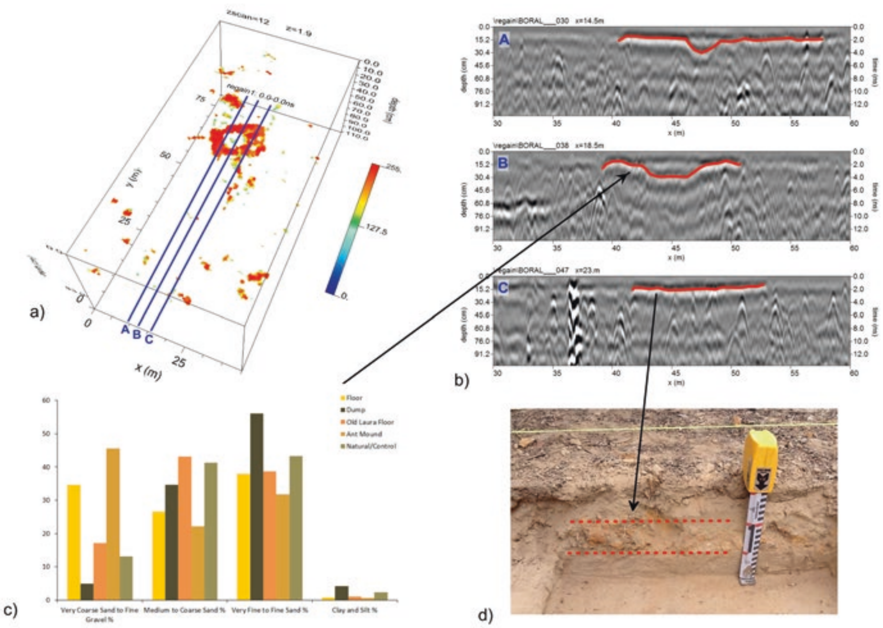

Fig. 2 An isosurface rendering of the officer's quarters ant bed floor with GPR transects A, B, and C (**a**). Reflection profiles for GPR transect A (Profile 030), B (Profile 038) and C (Profile 047) showing the ant bed floor (red line) (**b**). Coarse-grained particle size analyses show that ant bed floor and ant mound contained the highest fraction of coarser grains (**c**). Sediment profile of the excavated ant bed (red dashed lines) confirming the reflective planar surfaces (**d**). (Modified from Lowe et al. 2018a, b: Figs. 5 and 9)

Lastly, the mineral magnetic characteristics of local slag at the historical Irish settlement in South Australia were the cause of many positive magnetic variations at the site (Lowe et al., 2020).

Another meaningful change has been broadening geophysical approaches beyond a methodological focus on GPR and magnetic gradiometry particularly focused on the use of ERT (Ross et al., 2019; Simyrdanis et al., 2018, 2019). Here, ERT has predominantly been used for reconstructing palaeolandscapes associated with archaeological sites, mapping the stratigraphy of archaeological rockshelters, understanding earth mounds and for the 3D mapping of shipwrecks. This change has been brought about by the increased availability of this equipment, particularly due to an ERT equipment manufacturer (ZZ Resistivity) in Adelaide. The use of underwater ERT is a particularly exciting development as it has facilitated the 3D mapping of shipwrecks on the Murray River, which is the third-longest navigable river on the planet and was the inland artery of trade in colonial Australia (Bean, 1911) (Fig. 3a). From the launch of the first paddle-steamer Mary-Ann in 1853 until river trade was made redundant by railways in the early-twentieth century, the Murray River was the major means of transport for wool and station supplies for the booming pastoral industry, making it the most important trade route in colonial South Australia (Fig. 3b). This busy shipping trade has left a submerged record in the Murray River, with nearly 80 shipwrecks known to exist in just the part of the river within the South Australian border. This rich archaeological record has been

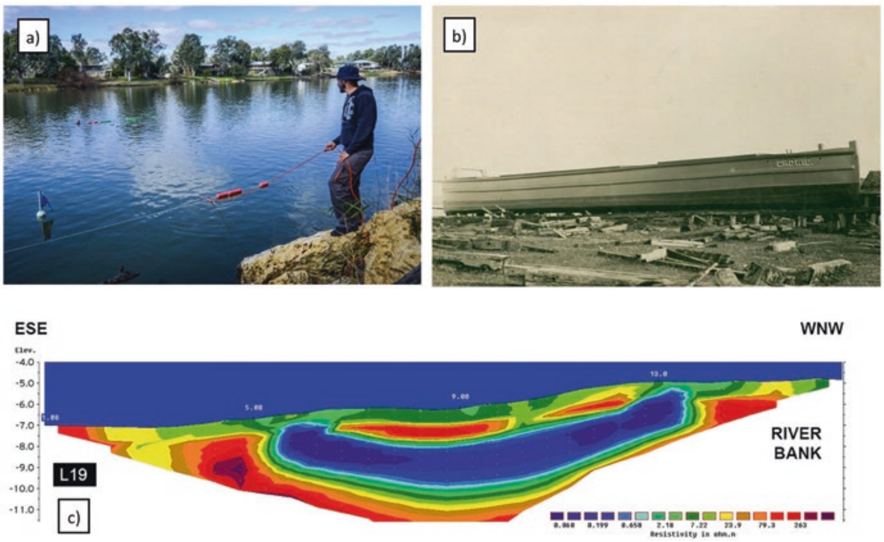

Fig. 3 ERT was used underwater to survey the wreck of the Crowie at Morgan on the Murray River. (**a**) Field survey procedure showing the draping of the ERT cable over the wreck between the river bank (right) and the centre of the river (left). (Image: This One Day Photography). (**b**) A picture of the Crowie on the stocks at Goolwa in 1911. (Image courtesy of the State Library of South Australia). (**c**) A 2D ERT profile through the Crowie wreck. (From Simyrdanis et al., 2019)

the subject of several previous investigations (Kenderdine, 1993); however, has always been hampered by the low visibility of the water. As a result, 23% of known wrecks have never been found, and an additional 19% have never been the subject of detailed investigation. Detailed research on the Crowie barge at Morgan on the Murray River has demonstrated that ERT has an important role to play in mapping wrecks that are submerged and sub-bottom in 3D, particularly in situations where they may be too shallow to obtain good results with acoustic techniques (Simyrdanis et al., 2018, 2019) (Fig. 3c). This approach has great potential to be applied in other parts of Australia's extensive network of inland rivers or in the littoral zone.

A final development, has been the substantial growth in Australian-based archaeological geophysicists applying their expertise on international sites including in Cambodia (Duke, 2021; Klassen et al., 2021; Lustig et al., 2018; Moffat et al., 2020a), the Caribbean (Giovas et al., 2019); Cyprus (Lowe et al., 2017), Greece (Donati et al., 2017; Papadopoulos et al., 2015; Sarris et al., 2018; Simon & Moffat, 2015; Simyrdanis et al., 2015), Indonesia (Calo et al., 2022; Maloney et al., 2022), Mongolia (Vella, 2018) (Fig. 4), South Africa (Armstrong et al., 2021; Herries & Fisher, 2008; Herries et al., 2008; Mackay et al., 2022), Papua New Guinea (David et al., 2008, 2009; Moffat et al., 2011), Syria (Casana et al., 2008) and Thailand (Duke et al., 2016). This trend probably reflects the greater availability of geophysical equipment in Australia compared to most countries in the region. However, it might also reflect the lower percentage of trained practitioners compared to the U.S. and Europe, as a majority of international projects were carried out by the author(s).

Fig. 4 GPR being used to map the stratigraphy of the Soyo site in Northern Mongolia by Dr. Bayarsaikhan Jamsranjav, as discussed in Vella (2018)

4 Discussion—What Has Changed?

Since the publication of Lowe (2012), numerous projects using geophysical methods have developed throughout Australia in both research and heritage management. These primarily include magnetic gradiometry and GPR, alongside an increased uptake of ERT and magnetic susceptibility, as discussed above. As mentioned, geophysics has been applied to various terrestrial and marine site types, including rockshelters, submerged landscapes, shell middens and shell mounds, historic sites, and cemeteries, both Indigenous and non-Indigenous and more recently, rock quarries. Such applications and datasets enhance the understanding of archaeological sites and landscape settings. Several Australian researchers were interested in geophysics, but as discussed in the review, they did not have many opportunities to use such techniques or collaborate with a skilled person in the methodology. Perhaps because of the review paper, followed by regional conference presentations, publications, invited guest lectures, and a few training courses within universities and Indigenous communities, there has been an increased uptake and interest in their use. As such, these projects manifested as examples of how these methods could be applied in Australia, forming a ‘web’ of collective research ideas that could be used to address important questions in archaeology and later to assist Indigenous communities in their heritage management (see Lowe & Law, 2022).

The aforementioned web was relatively small during 2011, with less than six professionally known geophysics practitioners in Australia. A key requirement in growing the discipline was to find a way that researchers and Indigenous and non-Indigenous heritage managers could become more familiar with the basic concepts and theory of archaeological geophysics and understand how it could fit into their research and cultural heritage initiatives. To start, presentations were given at school seminars and professional conferences such as the annual Australian Archaeological Association (AAA) in 2008 and 2011 to demonstrate that these applications were feasible in Australian research and publicise their potential. In addition, Flinders University offered a small two-day short course for 20 students as part of AAA 2008, which has now become a biannual 2-week graduate level field school (ARCH8808). This led to more research-driven projects utilising these methods at a variety of different site types while at the same time exploring their use in cultural heritage with commercial consulting companies. As other researchers became aware of the potential of geophysics on their sites, the opportunities transpired, and soon geophysical surveys were being conducted on some of the oldest known sites in Australia (Clarkson et al., 2017; David et al., 2017a, b; Lowe et al., 2016).

With help from colleagues advocating the use of near-surface geophysics within commercial consulting companies, the potential for geophysics grew even more prominent. Around this time, many geophysical surveys were being conducted for First Nations groups, specifically those interested in non-invasive ways to identify unmarked burials. Much of this uptake was related to the short courses offered by Flinders University but also the expertise of the practitioners in project planning. Results from several of these commercial projects were later presented at the AAA conference to highlight their potential and success outside research. Guest lectures at the University of Queensland for a Science in Archaeology course (ARCS2000) were held once a year with about 40 students per course since 2013, and a short course at James Cook University was offered in 2014 for about 25 undergraduate and graduate students, further creating awareness to students. In addition, a session dedicated to remote sensing technologies was offered annually at the AAA from 2013 onwards.

This has been paralleled by a considerable increase in the availability of geophysical equipment within archaeology departments in Australian universities and the inclusion of these techniques as part of undergraduate teaching in field methods courses. Nearly all archaeology programs now have some basic geophysical equipment, and a few have a world-class suite of equipment. Specialised topics in archaeo-geophysics remain rare (only Introductory Archaeological Geophysics at Flinders University) but most field methods courses now incorporate some training in geophysics as part of standard training in archaeology (Fig. 5). Additionally, the number of postgraduate students undertaking research in geophysical topics in archaeology has increased rapidly.

These more holistic applications of geophysics, beyond traditional anomaly detection, have enhanced our understanding of archaeological sites and landscape settings and have demonstrated the need for such techniques to be evaluated for

Fig. 5 Undergraduate Archaeological Field Methods students at Flinders University undergoing training in GPR, gradiometry and ERT data acquisition

inclusion in Australia's legislative and academic frameworks. Currently, in Australia, there is a growing number of cases brought under the *Aboriginal and Torres Strait Islander Act 1984* by Aboriginal and Torres Strait groups on threatened cultural heritage sites since the destruction of Juukan Gorge, a 46,000-year-old rock shelter destroyed by a mining company in 2020 (Commonwealth of Australia, 2021). Many practitioners and First Nations groups feel that Indigenous people should be empowered to control their heritage, yet the government has failed to provide custodians with the necessary funding and training to do so. As a result, many are leaning towards archaeo-geophysics as part of the heritage assessment as they can be a more responsible and ethical means of site investigation, particularly for human remains (Sutton et al., 2021) or *in situ* preservation (Colwell, 2016).

As such, many practitioners have chosen these technologies because they view them as a responsible and ethical means of study in research and consulting and because of their popularity among Indigenous communities (Wadsworth et al., 2021; Warrick et al., 2021). Increasingly, we see a shift towards communities and community-based projects that focus on the use of archaeo-geophysics as part of their heritage management, leading to broader social, cultural, political, and economic impacts for local communities (e.g., Nelson, 2021; Wadsworth, 2019). One example is the geophysical investigations on an area of unmarked Aboriginal mass graves at the Old Cherbourg cemetery in Cherbourg, a town and locality of the Aboriginal Shire of Cherbourg, Queensland, Australia (Lowe & Law, 2022). Formally known as the Barambah Aboriginal Reserve and founded as an Aboriginal settlement in the early 1900s, the Cherbourg community was significantly affected by Spanish Influenza in 1919. At least 15% of the community died from the flu in 3 weeks (Briscoe, 1996). Because the deaths happened so quickly, many were interred in mass graves in areas away from the current Aboriginal community—an area never demarcated. In 2019, 100 years after the event, local Indigenous Elders sought out specialists to carry out non-invasive remote sensing to find the mass grave sites and verify the oral histories about them. It was hoped that the people buried there could receive recognition for their final resting place and have a proper memorial (e.g., plaque or marker).

Using GPR and magnetic gradiometry, in combination with oral histories from the Indigenous community Elders, at least three mass graves were identified (Fig. 6). In the New Cemetery, at least two mass graves were detected, and one mass grave was in the Old Cemetery based on GPR contrasts resulting from soil disturbances (Lowe & Law, 2022). In this example, the community worked together to ensure their values about burial places were respected (and preserved) and that knowledge of the events of the past could be remembered by the community today. According to Eric Law, a Wakka Wakka elder, "We've got to remember these people because they are part of our community and they'll always be a part of our community" (Hegarty, 2019). More broadly, geophysics supported Indigenous aspirations around concepts such as 'Truth Telling' which focuses on Indigenous perspectives of colonialism and its impacts today to First Nations people (HCANZ, 2020). In this case, this ensures that Indigenous values about culturally sensitive places such as burials

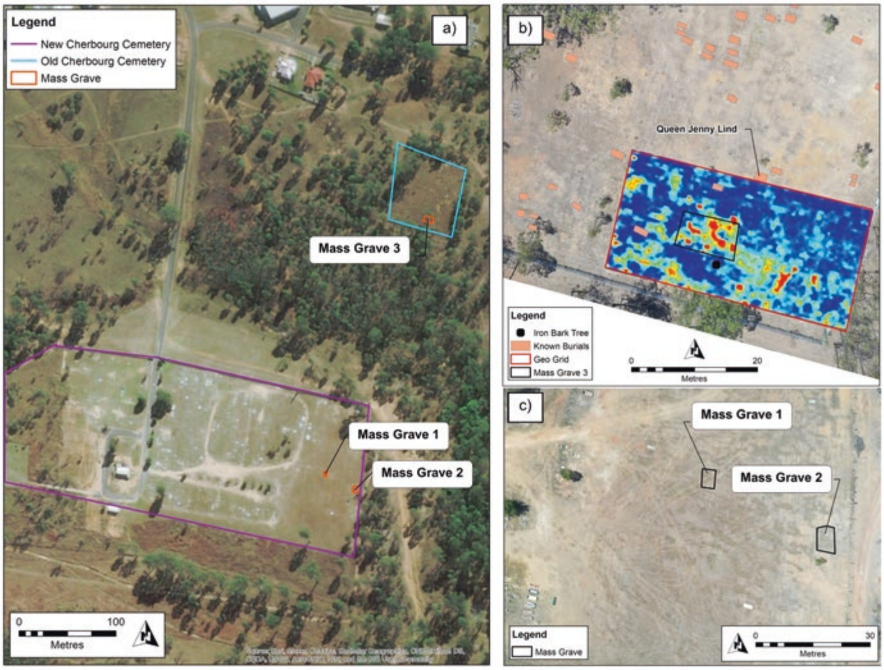

Fig. 6 Location of the two Cherbourg Cemeteries and the three Mass Graves (**a**). Overlay (depth 25–50 cm) of GPR amplitude slice map showing strong reflections relating to Mass Grave 3. Oral histories noted that a third mass grave was placed next to the ironbark tree (**b**). The location of two previously identified mass graves was found in a GPR survey conducted in 2012 (**c**). Note GPR data was not provided for the 2019 survey but a map showing the location of the unmarked and the two mass graves. Field inspection carried out with the community in 2019 confirmed the mass grave's location

are safe-guarded, and the lives are not forgotten. It also reiterates specific past cultural events of Indigenous significance and their reconciliation efforts.

While this increasing engagement with Indigenous communities is laudable, a challenge remains in transferring geophysical skills and equipment to peoples working outside of academia. No Indigenous or other community groups in Australia currently own their own equipment or have the skills and experience to undertake their own surveys. Similarly, few commercial archaeological organisations use these methods routinely as part of their commercial practice and fewer own geophysical gear. Rather, geophysics is most often employed on more challenging projects, particularly those involving graves, by specialist practitioners. This means that the cost of geophysical methods remains high and is an obstacle to true community self-determination in their use. We hope that this situation has changed should the state of archaeo-geophysics "down under" be reviewed again 10 years hence.

Another major limitation on the use of geophysics to answer questions about the Australian archaeological record is the relatively limited engagement with soil and sediment analysis (except for soil magnetics) by Australian archaeologists. In contrast to the significant increase in the availability and use of geophysical equipment the availability of equipment for soil and sediment analysis in Australian archaeology departments remain limited and training in these areas remains uneven. While this analysis has historically been undertaken in earth science departments, we see great advantage in more closely integrating these methods within archaeology. This has been made more possible due to the rapidly decreasing cost and operational complexity of instruments such as portable x-ray fluorescence and benchtop scanning electron microscopes.

Looking at the projects that have developed since 2012 verifies that a change is occurring and that these methods are being used much more frequently (Fig. 7) and on a wider range of topics within Australian archaeology. While many of the projects involve the author(s), it is evident that geophysical applications in archaeology are increasing, particularly as institutions, consultants, and local custodians learn about the advantages these techniques offer to archaeological research. From 2004 to 2009, publications had doubled for the first time since 1979, 30 years since the initial uptake of these technologies. While globally, training opportunities and geophysics popularity began in 1991 with the U.S. National Park Service course (DeVore, 1992), followed by the first issue of the journal *Archaeological Prospection* in 1994, this popularity was almost non-existent in Australia—only two peer-reviewed papers were published. Even with the first meeting of the International Society for Archaeological Prospection (ISAP) in 2003, which extended the network outside the U.K., the uptake was still low. However, the most notable change

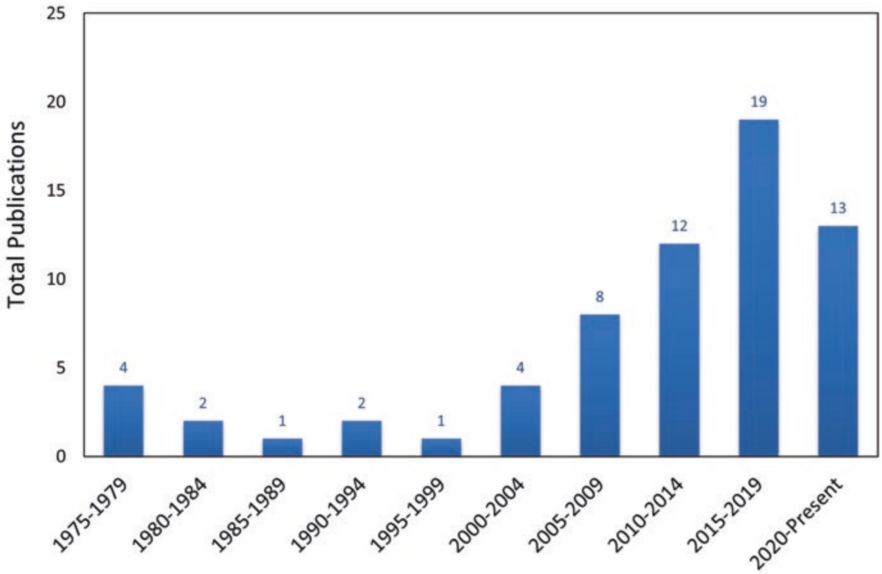

Fig. 7 Graph showing the number of published papers on geophysical surveys completed in Australian archaeology from 1975 until November 2021. Unpublished material has been omitted due to access availability. Note the significant increase in use in the mid-2000s

came from 2014 to 2019, where there was a shift in the advancement and acceptance of geophysics in Australia and an increase in contributors, much as what we saw in the U.S. and the U.K. (DeVore et al., 2018).

Interestingly, in the last 2 years (2020–2021), almost more publications have been generated than in the entire first three decades. Since 2000, there has been a 375% increase in peer-reviewed literature and a 175% increase since 2012. This is a positive outcome notwithstanding the limitations discussed in 2012 and the overall slow uptake. This also supports the initiative of SAGA and the desire to understand soil properties and the processes that affect the geophysical data—as the environmental setting of Australia plays a critical role in data acquisition and interpretation. This is evident in the last 10 years as shown in Fig. 8, where laboratory analyses combined with standard prospecting methods are now being used.

In summary, while challenges still exist today in Australia as well as worldwide in terms of archaeo-geophysics applications and uptake, there is still a slow, steady change in the uptake of digital technologies overall. Perhaps moving away from producing a "pretty picture" or finding things below the surface is what specialists need to do (or keep doing) when moving forward. One example might be to employ more of what Sunseri and Byram (2017) suggested in finding new shared languages for communicating our results to link their potential in interpretation with research design and testing more about what we see in environments that are heavily deflated. By providing suitable languages, researchers and practitioners might have more opportunities to consider the impacts of employing remote sensing technologies as a standard archaeological practice even more and use this information to find ways to address any archaeological challenges.

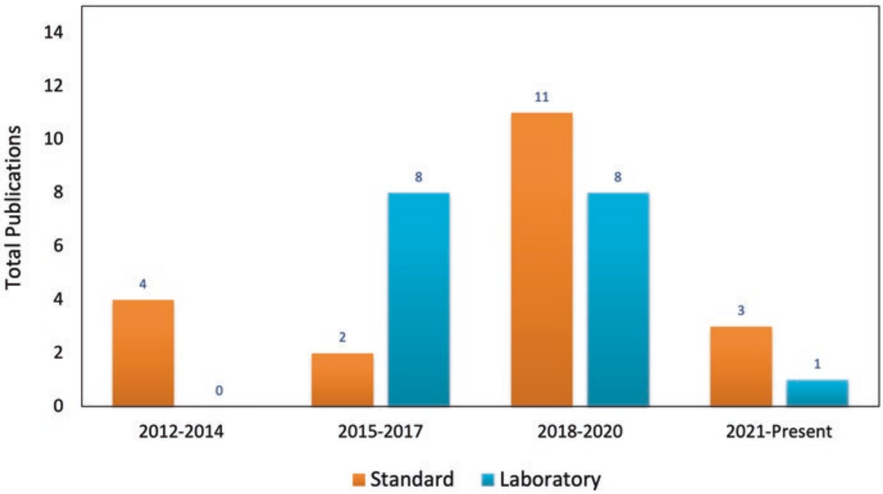

Fig. 8 Graph showing the number of published papers that involve standard archaeological prospecting and those studies that involve both standard and laboratory-based research in Australia

This might ensure their use beyond specialists only, but one where ALL stakeholders have a role in the design, interpretation and output of geophysical investigations. Refining our understanding of the geophysical signatures and how they relate to the human modification of the environment is also a part of this and builds on the limitations discussed in this chapter. The more we aim to bridge the gap between soil properties, geophysics and archaeology, the more we will improve this discipline and its usage in the future.

5 Conclusion

Despite its slow uptake the use of geophysics in Australian archaeology is making an increasingly important contribution to research and CHM. Many of the limitations identified in 2012 no longer exist. However, other problems that need to be factored when moving forward to encourage the use and adaptability of these methods have been identified. In particular, geospatial technologies are an essential tool critical for understanding social and ecological processes and the relationship between people and their environment, especially as they support engagement with the data and management of digital humanities. They also offer another form of visualisation that communities are leaning more towards, given their minimally destructive nature and assistance in conserving heritage landscapes. Yet archaeologists with geospatial expertise are in short supply in Australia.

As geophysical practitioners, we need to continue demonstrating the utility of geophysics in Australia and elsewhere by identifying suitable methods at varying archaeological features and site types and differing depositional settings and reporting both positive and negative findings. Secondly, we should consider building a catalogue of geophysical anomaly types to compare to and help us understand areas where contrasts are questionable. This might assist us when we think about space and how this has been modified by cultural and natural processes—especially processes affected by erosion and degradation. Ground testing anomalies through minimally invasive processes such as soil coring and soil chemical analysis will allow us to understand the geophysical results, providing the ability to accurately interpret the information.

Lastly, we need to continue to work more towards Indigenous and applied archaeology projects driven by communities and where community members hold an active role in all decision-making processes. Workshops are one means by which communities and relevant stakeholders can learn about the methodology and how they can support upkeeping management strategies where applicable. It provides capacity building in the acquisition of new skills that can help Aboriginal communities gain a better sense of when they can apply geophysical approaches to site interpretation. Such knowledge-sharing enhances field searches and creates positive impacts on developing heritage management plans and recommendations at the community level.

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Part II
Belgium

The Application of Geophysical Survey in Archaeological Research in Belgium: Current State and Future Perspectives

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Abstract Since its earliest applications in the 1970s, geophysical survey has been applied increasingly in Belgian archaeology. This was particularly the case within Flanders over the past decade. Academic archaeological research has played a fundamental role in disseminating available techniques, such as electrical resistance and magnetometer survey, and in advancing the use of electromagnetic induction- and ground penetrating radar instruments for archaeological prospection specifically. However, the dissemination of this expertise remains in its infancy and adoption in Brussels and Wallonia lingers behind. Although Flanders has seen a strong increase in such surveys over the past decade, the share that geophysical techniques take up in development-led archaeology pales to significantly wider used invasive prospection methods. Both a lack of tradition in archaeological geophysics as well as the dominance of systematic trial trenching as a prospection method underlie this slow uptake of geophysical approaches in development-led archaeology. In contrast, geophysical survey does play a significant role in academic (landscape) archaeological research and in the investigation of archaeological sites for scheduling. Within this general situation, the use of geophysical methods in Belgium is geared primarily towards specific expected types of sites, but, within the heterogeneous geological landscape, spans a wide range of environments.

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While progress has been made continually over the past decade, much room remains for further optimisation of the use of geophysical methods in Belgian archaeology. Here, improving protocols for the integration of complementary, invasive and non-invasive, survey methods adapted to the diverse geological and archaeological circumstances remains a key challenge. To enable these advances, current efforts to provide such a methodological framework, along with existing expertise across the nation, have to be disseminated beyond academic circles through initiatives, such as dedicated (post-)academic training and inclusion of both archaeologists and archaeological geophysicists. Hereby, the consolidation of a robust legislative framework, adhering to EAC guidelines, is required for implementing geophysics in (development-led) archaeology sustainably, similar to e.g. trial trenching. This should safeguard the quality, archiving, accessibility, and interoperability of resultant data.

1 Introduction

It is perhaps by virtue of its small surface area (30,528 km^2) that the Belgian territory has been subject of a vast range of high-resolution survey campaigns for a broad array of ecosystem services (Hassan et al., 2005). While regionalisation of Flanders, Brussels and Wallonia has stalled initiatives at a national scale from the 1970s onwards, the nation has a long-standing tradition of environmental mapping and surveying. Clearest examples are not only the early development of the 1:20.000 soil map (late 1940s–1970s) (Van Ranst & Sys, 2000) and 1:25.000 geological maps (1947–1977) (Boulvain, 1993) but also the extensive coverage of diachronic airborne vertical photographs from World War I onwards (Stichelbaut, 2006) and the public distribution of LiDAR data and derived products covering the entirety of Flanders (De Man et al., 2005; Meylemans & Petermans, 2017).

This survey density is part of a long tradition, building on historical cartographic endeavours from the sixteenth century onwards, e.g. by Pourbus (Trachet, 2018) and Ferraris (Vervust, 2016), as well as early geological mapping, e.g. by de Limbourg (Demoulin, 2018). After early attempts from the 1970s onwards, systematic inventorying of archaeological observations in Flanders has been ongoing since 2001 (Meylemans, 2004). This online *Central Archaeological Inventory*[1] (CAI) is partly public and fully open to registered users (ca. 50,000 records).

Such rich base maps are complemented by a particular richness of dedicated archaeological survey methods: starting from desktop research that hinges on the cartographic resource, complemented with invasive sampling approaches including borehole surveying and trial trenching, ideally combined in a case-specific manner.

This study aims to provide an overview of the current status of archaeological geophysics in archaeological research and archaeological heritage management in

[1] https://inventaris.onroerenderfgoed.be/waarnemingsobjecten/zoeken

Belgium. Over the past 15 years, geophysical survey methods have taken position between desktop and invasive approaches in a small share of the development-led projects (Meylemans & De Smedt, 2019). This prospection flow succinctly summarises the general approach to development-led archaeology, driven by the Valletta convention (Council of Europe, 1992). While not the sole motivator for conducting archaeological terrain exploration—archaeological surveys on sites not under threat do still take place for a variety of reasons—, development-led archaeology dominates the creation of new archaeological data.

2 Methodology

Aside from a review of legislation, an inventory of survey sites was made based on the CAI, the Flemish desk-based-assessment platform,[2] and an extended (grey) literature review. For each of the 311 inventoried survey projects, the employed technique, survey- or publication year, and survey objective were listed. For 306 projects, this inventory includes survey locations as points. The precise extents of all surveys as well as their specific method was not inventoried yet. Nevertheless, basic spatial analyses with other cartographic resources: the CORINE land cover (Büttner et al., 2004), the EGDI Surface Geological Map of Europe,[3] and the Belgian soil maps (Van Ranst & Sys, 2000) let us address the impact of the Belgian landscape and the nature of its archaeological features on geophysical investigations, both in academic research and in cultural resource management. We illustrate this by referring to selected key examples.

3 A Brief History of Archaeological Prospection in Belgium

Archaeological prospection is understood as the application of geophysical prospection methods in archaeology (e.g. Scollar et al., 1990) or as to the identification of areas of archaeological potential and individual strong anomalies using geophysical methods (Level I field strategy in Gaffney & Gater, 2003) in many countries and research traditions. However, in Belgium, the act of archaeological prospection includes the entire range of methods and techniques employed to detect, delineate, evaluate, and characterise archaeological sites and landscapes both invasively and non-invasively (e.g. S.n., 2019).

[2] https://loket.onroerenderfgoed.be/archeologie/notas/

[3] https://www.europe-geology.eu/

3.1 Aerial Photography

The current archaeological use of historical, vertical aerial photographs in Belgium originated in the late 1950s (e.g. Mertens, 1957) and has since then been applied with particular efficiency along the former World War I frontline (Stichelbaut, 2011). Along the use of legacy data starting around the same time, thousands of oblique aerial photographs were collected for archaeological purposes at the Centre Interdisciplinaire de Recherche Aérienne (CIRA) (Léva & Hus, 1975), followed by the universities of Ghent and Leuven (Meganck et al., 2004). However, systematic funding has waned recently and despite limited inventorying and thematic analyses, e.g. enclosure sites (Bourgeois & Nenquin, 1996) and Bronze Age barrows (De Reu et al., 2010), these collections remain understudied. The estimated workhours to catch up and disclose all available oblique aerial photographs surpass a decade. As a consequence, the usage of this resource in development-led archaeology remains limited to specific cases and inventoried subjects, e.g. World War I frontlines. However, as crop- and soilmarks are due to (often moisture-induced) soil contrasts, aerial photographs are not only essential to plan geophysical surveys, but they are also invaluable to interpret the resulting geophysical data (e.g. De Clercq et al., 2012b).

3.2 Walkover Survey

From the late 1970s to the early 2000s, walkover survey was employed to systematically inventory archaeological remains of dozens of municipalities (Nenquin et al., 1990; Van Daele & Tency, 2004). It was also applied in rescue archaeology and, in some regions, remains a widespread practice by amateur archaeologists (e.g. De Bock & De Meireleir, 2005). The results form a well-appreciated resource for academic researchers but have to be evaluated critically (Crombe et al., 2009; Trachet et al., 2017a).

Although inventoried results of past studies are used frequently in development-led desk-based assessments, the use of walkover survey has faded strongly and is barely practised in current archaeological studies in either development-led, heritage management or even academic frameworks.

Due to GNSS technology, allowing for artefact accurate walkover survey (AAS), this method has seen a limited revival in academic research. However, the full potential of AAS only reveals itself when combined with other methods, such as geophysics or aerial photography, to which it acts as a highly complementary method for assessing chronological and spatial parameters. When fully integrated with geophysics, UAV and LiDAR imagery as well as historical evidence, AAS has proven to be a useful tool to assess the archaeological record, e.g. of the medieval period, in a non-invasive way (De Clercq et al., 2018; Trachet et al., 2017a).

3.3 Trial Trenching

Whereas targeted test pits on known sites had already been used for a long time, developments abroad of systematic trial trenching as a survey method were introduced only gradually throughout the 1990s (De Clercq et al., 2012a; Meylemans et al., 2021). In the late 1990s, systematic 'Lorraine' (discontinuous) trial trenching was introduced for development-led prospection of large, rural areas (Blouet, 1994). More widespread adoption started only after 2004, due to changing legislation. Trenching patterns quickly evolved towards efficient continuous, parallel, 2 m wide trenches achieving an approximate area coverage of 10%. These are complemented by trench extensions ('observation-windows') with an area coverage of about 2.5% to resolve remaining uncertainties from systematic trenching. This has become rigid prospection methodology, easily applied in a commercial setting and embedded in the legal framework in Flanders.

While simulation approaches on a representative sample of archaeological sites without chronological differentiation generally confirm these approaches (Haneca et al., 2017), caution is advised due to a poor detection potential for low feature density rural sites and associated periods (De Clercq et al., 2011). Furthermore, this rigidisation of trial trenching methodology dissuades prospection at differing spatial scales, which is required to transcend the individual site (or project) level and to study intersite interactions as well as interactions with and within the archaeological landscape (De Clercq et al., 2011).

However, even if the legal framework prescribes the systematic trenching strategy, it allows for deviations (S.n., 2019). Nevertheless, through commercial market mechanisms, most warnings have been ignored in favour of a more easily implemented rigid system and currently little variability and innovation is observed in trenching strategies.

Due to this hard focus on systematic trial trenching for development-led archaeological prospection in Flanders, little room remains for integrating geophysical methods and trenching targeted on geophysical survey results, with few exceptions (e.g. Saey et al., 2016b).

3.4 Palaeolandscape and Archaeological Borehole Survey

In collaboration with geoscientists, who had been employing borehole surveys regularly since the interbellum, Belgian archaeologists started using this method to map buried palaeolandscapes for, primarily prehistoric, site contextualisation in the early 2000s (Bats, 2001). While the use for surveying soil features was abandoned relatively soon, manual borehole sampling was integrated into archaeological prospection as a means to detect Stone Age lithic artefact scatters in Flanders (e.g. Bats, 2007; Van Gils & De Bie, 2002), following developments in the Netherlands (Groenewoudt, 1994). As such, various research projects, often in a development-led archaeological framework, established strategies using Dutch (Edelmann) auger sampling to prospect selected positions within the reconstructed palaeolandscapes. More recently, sampling and sample processing parameters were evaluated using statistical (Verhagen et al., 2011, 2013) and empirical analyses (Crombé & Verhegge, 2015; Noens et al., 2013) and soon became standardised in regulations and development-led archaeology in Flanders (De Clercq et al., 2011), despite inherent imperfections addressed by e.g. Noens and Van Baelen (2014). Hereby, borehole survey for palaeolandscape reconstruction is considered a non-invasive method, whereas borehole survey for prospection of artefact scatters an invasive method from a legal standpoint.

Large scale and deeply impacting infrastructure works also led to the usage of mechanical coring, both for palaeolandscape mapping and archaeological sampling (Hissel & Van Londen, 2004; Verhegge et al., 2016b). To overcome the high cost of mechanical core sampling, additional methods for palaeolandscape mapping with higher spatial resolution, such as direct push sensing, primarily cone penetration testing, and geophysical methods, mainly electromagnetic induction survey, were investigated and introduced into development-led archaeology (Verhegge et al., 2016a).

3.5 Metal Detection

Although metal detecting is essentially a geophysical survey method for archaeological artefact detection, it is treated as a stand-alone discipline and a thorough discussion of its applications in Belgian archaeology is beyond the scope of this overview. Although illegal, non-professional practice was tolerated in Flanders until 2016 and in Wallonia until 2018 (Deckers, 2019). Since these dates, a legal basis was realised and regulations have become more stringent in Flanders and Wallonia. Hereby, metal detectorists are required to carry a permit, follow a code of good practice and report their activities and finds to the government. No specific legislation addresses metal detection in Brussels, although excavating artefacts without permit remains illegal (Jansen et al., 2020).

However, even if many permits have been issued, find reporting remains limited in Flanders (De Groote & Ribbens, 2021). This illustrates the distrust and disconnection from the archaeological community, despite efforts such as a citizen science platform[4] (Deckers, 2019). However, metal detectorists are frequently invited to work under supervision of professional archaeologists both in academic and development-led archaeological projects. A possible remediation through relating the metal detection community and (community) archaeological geophysics has not been explored yet.

[4] MEDEA: https://vondsten.be/

3.6 *Geophysical Survey Methods*

3.6.1 Common Evolution Before the Implementation of the Valletta Convention

Although integrating geophysical methods into standard Belgian archaeological workflows remains challenging, efforts had already been made to incorporate these into the standard non-invasive archaeological prospection toolkit roughly 50 years ago. Such efforts were mainly driven by investments in archaeological aerial photography by a select group of researchers in the 1950s and 1960s, paving the way for other, less conventional, non-invasive survey approaches. At the forefront of this pioneering work was the (private and independent) Centre Interdisciplinaire de Recherche Aérienne (CIRA; Interdisciplinary Centre for Aerial Research) established by Charles Léva, who recognised the potential of combining aerial photography with geophysical prospection from the onset. Exemplified by concerted actions such as the 1979 and 1986 conferences on 'Aerial Photography and Geophysical Prospection in Archaeology' (Léva, 1982, 1990), it was singly the seminal but off-time work of Jozef Hus in collaboration with Léva (Hus, 1982; Léva & Hus, 1975, 1984, 1987) that constituted the application of geophysical survey methods in Belgian archaeology for nearly three decades. Despite this early work and evolutions abroad, archaeological interest in geophysical methods waned throughout the 1990s (Fig. 1a), coinciding with the delayed standardisation of other survey methods and the slow development of a development-led archaeology. While unreported, the delayed spread of geophysical survey in archaeology could also be related to results being perceived as disappointing due to the complex subsurface environments of Belgium in combination with the ephemeral geophysical nature characterising a large portion of its (particularly rural and pre- and protohistoric) archaeology. Regardless of the reason, it is striking that across regions—in both academic and development-led frameworks—there was little to no uptake of geophysical approaches in Belgian archaeology during this period.

With the new millennium came a renewed academic interest into novel, landscape-oriented and non-invasive prospection approaches. Here, geophysical methods drew particular interest, which translated into several (academic and application-oriented) research projects that relied primarily on expertise from abroad (e.g. Masters & Stichelbaut, 2009; Quick et al., 2005; Strutt & Hay, 2003; Van Impe & Strutt, 2006).

3.6.2 Separate Ways After the Implementation of the Valletta Convention

Until the early 2000s, Flanders and Wallonia had been following a similar trajectory in the implementation of geophysical methods in archaeology. Despite some early applications by Léva and Hus (1975), the collaboration with experts (Quick et al., 2005) and early local expertise development (e.g. Charlier et al., 2001), geophysical

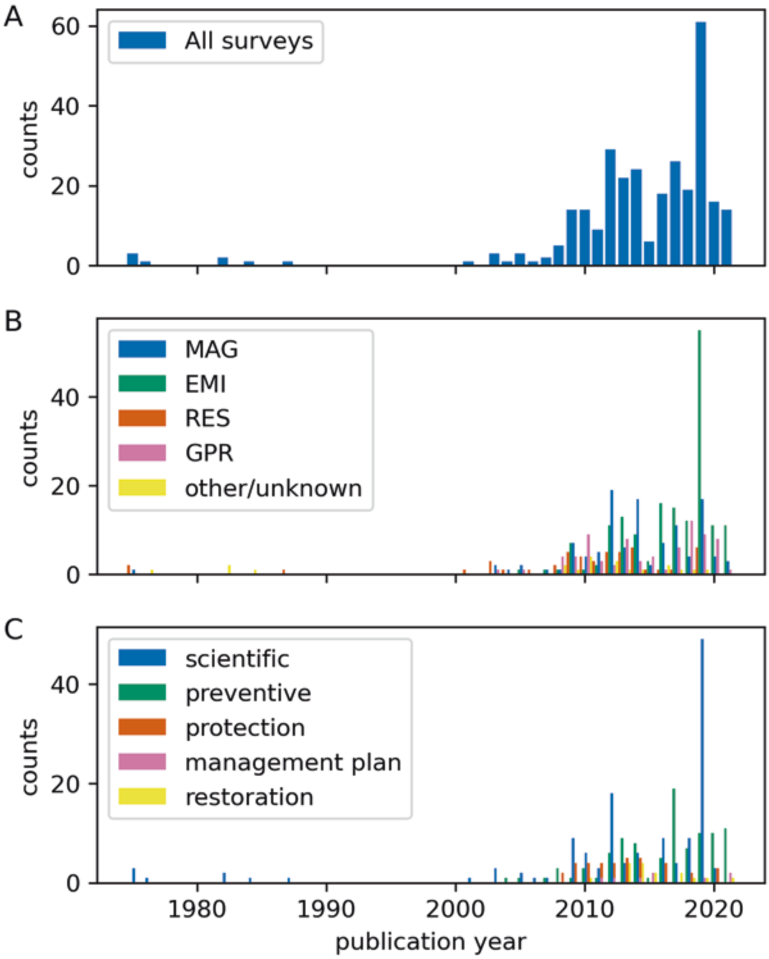

Fig. 1 (**a**) Inventoried survey projects counts and publication year; (**b**) projects counts per year of the most employed methods per year (*GPR* ground penetrating radar, *MAG* magnetometer survey, *EMI* electromagnetic induction, *RES* electrical resistance survey, *other/unknown* unknown; electrical resistivity (pseudo-)tomography, (Borehole) Magnetic susceptibility, Self Potential; (borehole) electrical conductivity, Geophysical tool for Archaeology based on Radiometric Physics, terrestrial seismic survey, Time domain electromagnetic induction, Time Domain Reflectometry and other techniques of volumetric water content sensors); (**c**) project counts per year classified according to survey objective

methods have been barely picked up in Wallonia and Brussels over the past two decades (Fig. 2a), with the exception of some projects with a scientific interest (e.g. Baltus et al., 2019; Lambot et al., 2018; Tabbagh et al., 2019). One explanation could be the limited budgets for the development-led archaeology, which is sponsored directly by the Walloon government budget. This contrasts starkly with the higher financing where the 'polluter pays'-principle is implemented such as in Flanders.

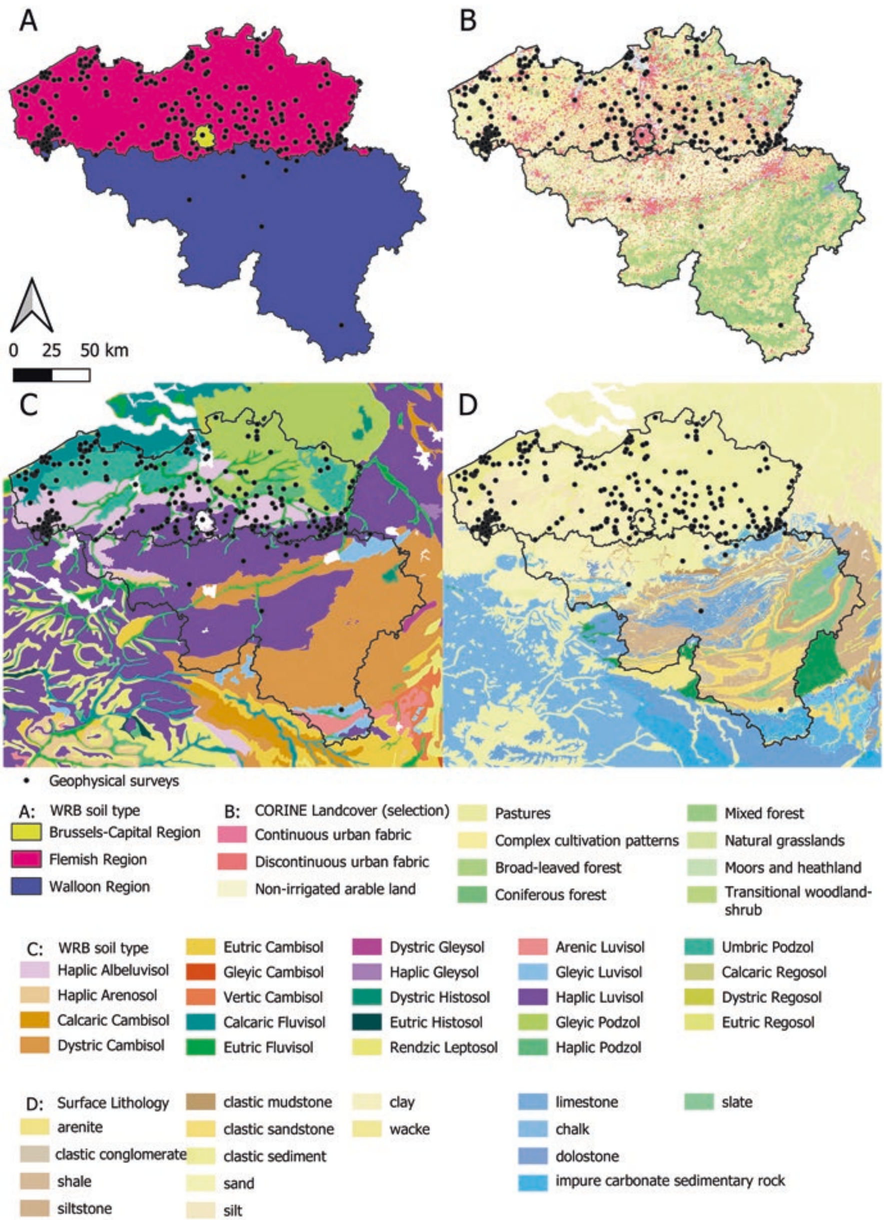

Fig. 2 Localised geophysical surveys in Belgium. Backgrounds: (**a**) Belgian regions, the highest administrative level responsible for archaeological legislation; (**b**) CORINE (CLC) 2018, Version 2020_20u1 (source + legend: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018, European Union, Copernicus Land Monitoring Service 2022, European Environment Agency (EEA). (**c**) ESDA WRB soil map (https://esdac.jrc.ec.europa.eu/) (The European Soil Database distribution version 2.0, European Commission and the European Soil Bureau Network, CD-ROM, EUR 19945 EN, 2004); (**d**) 1:1M map of the Geological Unit-lithology of the pan-European Surface Geology (EGDI) (https://www.europe-geology.eu/)

Another could be that, while geophysical expertise is present in various non-archaeological academic institutes in Wallonia, research lines (and associated training programs) dedicated specifically to the archaeological application of geophysics have been lingering behind. To redress this status quo, collaborations between Ghent University, Liège University and the Walloon Heritage Agency have recently been formalised through a dedicated archaeological prospection network,[5] the PROSPECT International Thematic Network. This unique network, coordinated by Ghent University, includes more than 20 international research institutions involved in all aspects of both invasive and non-invasive archaeological prospection and aims to create enduring, stimulating environments for education and stakeholder training, interdisciplinary research development, and concrete societal and economic impacts.

In the Flanders, (student) training and developments in the use of geophysical methods in archaeology, particularly electromagnetic induction (EMI) and ground penetrating radar (GPR), started with local expertise building at Ghent University from 2007 onwards (Simpson et al., 2009; Verdonck et al., 2009). Shortly afterwards, geophysical methods started to be employed increasingly for Flemish archaeological site scheduling projects (e.g. van Kempen & Keijers, 2009) and land management (e.g. Lehouck et al., 2007) by appointment of government agencies and executed both by research institutes and independent practitioners. From 2009 onwards, the developed expertise at Ghent University enabled an increasing number of research projects, developing prospection strategies for a range of landscapes and sites, ranging from prehistoric landscapes (Verhegge et al., 2012) to medieval settlements (De Smedt et al., 2013c; Trachet et al., 2017a) and World War I battlefield remains (Saey et al., 2016a). During this period, these academic as well as site scheduling projects constituted most geophysical projects undertaken, particularly in Flanders.

In development-led archaeology, geophysical methods were applied rarely (e.g. De Smedt et al., 2011), because they were not prescribed by heritage officials, except where other methods did not perform well (e.g. Saey et al., 2016b). Legislative changes in 2016 meant that requirements for archaeological evaluations in development-led archaeology are currently created by archaeological entrepreneurs and involve early career archaeologists with basic training in archaeological geophysics. After a dip in geophysical surveys in 2015, this has led to a continuing increase in use of geophysical methods in Flanders (Fig. 1a).

3.6.3 Survey Objectives

Throughout Belgian archaeology, published geophysical surveys have mainly had a scientific objective in the past (Figs. 1c and 3a). However, their incidence varies significantly with time and depends primarily on individual project funding and researchers. For instance, about a third of all surveys with a scientific objective

[5] PROSPECT ITN: https://www.prospect.ugent.be/

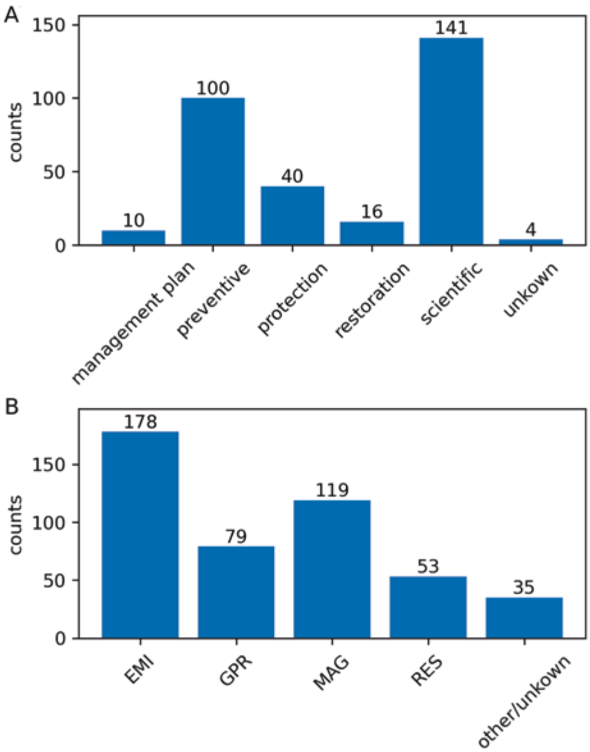

Fig. 3 (**a**) Inventoried survey project objective counts; (**b**) Inventoried survey method counts of 311 projects (*EMI* electromagnetic induction, *MAG* magnetometer survey, *GPR* ground penetrating radar, *RES* electrical resistance survey, *other/unknown* unknown; electrical resistivity (pseudo-) tomography, (Borehole) Magnetic susceptibility, Self Potential; (borehole) electrical conductivity, Geophysical tool for Archaeology based on Radiometric Physics, terrestrial seismic survey, Time domain electromagnetic induction, Time Domain Reflectometry and other techniques of volumetric water content sensors)

resulted from a single project and PhD thesis by Note (2019), creating a large peak in survey numbers in that publication year, while the number of surveys were evenly spread over the preceding 4 years.

However, development-led geophysical surveys have become increasingly frequent since 2012. Since 2016, 48 archaeological assessments (*archeologienota's*) were submitted involving geophysical survey methods in Flanders. Possibly, these numbers may rise further, because 64 applications to apply geophysical methods are submitted at the time of writing. However, this application number also include those which may well not be or have been followed by actual surveys. The mechanism behind of this increase remains unclear. It may be due to a changing policy of the Flemish Heritage agency, increasingly enforcing that geophysical methods are included in survey requirements, due to changing attitudes and training of

Table 1 Overview of yearly and total number of archaeological assessments (*archeologienota's*), the number of assessments using trial trenches and the number of assessments using geophysical survey in development-led archaeology in Flanders under the current legislation (2016–2021) until early 2022

Year	2016	2017	2018	2019	2020	2021	2022/ unfinished	Total
Total number of assessments	1006	3353	2692	2927	3115	3392	30	16516
Number of assessment through trial trenching	44	368	590	699	790	818	42	3351
Number of assessment using geophysical survey		7	7	12	8	14	64	112

commercial archaeologists writing the survey requirements, due to an increased attention to world war archaeology (cfr. infra), etc.

Nevertheless, the number of assessments involving geophysics remains marginal compared to the total number of desk-based assessments and evaluations employing trial trenches (Table 1). While site scheduling projects (Fig. 1c: protection) were an important instigator of geophysical projects outside academia, a decrease in funding equally reduced their number since 2014. Such studies have, however, been partially replaced by geophysical studies aimed at land management planning (where no immediate threat is present) and restoration projects (mainly targeting churches and their direct surroundings).

3.6.4 Employed Survey Methods

Before the late 2000s, the employed methods followed the trends in the UK because primarily experts from abroad were performing geophysical surveys in Belgium. However, the local academic developments in EMI led to a marked increase in its usage from 2009 onwards. Currently, about 40% of all inventoried surveys were done with EMI, although Note (2019) creates an outlier (Fig. 3b). The importance of EMI contrasts to other countries (Bonsall et al., 2014; Jordan, 2009; Stamnes, 2016; Viberg et al., 2011; Visser et al., 2011), which illustrates the impact of local expertise development and personal preference on geophysical survey practice. While the potential registration of two geophysical variables (electrical conductivity and magnetic susceptibility) in multiple soil volumes is certainly advantageous, the measurement volume of existing EMI configurations and lack of multi-sensor arrays limits the archaeological application potential as well. Despite a lack of strong academic focus, magnetometer survey is the second most applied survey method and remains frequently deployed, due to its survey speed and ease of use. Excluding the EMI surveys by Note (2019), magnetometer surveys would even comprise a similar share to EMI surveys. After the success of magnetometer survey in several site scheduling studies, primarily on Roman sites, it is now used increasingly in development-led archaeology carried out in the loess soils in the south-east of Flanders. Nevertheless, despite a clear potential in loess soils of Wallonia (e.g. Quick et al., 2005), magnetometer surveys remain rare here. Depending on the survey aim and environment, investigations abroad issue caution in relying only on magnetisation as geophysical detection property however (e.g. Bonsall et al., 2014; Jordan, 2009; Viberg, 2012). While electrical resistance survey was used frequently in the early years of Belgian archaeological geophysics, the number of applications has somewhat stagnated, possibly due to its labour intensity. As such, resistance survey has been surpassed by GPR, which has seen significant growth in the past 5 years. This follows international trends and is not only influenced by local expertise development (e.g. Verdonck et al., 2009) but also by an increasing number of applications in complex archaeological stratigraphies as well as a larger market for GPR outside archaeology (e.g. utility detection). In addition, the increased ability to perform mobile surveys and to collect and process data more rapidly facilitates GPR applications. However, landscape-scale GPR surveys, ubiquitous in e.g., Sweden (e.g. Viberg et al., 2020) or Norway (e.g. Gustavsen et al., 2020), are not yet applied in Belgium, despite many regions with dry, sandy soils. Other geophysical survey methods are applied infrequently and only in case-specific circumstances.

4 Archaeological Resource Management and Legal Implementation of Archaeological Prospection

The necessity for preventive, legally supported, development-led archaeological prospection became clear due to an increase in rescue archaeological projects during the late 1980s and early 1990s. During those years, rescue archaeology happened mainly in reaction to ongoing developments, while a preventive approach could embed archaeological research within the development planning process. Also during that period, Belgian archaeological heritage management was federalised into three regions: Brussels (officially: the Brussels-Capital region), Flanders (officially: the Flemish region) and Wallonia (officially: the Walloon region). Today, this regionalisation has led to different approaches in archaeological evaluations and site management, which influence the implementability of geophysical methods.

4.1 Flanders

When comparing the three Belgian regions, geophysics is best embedded in Flemish development-led archaeology from a regulatory perspective because the execution of archaeological evaluations is highly liberalised and directly funded by the developers. Nevertheless, geophysical survey is exempt from requiring archaeological permits, due to its non-invasive nature, which is favourable to scientific applications.

Although the legal implementation of development-led archaeological survey started earlier (Bauters et al., 2002; De Clercq et al., 2012a), geophysical survey specifically was included in regulations from 2016 onwards. Before that date, the use of detectors, implying metal detectors and not geophysical survey equipment, was restricted legally to permitted archaeological excavations (Deckers, 2019). Since 2016, the Flemish decree and resolution on immovable heritage includes a code of good practice.[6] This code is legally binding and describes the minimal requirements for archaeological research, including the methodological boundary conditions, and includes geophysical survey. Since then, commercial contractors both prescribe and execute archaeological evaluations. The Flemish heritage agency has adopted a coaching role with limited enforcement capabilities, which are employed primarily only after report submission. After submission, geophysical reporting, which is included within archaeological assessment reports (*archeologienota's*), is screened by Flemish heritage agency officials. Feedback is rarely given and quality controlling or correcting measures are generally absent.

The code of good practice approves of geophysical approaches to archaeological prospection in development-led frameworks, while simultaneously requiring that geophysical results are tested in all cases with other types of archaeological information to allow reliable archaeological interpretation. It can therefore only be used to select areas for further evaluation. It also states explicitly that, in itself, any geophysical survey that does not indicate anthropogenic features is insufficient to conclude that an archaeological site is absent. If applicable, the use of multiple survey techniques is preconditioned by the code. Furthermore, a geophysicist (requiring an academic diploma evidencing expertise in executing and interpreting physical measurements of soils and sediments to detect natural and anthropogenic features) determines the methodology and techniques in collaboration with the Certified Archaeologist, executes field measurements, interprets and reports them. Technical survey requirements conform to international guidelines, such as the EAC guidelines for the use of geophysics in archaeology (Schmidt et al., 2015), or refer to published literature only to a limited extend. This contrasts starkly to better established methods where technical requirements are more explicit and international guidelines and literature are included in Flemish guidelines e.g. for trial trenching (Haneca et al., 2016) or borehole survey (Van Gils & Meylemans, 2022). The requirements related to reporting are described more extensively and should ascertain reliable and comprehensive documentation of the performed research. Unfortunately, digital geophysical data archiving with the owner or a heritage depot, albeit prescribed by the code for all archaeological data, is rarely undertaken by the Certified Archaeologist. Only the geophysical survey report is archived within the archaeological assessment report.

[6] https://www.onroerenderfgoed.be/de-code-van-goede-praktijk

4.2 Wallonia

In Wallonia, an archaeological directorate was integrated within the spatial planning administration providing financing directly from the government budget for development-led archaeology in 1991. Its objectives and methods of action were confirmed and clarified by decree in 2018 and 2019. In general, the *Agence wallonne du Patrimoine* prescribes and executes archaeological evaluations autonomously. Geophysical prospection is mainly carried out for academic purposes and is seldom prescribed in any of the development-led site assessments or excavations (ca. 100/year), due to the limited government budget awarded to development-led archaeology. Therefore, it is not regulated specifically.

4.3 Brussels

In Brussels, development-led archaeology was legally implemented in 2004. As part of the building permit, the Directorate of Cultural Heritage can require developers to allow for archaeological research. This research is funded by the regional government and publicly tendered to licensed institutions, currently primarily both Brussels Universities (VUB and ULB), the Royal Institute for Cultural Heritage and the Royal Belgian Institute for Natural Sciences. Due to a lack of applications, no legislative framework for geophysical prospection has been developed yet. Indicatively, two scientific geophysical surveys for archaeology are known within Brussels to this date.

5 Belgian Landscapes and Archaeological Geophysics

5.1 Land Use

Given its limited surface area and population of ca. 11.5 million (an average population density of 375 inhabitants per square kilometre), it is no surprise that a high proportion (17%) of Belgian land-use is reserved for urban area (CORINE-continuous and discontinuous urban areas) (Büttner et al., 2004), whereas the extent of artificially modified areas (urban fabric; industrial and commercial areas; transport infrastructure; (air-)ports, dump, extraction and construction sites; parks, sports and leisure facilities) covers 20% of the country area (Fig. 2b). This (discontinuous) urban fabric forms a challenging environment for many geophysical applications. Nevertheless, 92 out of 306 located surveys were performed here (Table 2). This might be due to the location of many developments at modern town edges in combination with the coarse resolution of the CORINE landcover maps. Nevertheless, many modern Belgian cities and villages have deep historic roots making them an

Table 2 CORINE land cover classes of the inventoried geophysical survey projects. The class of a survey was determined by the majority of the pixels within the survey polygon

CORINE land cover class	Survey project count
211—Non-irrigated arable land	98
112—Discontinuous urban fabric	72
242—Complex cultivation patterns	56
231—Pastures	22
243—Land principally occupied by agriculture with significant areas of natural vegetation	18
111—Continuous urban fabric	6
142—Sport and leisure facilities	6
311—Broad-leaved forest	5
121—Industrial or commercial units	3
133—Construction sites	3
421—Salt marshes	3
123—Port areas	2
222—Fruit trees and berry plantations	1
312—Coniferous forest	1
512—Water bodies	1
No data	9

important subject of archaeological investigation. In contrast, (Early) Modern city foundations are relatively rare. More often, historic towns exhibit significant (early) modern alterations and expansions.

Non-irrigated arable land, land principally occupied by agriculture with significant areas of natural vegetation and complex cultivation patterns form the largest share of the land use (45%) and are accessible to archaeological geophysics when the land is not cropped. Intensifying agricultural practices, however, are increasingly shortening the time window for geophysical surveys. Nevertheless, more than half of all geophysical surveys (n = 172) were done on such cultivated lands. One main downside of this type of land use is the strong impact of tillage on geophysical results. Particularly the sand, sandy loam, and loam regions of Belgium have a long tradition of intensive agriculture and annual ploughing, reaching depths up to 0.6 m, which has homogenised many archaeological soil features to the naked eye, possibly only leaving geophysical ghost features (Simon et al., 2012).

Pasture makes up 11.5 % of Belgian land use. While these managed grasslands could be considered the most geophysical survey-friendly of all land use classes, only a small number of surveys (n = 22) was performed here, owing mainly to the lower suitability of most remaining pastures for modern settlement.

Forests (mixed, broad-leaved, coniferous) cover 20% of Belgium and are primarily located in Wallonia. Geophysical survey accessibility is often problematic here, but with additional localisation efforts, good results can be achieved where undergrowth is restricted (e.g. Pisz et al., 2018; Sikora et al., 2015). Nevertheless, only six geophysical surveys have happened here, leaving substantial room for improvement, particularly for land management and scientific research. Through the application of LiDAR in the past decades, many previously unknown archaeological sites and landscape features have been detected under forest. Geophysical evaluation of such LiDAR features to establish the presence and nature of these potential archaeological remains would further add to our understanding of the archaeological potential of the Belgian forests.

5.2 Soils and Geology

Any overview of the use of geophysical methods in Belgian archaeology requires understanding the geological and pedological setting in which these techniques are implemented. From the coastal plain and its polder area across the loess belt and up the Ardennes down to Belgian Lorrain, the Belgian subsurface provides a diverse and challenging backdrop for archaeological geophysics. The subsoil geology of Belgium is dominated by sedimentary rocks in the south and a thick cover of unconsolidated quaternary clastic sediments in the northern part (Fig. 2d). Based on the composition of this quaternary cover, the governing soil types and the depth to the underlying bedrock, Belgian (sub)soils can be broadly divided into six groups: (1) heterogeneous clayey, silty, sandy, and even peaty soils of the coastal plains and river floodplains; (2) sand soils; (3) sandy loam soils; (4) loam soils; (5) soils developed on shallow bedrock; and (6) urban soils. Within each of these soils, quartz makes up the bulk of the soil mineralogy and is complemented by clay minerals of which illite and kaolinite in the Ardennes (Mango-Itulamya et al., 2019) are the most common. Across the Belgian territory, these soil groups share some common geophysical characteristics. In general, the soil electrical conductivity can be considered as moderately conductive (e.g. Sillanpää, 1982) i.e. in the 10^{-3} to 10^{-2} S/m range. Exceptions exist in the coastal areas where saline groundwater is sometimes located within the first two meters below the surface (Gould et al., 2021). Such circumstances equally occur in the estuarine polder areas and along certain sea canals, where seawater seepage increasingly pressures overlying freshwater lenses, locally driving near surface electrical conductivities in the 10^{-1} to 10^{0} S/m range (Delefortrie et al., 2019; Gould et al., 2021). Since unconsolidated deposits are governed by the diamagnetic quartz fraction complemented with clay minerals, whereby naturally occurring magnetic iron oxides result primarily from pedogenesis and in absence of igneous parent materials, the shallow subsurface has an overall weak magnetic signal.

Unsurprisingly, the inventoried survey projects are located mainly on clastic sedimentary ($n = 88$), sand ($n = 74$), silt ($n = 41$), and clay ($n = 84$) geology (Table 3). Yet, few surveys occurred on consolidated geology, such as chalk ($n = 7$), limestone ($n = 3$), clastic mudstone ($n = 1$) and impure carbonate sedimentary rock ($n = 1$), despite high geophysical contrast expectations for archaeological features cut into consolidated bedrock. Consolidated geology occurs mainly in Wallonia, but the mostly sedimentary nature is not expected to hinder geophysical applications (Bonsall et al., 2014, p. 42).

Table 3 Subsoil lithology survey counts (derived from Geological Unit-lithology of the pan-European Surface Geology (EGDI)

Lithology	Count (*)
Clastic sediment	88
Clay	84
Sand	74
Silt	41
Chalk	7
Limestone	3
Clastic mudstone	1
Impure carbonate sedimentary rock	1
No data	7

When considering the topsoil (on the Flemish and Wallonian soil maps), almost one third of all surveys have occurred on loam (n = 67) (Fig. 2c: Haplic Luvisol), sandloam (n = 36) (Fig. 2c: Haplic Albeluvisol) or gravelly loam (n = 6) soil textures, employing a representative range of all available survey methods. A relatively small share of surveys happened on lighter soil textures, such as sand (n = 14), loamy sand (n = 18) and light sandloam (n = 19). The full range of techniques is represented here as well, but the limited number of GPR surveys (n = 9) on these soil textures is remarkable because the low signal attenuation of sandy soils benefits GPR applications. Particularly in the sandy soils of Northern Belgium (Fig. 2c: Gleyic, Haplic and Umbric podzol), more GPR applications are possible. On finer soil textures (clay and heavy clay), primarily of the coastal and river floodplains (Fig. 2c: Eutric fluvisol), 42 surveys were performed, mainly with EMI. Only three surveys on areas with mainly (heavy) clay soils were done with GPR, all of them on (moated) castle sites.

Aside from the geophysical properties of the soil matrix, its age is also relevant for the success of geophysical surveys. Stratigraphically younger sediments can impede detection of older archaeological remains due to their thickness or geophysical heterogeneity. A clear example are river- and coastal floodplains with (Late) Holocene sedimentation cover that protect but also impede detection of earlier archaeological remains. Furthermore, these overlying sediments often also incorporate more recent archaeological remains. The survey inventory shows that 139 geophysical surveys were performed on such floodplain sediments, where other methods are often challenged as well. In recent years, these embanked floodplains are reactivated purposefully to combat flooding (Smolders et al., 2020). This has destructive, erosive as well as protective, sedimentation effects on archaeological remains. However, it certainly hinders future prospections, which must be considered during development-led archaeological evaluations.

Similar to floodplain sediments, artificially raised soils impede geophysical detection of earlier remains, which is specifically important in the sandy soils of Flanders, since these have known significant *plaggen* soil formation since the Middle Ages (Bastiaens & Verbruggen, 1996). The thickness of this cover can be highly variable, however (e.g. Van Hove, 1997). Nevertheless, 15 surveys intersect with this mapped soil type. Many cities have also known historic and more recent

Table 4 Topsoil texture survey counts (derived from Flemish soil map 2.0 and Digital map of Soils of Wallonia)

Soil texture	Count (*)
A: Loam	67
OB: Built area	47
L: Sandloam	36
OT: Strongly altered soils	25
U: Heavy clay	21
E: Clay	21
P: Light sandloam	19
S: Loamy sand	18
Z: Sand	14
ON: Raised soils	7
G: Gravelly loam	6
OG: Debricked soil	4
OU: Depeated soil	3
L-E: Sandloam & clay	2
OC: Lost habitation	2
S-P: Loamy sand & light sandloam	1
V: Peat	1
M: Marl	1
A-L: Loam & sandloam	1
OE: Quarry	1
No Data	9

anthropogenic soil raising, impeding the detection of structural archaeological remains. Indeed 72 surveys were mainly done in areas mapped as built (code OB on the Flemish soil map and in Table 4) or strongly altered (code OT), already at the time of the soil map creation. Additionally, many areas along harbours and rivers have been raised (recently) for flooding protection, impeding geophysical detection of buried features. Seven surveys have been performed here (code OT). In addition, 10 surveys were done where the soil maps contain traces of other anthropogenic and possibly archaeological soil altering, mapped as lost settlement (code OC), debricked soils (code OG), de-peated soils (code OU) or quarrying (code OE).

5.3 Archaeological Geophysics in (Natural) Palaeolandscape Studies

Soils and sediments are not simply considered as matrices for archaeological remains in Belgian archaeology but are also subject of archaeological research themselves to prospect new sites and to contextualise already known sites, most often in floodplains. In the past, direct sediment and soil observations through coring or trenching were mainly employed for palaeolandscape mapping but these become less (cost-)effective as the required spatial resolutions, targeted depths and the development areas increase. While direct push sensing is one solution to overcome some of these challenges (Verhegge & Delvoie, 2021), buried palaeolandscapes are mapped increasingly using EMI. Another added value of geophysics in these studies lies in the detecting ‘off-site’ phenomena (e.g. land divisions and hydrographic networks), which are more easily missed through invasive methods. However, since these studies mainly aim to map natural landforms (De Smedt et al., 2013a) and larger anthropogenic land structuring features (Verhegge et al., 2017), the employed traverse spacings of these studies are somewhat larger (2–4 m) than the traverse spacings needed to establish the presence and nature of archaeological remains.

Geophysical palaeolandscape surveys occur particularly in prehistoric archaeology, e.g. along Late Glacial palaeolakes (De Smedt et al., 2013b) or in mapping peat and coversand palaeolandscapes below polders (Verhegge et al., 2016a), but also increasingly in the study of medieval reclamation landscapes (Verbrugghe et al., 2020). Also, in development-led archaeological evaluations, more precise palaeolandscape reconstructions could significantly decrease archaeological prospection costs, e.g. of archaeological core sampling (Crombé & Verhegge, 2015). For example, palaeolandscape EMI survey has already covered >4 km^2 of polders in the Antwerp harbour area.

Nevertheless, despite examples abroad (e.g. Chapman et al., 2009; Schneider et al., 2017) and suitable research questions (e.g. Usselo palaeosols as Final-Palaeolithic site context or early medieval sites below coastal dunes), GPR for palaeosol and palaeolandscape mapping is barely applied in the sandy soils of Belgium.

6 Frequently Occurring Archaeological Features or Sites in Belgium and Examples of Their Geophysical Surveys

6.1 Soil Features in Unconsolidated Deposits

The heterogeneity of the Belgian subsurface is matched by the complexity of its archaeology. In the unconsolidated deposits that govern the northern half of the country, many traces of past activity are ephemeral in their physical expression and resultant geophysical contrast. This is particularly true for (low-density) rural occupation traces throughout prehistory and well into the early historic period, which consist primarily of ‘negative’ features, such as postholes, humified remnants of wooden posts, pits, wells and ditches, and continues to be relevant until the late medieval period, due to scarce use of solid building-materials (natural rock and brick). Since little sedimentation has taken place outside floodplains after the start of the Holocene, the poor edaphic conditions and vulnerability to agricultural activity of the dryland settings provide little preservation potential for archaeological remains. Indeed, on many sites archaeological soil features are strongly homogenised with the soil matrix and/or only the bottom parts are preserved below the ploughing horizon. Together, this configuration translates to poorly detectable contrast for non-invasive survey approaches. Nevertheless, significant results can be obtained in the right conditions.

In the sand region, even relatively subtle features, such as organic layers within or gleying associated with the ditch fills of Bronze Age barrows (Verdonck et al., 2009) or more obvious medieval moats (Saey et al., 2014), have been mapped with GPR. Furthermore, presumed medieval soil features related to longhouse structures were detected using magnetometer survey at Snellegem (Loveluck & Tys, 2006). The origin of this contrast remains understudied, but it is one of few examples where magnetometer survey has detected assumed posthole structures in the sandy soils. Nevertheless, the ability of geophysical methods to map such low density settlements (although not in all circumstances) showcases the complementarity to standardised systematic trial trenching, which risks missing exactly these sites (De Clercq et al., 2011). Furthermore, at Maldegem-Kleit, a Roman/medieval enclosure site in a sandy soil overlaying a clayey geology, both the electrical conductivity and magnetic susceptibility data of multi-receiver EMI survey produced complementary results (De Clercq et al., 2012b; Saey et al., 2013). While the conductivity revealed the geological variation as well as ditch fills, the magnetic variations subtly revealed parts of these ditches and pits in the shallowest data layers. Since ditches were important features in land drainage and management in protohistory, Roman and medieval times in the low-lying areas of Northern Belgium, the ability to map enclosures or moated sites using their ECa contrast is valuable. However, many archaeological features at the site of Maldegem-Kleit did not exhibit magnetic enhancement, illustrating the perils of relying on one geophysical variable to study such subtle features. Interestingly, the magnetic variations did preserve within the ploughing horizon, demonstrating the danger of discarding topsoils archaeologically, which occurs all too often using trial trenching in development-led archaeology. In fact, the value of topsoil archaeology in combination with archaeological geophysics is further exemplified by the correlations between AAS and EMI survey at artefact rich sites, such as the lost harbour settlements of Hoeke and Monnikerede in the coastal plain (Trachet et al., 2017a). Even where pasture hampers walkover survey, molehill survey results have proven to correlate well to geophysical data (Trachet et al., 2017b).

In the loess region, archaeological soil features are occasionally nearly invisible to the naked eye. In one such case, a magnetometer survey was performed directly on top of an excavation surface and revealed several additional posthole structures (Celis et al., 2014), highlighting the benefits of non-standard survey strategies. Also in loess soils, a magnetometer survey at Waremme-Longchamps (Quick et al., 2005) has unveiled Neolithic enclosure ditches and longhouse features. The latter were not caused by postholes, but by domestic pits along the outer edges of the house walls, similar to discoveries in Riemst (Sevenants et al., 2011). As early as 1975, electrical resistance traverses over a cropmark feature uncovered an unmetalled road at a loess site in Sauvenière (Léva & Hus, 1975), which calls for more investigations of such features in the Belgian loess.

6.2 (Brick-)stone Features in Soft Soils

(Brick-)stone archaeological features and structures are known to exhibit better electrical and dielectric contrast within soft soils than soil features (Conyers, 2013; Gaffney & Gater, 2003; Schmidt, 2013). Within a low magnetic background, ceramic building materials demonstrate a magnetic contrast as well (Aspinall et al., 2008). While stone construction materials are widely available in Wallonia, their impact on geophysical survey results is rather limited due to a lack of surveys. However, the GPR results of the Roman villa of Mageroy illustrate the potential in mapping natural stone walled structures in a (locally) unconsolidated soil (Baltus et al., 2019). In the loamy to sandy soils of northern Wallonia and Flanders, natural stone building materials are only present in few areas and often consist of low quality sandstones. Therefore, they only started to be used in the Roman period for constructing more monumental structures and infrastructure. The Roman age also signifies the first use of ceramic building materials. As such, successful magnetometer surveys were performed on several vicus sites in the loess region (Charlier et al., 2001; Wesemael & Nicholls, 2014). In the Middle Ages, stone building materials restarted to be used in the 10th century in northern Belgium, mainly for monumental structures (e.g. churches). From the 14th century onwards, particularly brick masonry is considered a more common building material (Debonne, 2015) and smaller quantities were also used as footings and foundations of common wooden structures. As such, geophysical methods are widely used in (post-)medieval archaeology, for instance charting rural buildings in the outer court of the abbey of Boudelo using EMI magnetic susceptibility (De Smedt et al., 2013c), as well as monumental castles (Simpson et al., 2009).

Thanks to the success in mapping (brick-)stone remains, appropriate survey strategies are readily available to map such sites in soft soils with magnetometer survey, electrical resistance survey or ground penetrating radar survey, depending on the background soil and research questions in academic research, in site scheduling and increasingly in development-led archaeology.

6.3 Complex Urban Stratigraphies

In Belgium, complex stratigraphic sequences primarily occur in urban settings. Few cities, such as Tongeren (Wouters et al., 2019) and Tournai (Devos et al., 2020) have a significant Roman stratigraphy . However, many urban centres developed during the Middle Ages (Devos et al., 2020). As such, 58 historic city centres are protected archaeologically (Archeologische Zone) in Flanders. However, due to their continuous habitations, structural remains are frequently covered with thick deposits of urban waste as well as modern (underground) infrastructure. Therefore, historic city centres form complex environments for geophysical applications. Nevertheless, 26 surveys have already happened within the border of protected historic medieval town centres in Flanders. Unsurprisingly, 18 of these surveys were done with GPR, due to the complexity of the vertical stratigraphies. A significant proportion of these are church studies where the subsoil is mapped in the framework of renovations. The city centre of Brussels has only seen one geophysical survey on its central square, but it did reveal several basement structures illustrating that the square did not always function as such (Tabbagh et al., 2019). On the other hand, a GPR survey on the quays of Antwerp illustrated the difficulties in acquiring useful results in urban settings (Verdonck, 2010).

6.4 World War Battlefields

The well-inventoried historic aerial photographs of the World Wars form a significant resource for desk-based research. Geophysical methods (primarily EMI and magnetometer survey) are used increasingly as research tools by themselves or as an intermediary step before invasive trenching to accurately locate and check the presence of photographed traces. As such, an important cluster of geophysical research projects is located along the frontlines of World War I. The work of two archaeological geophysicists, P. Masters (Masters & Stichelbaut, 2009) and particularly N. Note (e.g. Note, 2019; Note et al., 2019; Saey et al., 2016a), has resulted in a marked concentration of surveys here. Evaluating World War I remains forms an important part of archaeological practice and development-led archaeology in this region, not only for heritage management but also for unexploded ordnance detection (UXO) and retrieval of human remains. Since the relatively recent age of the conflict, remains are usually well preserved. In addition, the soil impact is large, particularly where the frontline was relatively stable for longer periods and infrastructure was dug deep into the subsoil, leading to significant electrical contrasts. Furthermore, the materials used are very often (at least partially) ferrous, increasing the magnetic signal, which can be both supportive, if associated with features, and disadvantageous, if creating survey noise. As such, primarily EMI and magnetometer survey have identified trenches and associated structures, bomb and mine craters, military camps, tank remains, etc. (Note, 2019 and references therein). Following the academic research results, the implementation of geophysical methods in development-led archaeology has already started on these site types and is projected to grow in the future. Despite the absence of a legal framework that encourages active grave detection or UXO detection, EMI data filters to detect large metallic objects (Saey et al., 2011) and spatial analyses integrating EMI data and historical photography have been developed (Note et al., 2018). Integrated geophysical surveys for development-led archaeology, grave and UXO detection happen on an *ad hoc* basis on World War sites.

7 Discussion and Conclusion

7.1 From Academic Research Tool to Development-Led Archaeology

While pioneers made significant developments, Belgium's reliance on expertise in archaeological geophysics from abroad limited applications until roughly 15 years ago. Since then, particularly in Flanders, local expertise development in EMI and GPR survey has led to increased geophysical applications, including other methods. Especially in the widespread use of EMI, Belgium is spearheading internationally. However, Wallonia and Brussels are still seeing few geophysical surveys. Nevertheless, the different legal implementation of the Valletta convention could allow wider prescription and application of geophysical survey by the regional governments here if expertise is obtained (in Flanders or elsewhere) and government budget constraints allow it.

Early geophysical applications were mainly conducted in the framework of academic research or for site scheduling. Nowadays, academic research projects incorporate geophysical methods in a systematic way and as part of environment-adapted multi-method prospection protocols in landscape archaeology. In development-led archaeology, on the other hand, geophysical survey is only used in a negligible share of evaluations. Still, these applications have risen significantly over the past decade in Flanders, despite an awkward legislative implementation in commercial archaeology. These applications, and their success, unfortunately remain highly dependent on the individual archaeologist commissioning, and the geophysicist executing the survey. Moreover, these surveys are often stand-alone operations with little targeted invasive evaluation, feedback nor a full integration with other (archaeological) survey methods applied, most likely because of financial reasons, time constraints, lack of communication, etc.

Geophysical methods do not only need further integration within the development-led archaeological project management. Another pathway to a more widespread implementation could lie in drawing closer to the application of geophysics in other types of project management. After all, similar geophysical methods are also used in applications such as the detection of unexploded ordnance, utility mapping, groundwater studies and precision agriculture. Data sharing between these fields, which hinges on increased awareness and open cross-disciplinary and -institutional communication, could create mutual benefits.

7.2 Guidelines, Commission, and Training in Development-Led Archaeology

Through the results of the past years, the need for international guideline implementation is showing increasingly to enable a fair market and achieve optimal results. Nevertheless, the rigid approaches used in Flemish commercial trial trenching and borehole survey illustrate both the benefits and risks of standardisation. Since universally applicable technical methodologies are nearly impossible to make, it would be more practical to follow a discursive approach as suggested by Schmidt (2019) and to implement the EAC Guidelines for the use of geophysics in archaeology (Schmidt et al., 2015) in the code of good practice in Flanders. This should result in more detailed, prescriptive project specifications than at present.

However, the EAC guidelines recommend involving expertise of archaeological geophysicists in designing project specifications. In the future, this could fit well within current development-led archaeological practice in Wallonia and Brussels. However, this would not fit well within the current practice in Flanders. Here, archaeological briefs are designed commercially, cheaply and in a relatively standardised manner. An archaeological contractor decides if geophysical survey is applicable when writing the desk-based assessment and selects further research measures, often without involving geophysical experts. In addition, geophysical survey is often perceived as an additional cost, since invasive prospection has to be applied as validation anyway. Deviating from the standard code of good practice, the commission of a geophysical survey increases the cost of designing an archaeological brief as well as executing an evaluation. Therefore, geophysical and other non-invasive methods are rarely prescribed within this commercially driven rigorisation of survey methodology in a development-led archaeological heritage management environment.

Moreover, if geophysical survey is used at all, the most appropriate methods are not always applied. Hence, further methodological education and training of archaeologists is required as well. This has to be combined with further expertise building to establish integrated survey protocols and make geophysics a fully-fledged tool in the non-invasive assessment of the Belgian archaeological record.

7.3 The Importance of Prior Knowledge

Whilst the geology of Belgium is supportive to many geophysical applications, its soils are highly variable and require significant geophysical expertise for optimal results. The complexity of land use amplifies this necessity, because it might impede geophysical survey results. Inherent to geology and soils in northern and central Belgium, the nature of settlement soil traces (e.g. postholes) is rather ephemeral in the absence of deeply dug archaeological traces, particularly in the absence of (brick)stone.

Considering the risks involved in missing archaeological heritage of low-density soil feature sites (unrecorded destruction), a general development-led application of geophysical survey replacing or as efficient as systematic trial trenching could not be advocated. The past results have shown that if archaeological and geophysical prior knowledge is available about the nature and setting of a site, well-reasoned decisions can be made to use geophysical methods efficiently in combination with invasive methods, generating added knowledge values.

However, development-led applications without sufficient prior knowledge on both the archaeology and the (natural) background of the site are ill-advised as argued by Hulin and Simon (2020). Indeed, in many development-led projects the archaeological remains as well as their geophysical signal are indeterminable at the start of the project.

If investigated sites are not threatened (e.g. academic research, protected site management or site scheduling studies), a landscape-based combined array of non-invasive studies should always be given preference, if they can answer the research questions and/or optimise later invasive research. In these cases, the threat of non-detection is smaller and often only resulting in reduced archaeological scientific knowledge, rather than unrecorded destruction.

7.4 Benefits of Geophysical Methods in Archaeological Prospection

While the cost-effectiveness for coverage of geophysical methods in comparison to systematic trenching is often argued, this can only be achieved if significant prior knowledge of the site's archaeology and pedological background is available (Hulin & Simon, 2020). Without this prior knowledge, multi-method and high-resolution geophysical survey would still need to be complemented with systematic trial trenching to evaluate the broadest range of possible archaeological remains, increasing costs significantly. However, recording geophysical variables in addition to visual inspection of the trench surface would include those 'ghost' features with a geophysical signal but invisible to the naked eye or those preserved in the topsoil.

Since geophysical methods are mostly non-destructive, their application could be beneficial as a risk management tool to avoid the damage of valuable archaeological remains in cases where development plans are adaptable. However, the selection of 'empty' areas for adapted development plans still require further evaluation because a lack of geophysical evidence of archaeological remains cannot be interpreted as an absence of archaeological remains.

In addition, certain pedological or geological environments (e.g. coastal regions or fluvial floodplains with shallow groundwater tables) are particularly challenging environments for standard systematic trial trenching or require costly coring surveys. In these circumstances, geophysical survey can guide these efforts and increase the (cost-)efficiency of these actions.

Specific types of archaeology, such as Neolithic settlement traces on sandy or loess soils, are also hard to detect through trial trenching, due to a lack of visible contrast or the sparse spatial layout of the features. If the detectability of such features is established, the density of geophysical measurements facilitates mapping structures and site layouts.

Indeed, a lack of visible contrast does not necessarily exclude geophysical contrast or vice versa. As such, predicting geophysical contrast is essential to optimise survey choices further in the future (e.g. Verhegge et al., 2021). Ongoing geophysical research of archaeological features as well as natural soil variations aims to derive geophysical contrast from (dynamic) soil properties quantitatively and may prove valuable (Boddice et al., 2013; Fry, 2014; Schmidt et al., 2017; Schneidhofer et al., 2017). However, geophysical experts can currently also provide qualitative answers here. Further integration of geophysical data with other methods beyond the qualitative level is currently investigated academically and may lead to more widespread application in the future. However, this will require including geophysical expertise in projects in a more comprehensive manner, beyond the non-invasive, prospective phase.

7.5 Data Archiving and Publishing

The analyses of this paper were based on a superficial (metadata) analysis of an inherently incomplete survey record. Not all surveys were fully reported and not all reports were publicly available. However, this has improved in Flanders, where development-led reports are publicly available since 2016. More in-depth analyses require at least access to all reports and preferably the (raw) survey data themselves. This currently impossible of a lack of archiving of old reports and geophysical data in general.

Under current practice, the inventory of this significant resource risks becoming insurmountable, as has happened to the Belgian oblique aerial photographic record. Without proper data archiving and publishing strategies in place, gathering legacy geophysical survey data in person is currently time consuming and sometimes impossible (see Bonsall et al., 2014), often preventing reuse of collected datasets. Although international archiving guidelines exist (Schmidt & Ernenwein, 2013), few guidelines are implemented except for the limited prescriptions in the Flemish code of good practice (Hacıgüzeller et al., 2021; Lombaert & Vanstappen, 2014). The necessary data infrastructure is currently absent. In addition, while legislation obliges archiving of the digital and physical archaeological ensemble either in archaeological archives or by the owner, this is rarely enforced (and therefore scarcely practised) in geophysics. Thus, geophysical data archiving and publishing relies on the goodwill of the archaeological geophysicists themselves.

7.6 Archaeological Feedback

To further deepen analysis of geophysical contributions to archaeological research (questions), the often-linear trajectory in development-led archaeological evaluations (desk-based assessment > prospection > excavation > archiving) needs to be left and an archaeological feedback loop created by both archaeological geophysicists and field archaeologists. On the one hand, this could inform geophysical experts about the reliability their interpretations and bolster future interpretations. On the other hand, this provides the archaeologist with improved interpretations as well as a better understanding of archaeological geophysics. This needs to happen at least after invasive investigations but preferably during them to allow for in situ- or excavation surface geophysical measurements. Only in these circumstances, the actual contribution of geophysical survey to answering archaeological research questions can be assessed in more depth.

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Part III
Bulgaria

Synergy of Environmental Magnetism and Archaeomagnetism for the Benefit of Archaeology—State of the Art in Bulgaria

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Abstract Environmental magnetism is recognised as a sensitive tool for reconstructing various processes related to the iron cycling in the terrestrial environment. Besides, archaeomagnetism as an interdisciplinary method in archaeology provides geophysical tools for dating and synchronisation of burnt clay remains throughout the last ~8000 years. Linking both research directions opens up far-reaching opportunities for a complex characterisation of ancient human occupation and its impact on the environment. In this contribution, we summarise the state of the art in the synergetic application of the archaeo- and environmental magnetism carried out in Bulgaria during the last decades. We showcase various examples from our practice to demonstrate the potential of this approach for enhancing our understanding of the ancient world.

1 Introduction—Basic Principles of Environmental Magnetic Technique Applied to Archaeological Context

The principles of environmental magnetism are based on the link between the set of (soil) environmental parameters, such as for instance climate (through temperature and precipitation), lithology, time (Schaetzl & Anderson, 2005) and related dynamics of iron (oxy)hydroxides synthesis conditions and transformation pathways (Cornell & Schwertmann, 2003). The impact of human's influence on the above association is in the core of the application of environmental magnetism techniques in archaeological prospection (Fassbinder, 2015) and artefact research.

The incorporation of environmental magnetism approach into archaeological research has been rather sparse so far, and focused mainly on investigations of anthropogenic deposits in caves (Vergès et al., 2016; Carrancho et al., 2016), while

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applications to other archaeological contexts are rare (Mooney et al., 2003). Therefore, a need to demonstrate the high potential impact of applying environmental magnetism approach in various topic-oriented archaeological frameworks is welcome. In this contribution, we intend to summarise our experience on the application of magnetic investigations of soils, sediments and archaeological materials of fired clays and show major possible fields of applicability, providing potentially high impact for archaeology. In this respect, this summary fits with the general objectives of the SAGA COST Action to create a better and mutually beneficial link between archaeo-geophysics and archaeology.

The major mineral magnetic parameter in environmental magnetism is volume low-field magnetic susceptibility (k, measured in SI units) or mass-specific magnetic susceptibility (χ in units m^3/kg). The concentration of strongly magnetic iron phases in the measured material is the major factor, determining the magnetic susceptibility value, although grain size of the magnetic fraction also plays a role (Thompson & Oldfield, 1986). Magnetic properties of soils are widely utilised as receptive recorders of paleo-environmental conditions during their development (Liu et al., 2012; Jordanova, 2016; Maxbauer et al., 2016). Magnetic grain-size sensitive parameters additionally enlarge the toolbox for extracting relevant paleoenvironmental information from soils. Frequency-dependent magnetic susceptibility (χ_{fd} or $\chi_{fd}\%$) provides important indications of the presence of very fine nanometre-sized magnetic particles which are usually of pedogenic origin in natural soils (e.g. Maher, 1998). Laboratory-induced remanent magnetisations—Anhysteretic (ARM) and Isothermal (IRM)—give further grain-size sensitive traces, linked to (pedogenic) formation of stable single-domain magnetite grains (Maher & Taylor, 1988) and/or presence of weakly magnetic hematite and goethite mineral fractions, respectively. Identification of the mineral magnetic phase(s) in natural materials additionally provides knowledge about the processes and stability of iron containing mineral phases which are related to environmental factors (Cornell & Schwertmann, 2003).

Archaeological remains of burnt clay are composed of fired natural materials (clays, soil, sediments, etc.) which have been strongly influenced by thermal processes. Firing to high temperatures causes various thermo-chemical transformations in the clay/soil mineralogy including dehydration, oxidation, dehydroxylation, decomposition and formation of new phases (Murad & Wagner, 1998; Murad, 1998). Along with the change of all physical/chemical properties, magnetic properties of fired clay are also strongly influenced by heating (Le Borgne, 1955; Jordanova et al., 2001; Beatrice et al., 2008). Thermo-chemical growth of new iron oxides drives the magnetic enhancement of fired materials through formation of strongly magnetic phases like magnetite and maghemite (Murad & Wagner, 1998; Wagner et al., 1998), although prolonged firing in air results in dominance of weakly magnetic hematite (α-Fe_2O_3) and/or other Fe_2O_3 mineral phases, such as ε-Fe_2O_3 (McIntosh et al., 2007).

A compilation of basic magnetic data of archaeological materials from fired clay remains provides a general overview of the distribution and variability of magnetic susceptibility (χ) and frequency dependent magnetic susceptibility ($\chi_{fd}\%$). Materials from burnt clay (e.g. house destructions; burnt soil; remains of unknown origin), bricks (from AD period) and hearth/kilns (materials from preserved structures (hearths, kilns, ovens)) are compiled from the collection inventory of the Bulgarian archaeomagnetic database (Kovacheva et al., 2014). The pottery data originates from ceramic fragments from six major ceramic manufacturing centres in Bulgaria. Histograms of χ and $\chi_{fd}\%$ distribution are shown in Fig. 1. The data demonstrate that the magnetic susceptibility of different archaeological materials varies over a wide range, but in all materials χ is positively skewed (Fig. 1). The highest median is obtained for pottery and the lowest for baked clay. Positive skewness is frequently observed for environmental variables, which cannot take negative values and are thus constrained by zero (Parkin & Robinson, 1992). Although the highest number of samples investigated from baked clay and hearths/kilns have their χ between (100–300) * 10^{-8} m^3/kg (Fig. 1), a second group in the range (400–600) * 10^{-8} m^3/kg could be noticed. The most scattered is the histogram of χ for brick materials. Percent frequency dependent magnetic susceptibility ($\chi_{fd}\%$) exhibits differing distribution for the four materials categories. For baked clay the $\chi_{fd}\%$ distribution is close to normal, for hearths/kilns it is negatively skewed (Fig. 1) and for bricks it is positively skewed. Pottery materials show also negatively skewed histogram. Nevertheless, calculations of the median $\chi_{fd}\%$ gives a value of 8% for all kind of materials. The distribution of $\chi_{fd}\%$ values across the various baked materials suggests that firing produces the most significant portion of fine superparamagnetic grains during brick's production because among all materials more brick's samples exhibit $\chi_{fd}\% > 8$ (Fig. 1). This is consistent with the production technology of the materials, requiring high firing temperatures, usually well above 850–900 °C for a prolonged time (Boccalon et al., 2019; Lopez-Arce & Garcia-Guinea, 2005), while ovens/kilns for domestic usage and spontaneous firing (for the class of baked clay materials) commonly do not achieve such high temperatures. In contrast to those

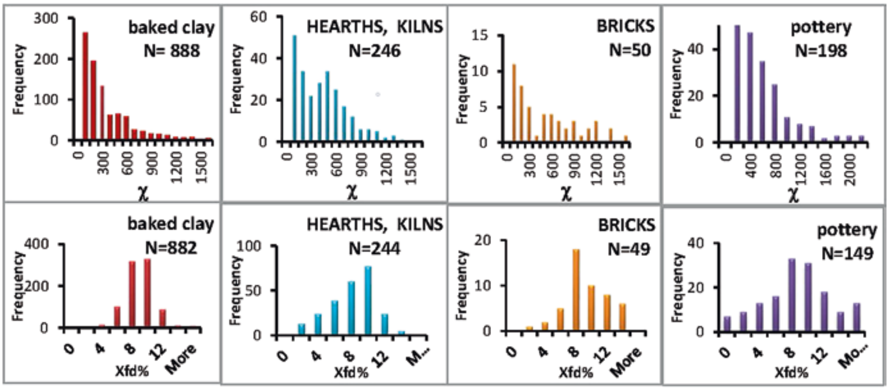

Fig. 1 Histograms of mass-specific magnetic susceptibility (χ) in "10^{-8} m^3/kg" and percent frequency dependent magnetic susceptibility ($\chi_{fd}\%$) for various types of archaeological materials of fired clay—"baked clay" (fired destructions; burnt soil; remains of unknown origin); hearths/kilns (materials from preserved structures); bricks and pottery. "N" denotes the number of samples included in each category

fired structures, natural soils exhibit much weaker magnetic enhancement, reaching usually (80–100) * 10^{-8} m^3/kg and depending on the soil type and respective inherent pedogenic processes (Jordanova et al., 2016). It should be noted, however, that anomalously high soil susceptibilities may be obtained for natural soils developed on strongly magnetic parent materials (Grison et al., 2015).

2 Magnetic Susceptibility and Equivalent Firing Temperature of Archaeological Remains of Burnt Clay May Yield Functional Information About Ancient Environmental Settings

In a recent study (Jordanova et al., 2020a) we investigated burnt clay materials resulting from destructive open fires, not related to human house-hold activities (cooking, ware production, etc.). The collection includes materials from 18 Neolithic sites from Bulgaria. The most important characteristic of all sites is that they were affected by an extensive fire which ended their existence. These sites are dated between ~6000 BC and ~4000 BC, spanning the local Early- Late Neolithic and Eneolithic periods (Görsdorf & Bojadziev, 1996). The aim of the investigation was to probe the sensitivity of the basic magnetic property parameters against the most important environmental variables playing role (e.g. climate, lithology, time). In addition to low-field susceptibility and frequency dependent magnetic susceptibility, we involved in the analysis results from the evaluations of the maximum firing temperatures achieved during fire (T_{fire}). Determinations of T_{fire} were accomplished utilising the method proposed by Rasmussen et al. (2012). This method is based on the assumption that during ancient pottery firing the fraction of iron (oxy)hydroxides in the initial clay material was chemically transformed due to heating and thus the magnetic mineral fraction would be thermally stable during laboratory re-heating to temperatures lower than the maximum ancient firing temperature. When passing this threshold temperature, iron oxides would continue further transforming along with the appearance of new or the disappearance of existing magnetic minerals. Thus, the abrupt change in magnetic susceptibility during laboratory re-heating tentatively indicates the maximum firing temperature achieved during the ancient pottery production (Rasmussen et al., 2012). More details on the methodological aspects can be found in Jordanova et al. (2020a) while here we would like to focus on the main outcomes related to geoarchaeological aspects. Results for the firing temperature estimates are considered at *site* level taking the average of all the individual determinations. Further on, data obtained at site level are considered according to the division of the Neolithic period in the Balkan Peninsula, as used in Marinova and Ntinou (2018). The summary of the T_{fire} estimates for each period is shown in Fig. 2 using bean plot (*BoxPlotR* software (http://shiny.chemgrid.org/boxplotr/) (Spitzer et al., 2014)). Together with the calculated median T_{fire} value, individual determinations are also visualised along with the data density distribution.

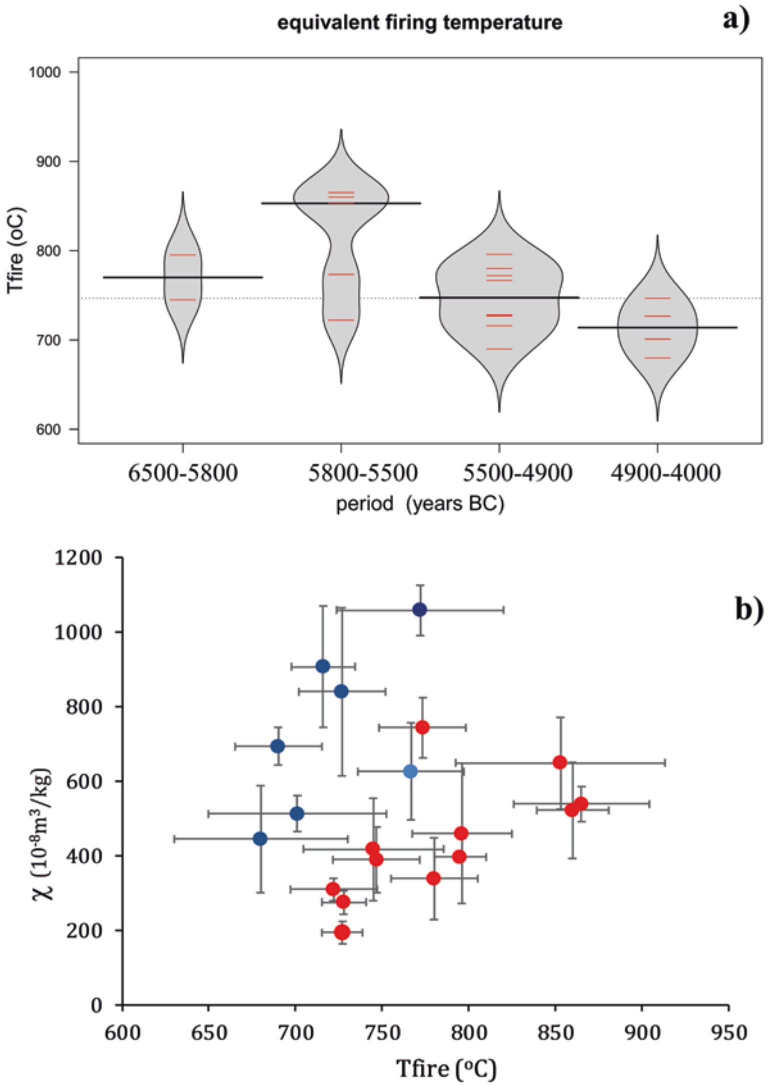

Fig. 2 (**a**) Bean plot of the distribution of firing temperature estimates (T_{fire}) for the four time periods. Black bold lines show the medians; red lines represent individual data points; shaded polygons represent the estimated density of the data. Plot created using BoxPlotR software (http://shiny.chemgrid.org/boxplotr/) (Spitzer et al., 2014); (**b**) bi-parametric plot of magnetic susceptibility (χ) versus firing temperature (T_{fire}) averaged at site level. Each data is represented with its standard deviation in both parameters. Red symbols denote sites located in south Bulgaria (relative to the Balkans mountain chain), while blue symbols denote sites from North Bulgaria

As it is seen in Fig. 2a, a highest T_{fire} ~ 815 °C median is attained in the period 5800–5500 BC, followed by systematically lower T_{fire} medians in the succeeding periods of the Neolithic. Plotting the relation of magnetic susceptibility vs. T_{fire} (Fig. 2b) estimates at site level, two distinct trends are clearly observed—the steeper linear trend is obtained from sites located in North Bulgaria (blue symbols), while all other sites located south from the Balkan chain obey to a different linear tendency. This implies that for the same T_{fire} estimates burnt clay from the sites located at the Danube plain (north from the Balkan Mountain chain) acquire a stronger magnetic susceptibility when compared to the other sites. The major influencing factor should be sought in the lithological differences in surface geology across the territory. In the Danube area the main lithological unit is represented by loess deposits (Evlogiev, 2006), with significant content of calcium. In contrast, sites from south Bulgaria were built mainly in Quaternary sediments deposited along the river valleys (Spassov et al., 2006). Those sediments are dominantly composed of alluvial- to lacustrine deposits containing mostly sands, sandy clays and clay-shales. As demonstrated in the work of Maniatis et al. (1981), calcium presence strongly affects the clay properties, including formation of high amount of iron oxides upon heating. These authors conclude from their results that destruction of calcareous clays during firing produces aluminosilicate matrix which effectively traps the iron ions and iron oxides do not grow easily upon further heating. In contrast, in Ca-free clays heating to increasing temperatures favours increasing amount and size growth of new iron oxide particles (Maniatis et al., 1981). Other factors, like the wood used for the construction of Neolithic houses, as well as the use of dung into daub preparation (Kruger, 2015), also can influence the firing process and the amount and kind of iron oxide phases formed. Such organic additives in clay aid creation of reducing condition during firing and enhance the process of sintering at temperatures above ~800 °C. Therefore, multiple factors determine the amount and size of iron oxides formed during firing. Therefore, the degree of magnetic susceptibility enhancement upon firing is variable and results in wider changes of χ and T_{fire} at site level (Fig. 2b). Despite the data scatter, the estimated T_{fire} medians for the major time intervals during the Neolithic suggest maximum values in the interval 5800–5500 BC with decreasing values towards the Eneolithic (Fig. 2a). Such evolution is consistent with the major climate conditions and palaeofire regime during the Holocene. An increase in global fire activity during the climatic optimum in the Middle Holocene is reported in a number of works (e.g. Brücher et al., 2014 and references therein).

3 Environmental Magnetism as a Tool in Reconstructing Extinction Fire in Ancient Neolithic Settlement

In several Neolithic sites in South-East Europe and Anatolia the phenomenon of burnt houses was discovered (Brami, 2014; Stevanović, 1997). Sintered daub defined as a mixture of clay and organic materials like straw, grass, animal dung, etc. (Kruger, 2015) provides important information about the firing conditions and interpretation of structural burning in the archaeological record (Harrison, 2013). We carried out a detailed and extensive study on a large collection of burned clay materials from the Neolithic site Mursalevo-Deveboaz (Jordanova et al., 2018) with the aim to reconstruct the maximum temperatures reached during the fire which ended the settlement's life. The prehistoric village is dated to a later phase of the local Early Neolithic (ca. 5700–5500 BC). Remains of 62 houses from the second half of the Early Neolithic and 13 houses from the beginning of the second half of the Late Neolithic, all destroyed by extensive fire were unearthed during archaeological excavations. Mineral magnetic analyses involving a set of techniques were applied to investigate the iron oxide phases and magnetic grain sizes responsible for the enhanced magnetisation of burned clay materials. A large quantity of magnetite/maghemite and hematite, all of very fine (nanometre) grain size were evidenced through detailed multi-parameter rock magnetic analyses (Jordanova et al., 2018). Firing temperature estimates using the magnetic susceptibility method for 148 samples of different colour vary between 680 and 1140 °C (Jordanova et al., 2018). It was established that the obtained T_{fire} is generally linked to the predominant colour of the daub piece (Fig. 3). The lowest T_{fire} is characteristic for brown coloured daub, followed by orange-red daub. The highest T_{fire} were registered in materials from vitrified violet to yellow colour of the daub (Fig. 3). It is well known that the colour of thermally altered clay is primarily determined by the pigmentary iron oxides (Murad & Wagner, 1998; Cornell & Schwertmann, 2003). Further, laboratory combustion synthesis of iron oxides reveals a definitive link between the temperature of solution combustion synthesis and the colour, as well as the grain size of the iron oxides synthesised (Toniolo et al., 2007). The magnetic data obtained from our large-number daub collection suggest an increase in the magnetic grain size from superparamagnetic towards single-domain with increasing firing temperature. Moreover, for samples dominated by strongly magnetic magnetite/maghemite phases a linear relationship between low-field magnetic susceptibility and the T_{fire} estimates is evidenced (Jordanova et al., 2018). This rule is not obeyed by vitrified violet-coloured and yellow daub which contain high amounts of hematite. Therefore, considering our experimental data and the evidence from laboratory synthesis of iron oxides, we hypothesised that the major mechanism responsible for the extreme firing of Neolithic houses is related to a combustion event.

4 Mineral Magnetic Properties of Archaeological Materials from Mining Archaeology Settings Are Powerful Index for Their Recognition and Allocation

The Balkan Peninsula and the Bulgarian territory in particular, are part of the global-scale collision zone of the Alpine–Himalayan orogenic belt (Marchev et al., 2005). The tectonic units of the Alpine–Balkan–Carpathian–Dynaride orogenic system

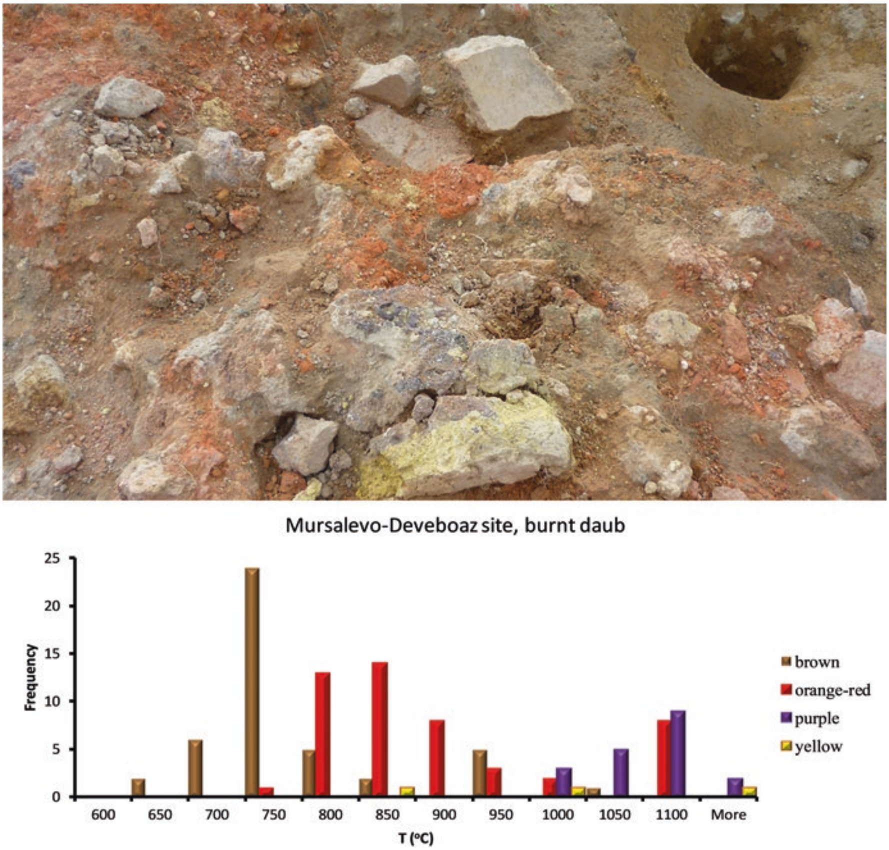

Fig. 3 Distribution of firing temperature estimates (T_{fire}) from Neolithic house destructions in Mursalevo-Deveboaz, as related to the dominant colour of the materials, according to the legend shown. The photograph displays variations in colour of the fired materials

(Heinrich & Neubauer, 2002) determine the most important structural geology features. Therefore, various ore deposits have been explored since ancient times (Popov & Jockenhövel, 2011; Radivojević & Roberts, 2021). We have studied a collection of samples from the Late Bronze Age open-pit gold mine at Ada Tepe in the Eastern Rhodopes (South-Eastern Bulgaria) (Jordanova et al., 2020b). The most recent radiocarbon dates suggest that gold mining had started in the early fifteenth century BC (Popov & Jockenhövel, 2018). Thus, at this stage of the progress of mining archaeology, Ada Tepe is considered as the oldest known open pit gold mine in Europe. The collection consists of 177 samples, representing materials from waste heaps, pristine rocks, natural soils and soils from cultural layers. Detailed mineral magnetic investigations of the collection aimed to identify the main magnetic minerals and their magnetic grain-size characteristics and classify the materials independently of their archaeological assignment. Thus, results probe the suitability of mineral magnetism itself as a tool for identifying archaeological materials associated with ancient mining activities. A set of mineral magnetic techniques (thermomagnetic analyses of high-temperature behaviour of magnetic susceptibility, decomposition of isothermal remanent magnetisation acquisition curves into coercivity components) was used to identify the major iron (oxy)hydroxides in the materials. Magnetite/maghemite, hematite, goethite and pyrrhotite were identified as an outcome. Magnetic parameters, including magnetic susceptibility and its frequency dependence, remanent magnetisations (anysteretic and isothermal) and a set of bi-parametric ratios were subjected to statistical treatment to retrieve the most reliable number of clusters, describing the variability in the magnetic properties of the materials (Jordanova et al., 2020b). It was found that four clusters explain in the best way the variability of magnetic data. Respective average values with their standard deviations obtained for the four clusters are shown in Fig. 4. As seen from the figure, clusters 1 and 4 display relatively similar magnetic parameters, but in cluster 1 the anhysteretic remanence (ARM) has significantly higher values compared to cluster 4. This suggests that materials in cluster 1 contain higher amount of stable single-domain magnetite/maghemite fraction (Maher, 1988). At the same time, the

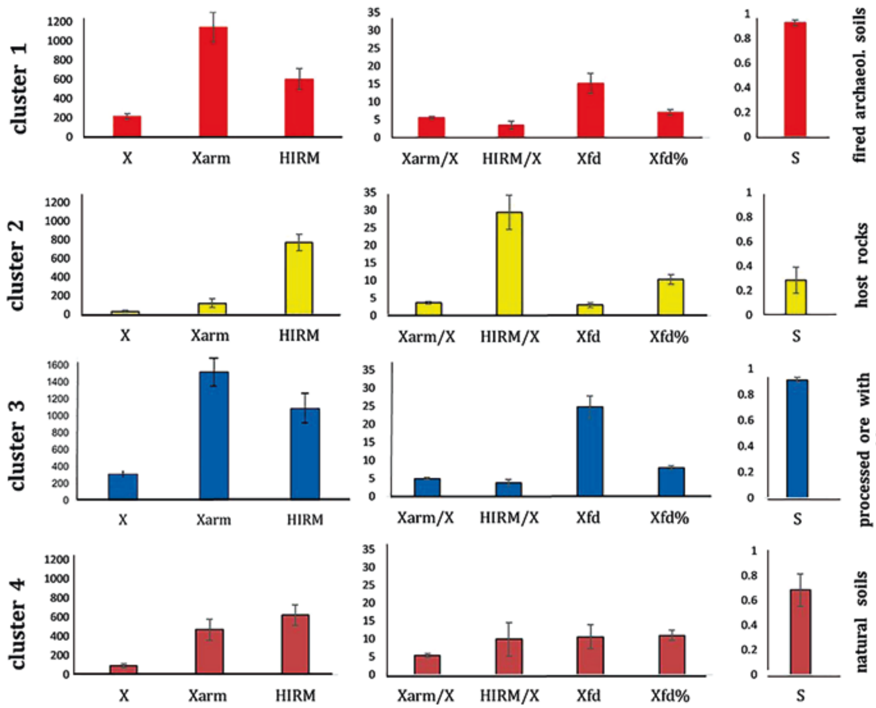

Fig. 4 Distribution of mineral magnetic parameters for samples from Ada Tepe according to the four clusters separated by statistical analysis. The following variables are shown: magnetic susceptibility (χ), anhysteretic susceptibility (χ_{ARM}), hard isothermal remanent magnetisation (HIRM = 0. 5 * (IRM_{2T} − $IRM_{0.3T}$)); ratios: χ_{ARM}/χ, HIRM/χ; frequency-dependent magnetic susceptibility (χ_{fd}), percent frequency dependent magnetic susceptibility (χ_{fd}%), S-ratio (S = $-IRM_{0.3T}/IRM_{2T}$)

superparamagnetic fraction, characterising the finest magnetic grains (usually having pedogenic origin (Dearing et al., 1996)) is less represented. Such relationship is characteristic for fire-affected soils (Jordanova et al., 2019) and cluster 1 is thus attributed to burned soils. Cluster 2 is a particular group of samples showing very low susceptibility and high concentration of magnetically hard minerals (hematite and goethite) (e.g. high HIRM values and low S-ratio, as seen from Fig. 4) and is thus ascribed to host rocks. Samples grouped in cluster 3 have the strongest magnetic enhancement, as seen from the maximum values of χ, χ_{fd}, χ_{ARM} (Fig. 4). The hard isothermal remanence (HIRM) is also elevated but it is most probably due to the presence of moderately high-coercivity minerals since the S-ratio is relatively high. Thus, materials from cluster 3 were attributed to burnt sediments/soils and heap material from rock processing with the use of fire. Finally, samples from cluster 4 show magnetic parameters which are similar to those ones for natural soils (e.g. Jordanova, 2016) and therefore these materials were defined as natural soils. After assigning each cluster to a particular type of material, the cluster members were plotted on a spatial map depicting the archaeological observations and attributes (Jordanova et al., 2020b). Comparison between the mineral magnetic results and archaeological information showed an exceptionally good match. This allowed us to conclude that the mineral magnetic approach, combining various rock-magnetic parameters of distinctive natural and human-affected relics of ancient ore mining is a highly promising and efficient tool for identification and classification of materials found in archaeological excavations.

5 Recovery of Ancient Firing Temperatures of Archaeological Pottery Fragments by Magnetic Susceptibility Method

Pottery fragments are the most common and abundant finds in archaeological sites. They are used to constrain the dating period of the respective site and/or inhabited layer, as well as to project the societal links and technologies through time and space (e.g. Loney, 2000; Shennan & Wilkinson, 2001; Borck et al., 2020; Pawlowicz & Downum, 2021). Determinations of firing temperatures of pottery sherds could provide valuable analytical data for considering archaeologically relevant aspects—provenance studies, characterisation of ceramics technologies, their social links and spatial spread in time (Damjanovic et al., 2014). Pottery firing procedures differ in relation to duration of the firing process, heating/cooling rate, maximum firing temperature, soaking time, firing atmosphere, etc. Complex interplay of all these factors determines the final characteristics of the pottery. Several papers already report data on reconstruction of pottery firing temperatures using the method of magnetic susceptibility (Rasmussen et al., 2012; Goodwin & Hollenback, 2016; Karacic et al., 2016; Kostadinova-Avramova et al., 2018; Lesigyarski et al., 2020; Jordanova et al., 2019) as well as other mineral magnetic signatures (Spassov & Hus, 2006; Tema &

Ferrara, 2019; Tema et al., 2022). In this contribution, we summarise data obtained for firing temperature estimates of pottery from several Bulgarian archaeological sites, representing major pottery production centres. Detailed information could be found in the devoted articles (Kostadinova-Avramova et al., 2018; Jordanova et al., 2017, 2019; Lesigyarski et al., 2020). In addition, we summarise here the obtained data on firing temperature determinations in the different sites according to the archaeological periods covered (Table 1). Since for the pottery wares one important classification mark is their purpose of use (serving ware vs cooking ware, decorative, etc.), in Table 1 data for the maximum firing temperature (T_{max}) are sub-divided also related to this index. As it is seen from Table 1, the major inference that could be stated is that the firing temperatures for pottery production increase towards more recent times, as also concluded earlier (Kostadinova-Avramova et al., 2018). In order to be able to look for differences related to T_{max} and the purpose of use of the pots, it is important to have more numerous sets of single determinations. Nevertheless, as pointed out by Kostadinova-Avramova et al. (2018), the main tendency of indistinguishable T_{max} during more ancient epochs (Middle Bronze Age (MBA), Early Bronze Age (EBA)) suggests no selective use of different kilns for pottery baking by ancient potters, while during most recent times (e.g. for example ceramic centres in Pliska and Veliki Preslav, see Table 1) T_{max} obtained for the serving wares, and especially the glazed ones are significantly higher compared to T_{max} determined for the cooking pots. This finding corresponds well to the technological refining of pottery production with time. The lowest T_{max} in our dataset summarised in Table 1, are obtained for black coloured pottery fragments from the Early Iron Age (see sites Dragovishtitsa and Gluhite kamani). As commented in many archaeological studies, this period is characterised by a strong decline in societal and cultural development of human occupation in Eastern Mediterranean and West Asia (Kostadinova-Avramova et al., 2021 and references therein). Various studies show that black-coloured pottery is most often produced in "pit firing", while red-coloured pots were produced in kilns (a more sophisticated and requiring refined skills technology) (e.g. Maritan et al., 2005).

Furthermore, complementary to determinations of firing temperatures using the low-field susceptibility, more advanced mineral magnetic analyses aiming to establish also magnetic grain-size and colour characteristics of pottery and burned clay materials were carried out on a pilot collection of materials (Jordanova et al., 2019). The main results demonstrated that the grain size of the secondary iron oxides vary from superparamagnetic to stable single domain or pseudo-single domain. Pottery sherds were shown to contain more often hematite in comparison with burnt clay from house destructions. Importantly, combination of mineral magnetic analyses and spectroscopic colour measurements demonstrate that the ratio "value/chroma" shows an inverse relation with the ancient firing temperatures, as determined using magnetic susceptibility method (Jordanova et al., 2019). Specific regressions were obtained for different sites (e.g. different source clays), suggesting potential use of this relation for provenance studies.

Table 1 Summary of the data for the firing temperatures of pottery from several archaeological sites

Site	Period	$T_{(average)}$ ± st.dev.	N	$T_{serving}$ ± st.dev.	$N_{serving}$	$T_{cooking}$ ± st.dev.	$N_{cooking}$	source
Plovdiv	MBA	735 ± 10	4	730	2	730	1	1, 2
	4–3 c BCE	713 ± 58	14	725 ± 66	4	703 ± 59	9	
	2–1 c. BCE	761 ± 68	7	810 ± 40	2	715 ± 34	4	
	2–3 c. CE	795 ± 45	42	808 ± 54	21	781 ± 35	14	
	4 c. CE	823 ± 53	6	857 ± 12	3	787 ± 60	3	
	11–12 c. CE	863 ± 70	3	790	1	860	1	
Dragovishtitsa	EBA	800 ± 35	6	777 ± 31	3	823 ± 23	3	1
	EIA	635 ± 19	4	635 ± 19	4			
	7–8 c. CE	694 ± 109	5			694 ± 109	5	
Gluhite kamani	EIA I	506 ± 13	11	473 ± 74	6	638 ± 165	5	3
	EIA II	658 ± 102	31	632 ± 117	14	654 ± 131	16	
Pliska	8–9 c. CE	792 ± 60	25	801 ± 63	20	745 ± 19	4	1
	10–11 c. CE	814 ± 56	43	798 ± 45 848 ± 52 glazed	10 9	819 ± 54	16	
Veliki Preslav	10–11 c. CE	877 ± 68	15	920 ± 14 932 ± 28 glazed	2 9	818 ± 72	5	1
	12–13 c. CE	883 ± 72	19	870 ± 57 921 ± 49 glazed	4 7	770 ± 28	2	

Data are shown according to the archaeological period ("*MBA*" Middle Bronze Age, "*EBA*" Early Bronze Age, "*EIA*" Early Iron Age). Temperature estimates ($T_{aver.}$) are shown in degrees Celsius. "N" denotes the number of samples in each group. Data are separated according to the pottery's use as "serving ware" ("$T_{serving}$") and "cooking ware" ("$T_{cooking}$"). Data source is indicated in the last column, as follows: 1—Kostadinova-Avramova et al., 2018; 2—Lesigyarski et al., 2020; 3—Jordanova et al., 2017

6 The Power of Classical Archaeomagnetism—Bulgarian Master Curves of Geomagnetic Field Variations

The beginning of archaeomagnetic studies in Bulgaria was set in 1967 by Prof. Mary Kovacheva. Due to continuous work and successful cooperation between Bulgarian archaeomagnetists and archaeologists, a unique archaeomagnetic database of geomagnetic field determinations has been accumulated for more than half a century. It represents an extended local series of the three main geomagnetic elements—declination (D), inclination (I) and intensity (Fa), recovered from the same baked clay materials and covering almost completely the last 8 millennia. Bulgarian archaeomagnetic data are part of the global database GEOMAGIA50.v3 (http://geomagia.ucsd.edu) and are crucial for the construction of the geomagnetic reference curves of the Balkans and South-Eastern Europe (Pavón-Carrasco et al., 2010; Tema & Kondopoulou, 2011). Over the years, the secular variation curves (also called reference curves) for Bulgaria have been calculated several times (e.g. Kovacheva et al., 2009, 2014) since the database undergo regular updating and revision. In the most recent compilation (Kovacheva et al., 2014) the D, I and Fa reference curves were smoothed by Bayesian statistics (Lanos, 2004) applied to 310 reference points obtained by archaeomagnetic investigation of numerous, relatively evenly distributed in space, archaeological sites of different age (Figs. 5, 6 and 7).

The most ancient traces of settled life in Bulgaria date back to the 7th millennium BC. The Bulgarian **Neolithic** is divided into several stages differing in the time of onset and duration. The beginning of the early Neolithic is considered to be at 6300/6200–6100 BC, and the end of the late Neolithic is constrained to 4950–4850/4800 BC (Görsdorf & Bojadziev, 1996). There are plenty of multilayered Neolithic settlements that have been inhabited for centuries. Many of them are well stratified and possess a sufficiently precise chronologies based on detailed archaeological studies and series of radiocarbon dates. Additionally, there are almost always burnt building levels, rich in well baked clay remains (dwelling walls, floors, roofs, hearths, ovens, etc.). Therefore, the Neolithic is particularly favorable for archaeomagnetic purposes (Kostadinova-Avramova et al., 2014, 2020). A total of 51 archaeomagnetic determinations belong to this period.

Similar to the Neolithic, there are also a variety of artefacts from the **Eneolithic** and **Bronze Age** that are suitable for archaeomagnetism. The discovered settlements remain largely multilayered, frequently with extensive fired building levels. The earliest findings from the Eneolithic date to ~4900 BC, and the latest to ~3800/3750 BC (Boyadziev, 1995). The archaeomagnetic results are summarised in 42 reference features. It follows that a transitional period separating the Late Eneolithic from the Early Bronze Age (~4100–3200/3150 BC) providing only 8 reference points due to the scarce archaeological sites of that time (Fig. 6). The most plausible explanation is palaeoclimatic environment with relatively high average annual temperatures and severe drought assumed for the end of the Eneolithic (Todorova, 1995). The problem of missing occupation traces within this period was

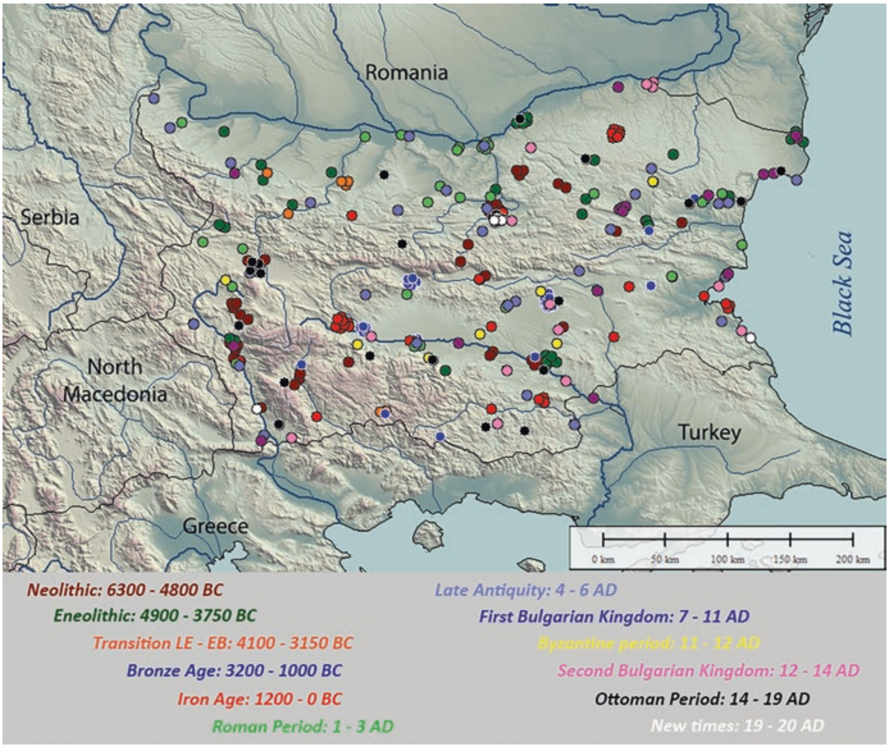

Fig. 5 Distribution of the archaeomagnetically studied sites at Bulgarian territory. Different archaeological epochs and historical periods are shown in different colors. Abbreviations: *LE* - Late Eneolithic; *EB* - Early Bronze age

extensively examined through a multidisciplinary study, both for Greece and Bulgaria (Tsirtsoni, 2016 and references therein). It is believed that Bronze Age culture began to spread in Bulgarian lands around 3200/3150 BC and developed until ~1100/1000 BC. A total of 44 archaeomagnetic determinations, concentrated mainly in the Early Bronze Age, cover these two millennia (Fig. 6). The Middle and Late Bronze Ages are much less studied because of the small number of archaeological sites discovered.

The **Iron Age** spans the last 1200 BC and is perhaps the most unfavourable for archaeomagnetism (Kostadinova-Avramova et al., 2021). Many researchers (e.g. Weninger et al., 2009; Drake, 2012) discuss the decline of the ancient societies in the Eastern Mediterranean and Western Asia between the 13th and 9th c. BC as a consequence of drastic climatic and environmental changes. This affected the life in the Balkans as well. The archaeological finds from the first Iron Age phases testify to lower population density, human migration, tribe incursions, weak trade relations, etc. The settlements are generally short-lived, with thin cultural layers, poorly stratified and often located at high naturally protected and almost inaccessible places. Due to all the above, well-studied archaeological sites with clear

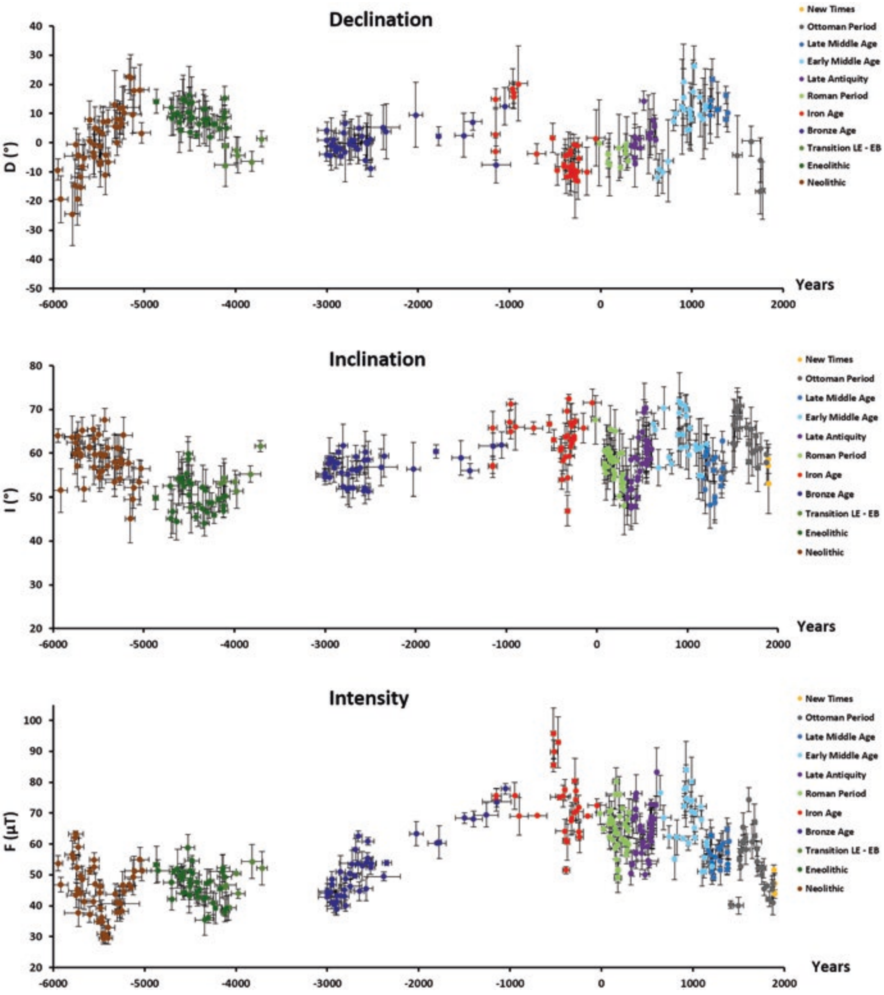

Fig. 6 Archaeomagnetic data with the corresponding errors over the time scale

stratigraphy and stable chronology that can serve as benchmarks, are rather an exception. Additionally, the materials collected are quite often unsuitable for palaeointensity determinations and fail to restore this element because the Iron Age thermal constructions (hearths, household ovens and non-specialised production furnaces) are usually poorly preserved, short-term used, and the attained firing temperatures rarely exceed 600 °C. Therefore, only for a half of the 40 reference features available, the full geomagnetic field vector was determined.

The Antiquity age in Bulgaria is divided into early **Roman Period** (I–III AD) and **Late Antiquity** (IV–VI AD). It is attested by numerous historical and archaeological monuments, well studied in terms of material culture, evolution, and chronology. Workshops with furnaces specialising in various types of production were

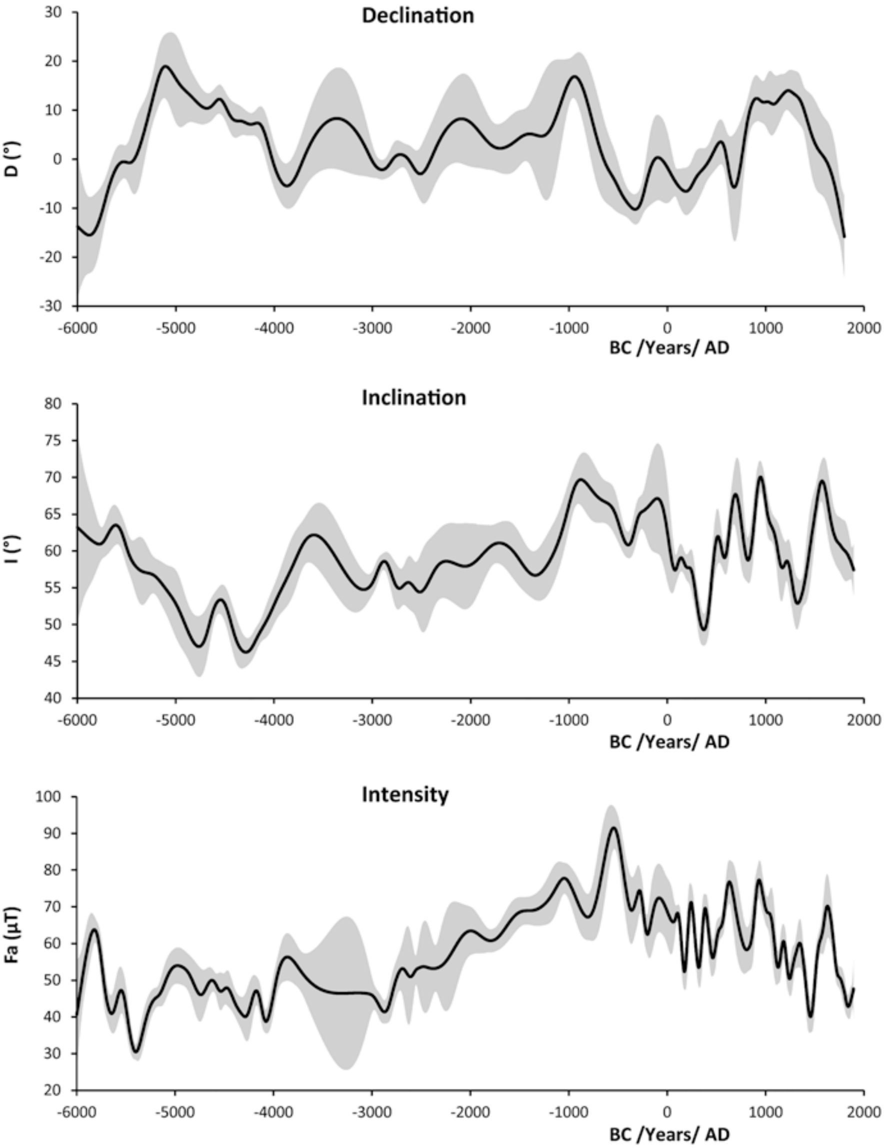

Fig. 7 Bulgarian secular variation curves of the three geomagnetic field elements—inclination (I), declination (D) and intensity (Fa) (Kovacheva et al., 2014)

common during this era. The usual firing temperatures are tending to exceed 800 °C, which favours the success of archaeomagnetic analyses. A total of 81 reference features belong to the Antiquity—39 from the Roman period and 42 from the Late Antiquity. Unfortunately, about 65% of the materials studied are bricks for which only I and Fa were restored i.e., the secular variations of magnetic declination are based on a smaller data number.

The **Middle Ages** can generally be divided into Early (VII–XI AD) and Late (XII–XIV AD). The remains of Early medieval settlements indicate that the technological progress in the Antiquity was followed by a decline in many aspects of life affecting not only the quality of the discovered ceramic products, but also the nature of the thermal structures. Nevertheless, baked clay objects with sufficiently precise chronology are not lacking due to the presence of numerous archaeological and historical evidence. The reference features involved in the archaeomagnetic database are a total of 50 (29 early medieval and 21 late medieval) and 30% of them are bricks.

For the **Ottoman period** (XIV–XIX AD) the bricks studied are the majority—80% or 22 out of 27 reference features. As a result, the declination variation curve is based only on 5 data (Fig. 6). Mainly bricks are collected also from the period covering the time after the **Liberation** to the present day, and the five archaeomagnetically studied archaeological sites produce single result for D.

The archaeomagnetic data accumulated over more than half a century of research allows to trace the patterns in the three geomagnetic characteristics during the last 8 millennia (Fig. 7). A general trend of increasing intensity from the Neolithic to the middle of the first millennium BC followed by a subsequent decrease is undoubtedly evident. The lowest Fa values (~30 μT) were observed circa 5400 BC (first half of the late Neolithic), and the highest (~96 μT) circa 525 BC (Late Iron Age). Three consecutive maxima for the intensity can be assumed at the beginning (~5800 BC), the middle (~5550 BC) and the end (~5000 BC) of the 6^{th} millennium, while during the Eneolithic, Fa changes do not seem so significant. At the same time, the magnetic declination turns from strongly western, at the beginning of Neolithic, to eastern, at the end of the epoch. The subsequent smoother transformation in D during the Eneolithic shifts again to more western values. Magnetic inclination decreases significantly from Neolithic to Eneolithic with a maximum around the middle of the 5^{th} millennium. Despite the few results from Late Eneolithic—Early Bronze Age transition, as well as from the Middle Bronze Age, a relatively smooth increasing intensity accompanied by D and I values close to the present ones can be admitted. Only additional high-quality archaeomagnetic data could help to define the secular variations of the 4^{th} millennium BC and the Middle Bronze Age in detail. The Iron Age is characterised by high to maximum intensity. A significant decrease in Fa, accompanied by an inclination minimum and a strongly western declination was observed around 400 BC. During the Antiquity, archaeomagnetic data suggest rapid changes in the geomagnetic field intensity and a significand variation for I, which at the beginning of the Roman period is of ~65°, then decreases to ~45° and increases again up to ~70° in the end of Late Antiquity. Due to the large percentage of the bricks studied, magnetic declination for these periods is insufficiently defined. The early Middle Ages are characterised by an intensity decrease at the beginning and a relatively rapid increase and a subsequent decrease at the end of the period, while for the late Middle Ages Fa does not change much. The inclination tends to decrease from the early to the late Middle Ages, and D values turn from western to eastern.

Despite the large percentage of bricks from the Ottoman time, a new shift in D from east to west is evident. Along with this, I values at the beginning of the period are very similar to those in the early Middle Ages and then another decline occur. A well-expressed Fa peak exceeding 70 μT, is defined in the middle of the Ottoman period, while at the beginning and the end of it, the geomagnetic field magnitude is around 40 μT.

The main Bulgarian geomagnetic secular patterns are generally consistent with those observed in the Central Mediterranean and in Western and Central Europe (e. g. Hervé et al., 2017; Osete et al., 2020; Schnepp et al., 2020a, b; Rivero-Montero et al., 2021, etc.). In the last years, more and more archaeomagnetists (Gallet et al., 2003; Shaar et al., 2011; Osete et al., 2020; Rivero-Montero et al., 2021; Tema et al., 2021 etc.) focused their scientific interest on proving and explaining the short-term geomagnetic events called "spikes" (Shaar et al., 2011) and "jerks" (Gallet et al., 2003). So far, the Bulgarian secular variation curves do not show indication for any of these events (Kostadinova-Avramova et al., 2020, 2021).

The potential of archaeomagnetism in archaeological research is well-known. The Bulgarian geomagnetic secular variation curves are successfully used for absolute dating since more than 40 years (e. g. Kovacheva, 1989; Jordanova et al., 2004; Kostadinova & Kovacheva, 2008; Kostadinova-Avramova & Kovacheva, 2015, etc.). The dating compares the obtained archaeomagnetic results for a site (or a feature) with the local reference curves representing D, I and Fa variations in the corresponding period, and several possible intervals are usually distinguished (Fig. 8a). The final solution is a combination of all defined intervals (Fig. 8b) and depends not only on the accuracy of the experimental results and the reference curves used, but also on the rate of the geomagnetic field change during the period in question. Furthermore, the magnetic analyses are applied not only to compare and synchronise archaeological structures (Kostadinova-Avramova et al., 2014), but also to draw conclusions about the firing conditions and temperatures reached, which are informative for the technological development of the respective society (Jordanova et al., 2018; Kostadinova-Avramova et al., 2018).

7 Conclusions

In this overview of the combined archaeomagnetic and environmental magnetic research carried out in Bulgaria, we present and discuss several major milestone areas of application in archaeology. Case studies on advantageous utilisation of magnetic signature of iron oxides retained in fired archaeological materials—house destructions, pottery, ovens, etc.—demonstrates the vast array of potential applicability of rock magnetism. It is shown that mineral magnetic parameters of fired clay materials, combined with estimations of the maximum firing temperature using magnetic susceptibility method, can provide valuable information for paleoenvironmental conditions in case of open-air settlement fires or ancient mining activities, as

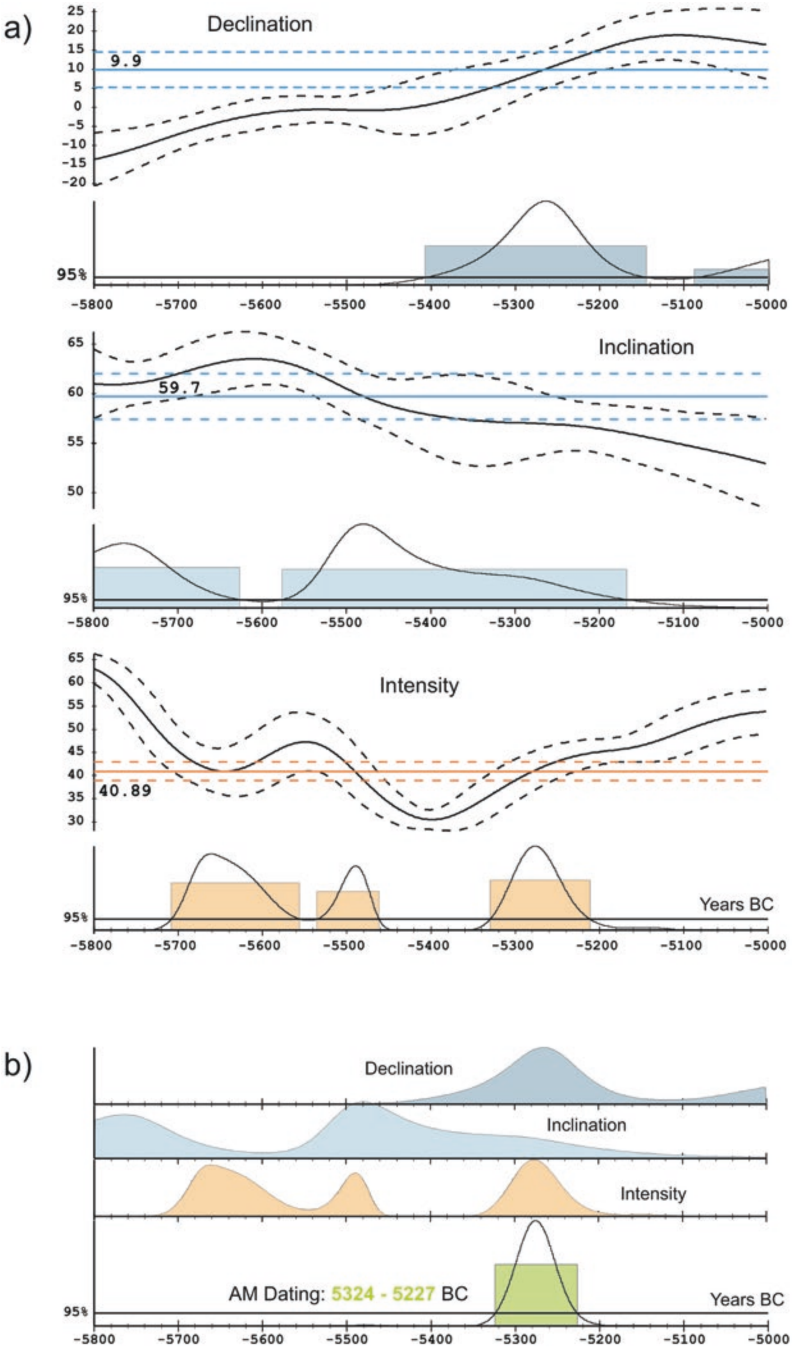

Fig. 8 Archaeomagnetic dating for the Neolithic site Sharkov Chiflik (Kostadinova-Avramova et al., 2020): (**a**) comparison of the I, D, Fa results obtained with the corresponding reference curves and (**b**) combination of the individual dating results and final archaeomagnetic solution with 95% probability density

well as technology-related aspects in case of pottery. Furthermore, advanced state of archaeomagnetic database compiled for the territory of Bulgaria allows performing rigorous archaeomagnetic dating and synchronisation of archaeological sites.

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Part IV
China

Archaeological Geophysics in China – A Historical Perspective

Wenke Zhao and Bangbing Wang

Abstract Geophysical methods can efficiently identify and map archaeological features or changes in the matrix of a site. They have been extensively used in Chinese archaeological prospection since the survey for the Mausoleum of the Emperor Wanli of Ming Dynasty in mid-1950s. The evolution of archaeo-geophysics in China is closely linked to advances in emerging geophysical technology, the needs of non-destructive detection from the archaeological community and Chinese fast-growing economy. Throughout the past 70 years, researchers and practitioners witnessed the rapid development of geophysics in the field of Chinese Archaeology. In this chapter, we introduce some key archaeo-geophysical events, for example, a multi-geophysical project was performed by China Geological Survey (CGS), to evaluate the applicability and the effectiveness for archaeological characterisation at the Mausoleum of Qinshihuang, i.e. the first Emperor of the Qin Dynasty, during 2002 and 2003, the scale of which has been the largest in Chinese archaeo-geophysics so far. Besides, we divide these events into four periods, i.e. embryonic stage (1950s–1980), initial stage (1980–2000), development stage (2000–2010), and internationalisation stage (2010–present). Moreover, we also provide some significant case studies, namely ancient city sites and ancillary building remains, ancient tombs, cultural heritage protection, urban underground remains, and underwater archaeology. In a word, the development has paved the way to regular use of geophysical methods in almost all types of potential archaeological interests in China.

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1 Introduction

Archaeology is the study of human activity through the recovery and analysis of material culture, using prospection, excavation and eventually analysis of data collected to learn more about the past. Most archaeological sites are not so conspicuous as the Pyramids and the Great Wall, rather they are buried underground or submerged under water all over the world. Archaeologists have to look for clues from the remains of mounds, stone buildings, city walls and other remnants left on the surface, such as pottery pieces, variegated soils, or suspicious caves. Furthermore, field excavations are required to investigate the ancient remains, and also to analyse the various relationships between the remains and the surrounding environment. While archaeological excavations are reproducible and protective, they are also invasive.

Modern Chinese archaeology began with the excavation and discovery of painted pottery remains in Yangshao Village, Mianchi County, Henan Province in 1921. Over the past 100 years, Chinese archaeologists have made a series of major discoveries, demonstrating the origin, development context, and splendid achievements of Chinese civilisation (An, 1992). Without any doubt, the development of Chinese civilisation occupies a unique place in the world. New archaeological discoveries in recent decades have attracted great attentions from the academic community and the public. However, because of the language barrier between China and Western countries, there are few English written review papers and monographs published for Western readers on Chinese archaeology, particularly on Chinese archaeo-geophysics. Therefore, we provide a brief introduction of key archaeo-geophysical events in China and some significant case studies, to commemorate and celebrate the many achievements during the 100th anniversary of the modern Chinese archaeology.

The traditional underground detection tool is the Luoyang Spade for Chinese field archaeologists, with a semi-cylindrical spade head and a long spade handle, which was originally invented and widely used by tomb robbers (e.g. Feng, 2016). However, it has become one of the most useful field archaeological tools in the past century in China, as different characteristics of soil and its inclusions can be identified by virtues of drilling cores with a few centimetres in diameter, and several meters, even more than 10 m in depth. With relative dense drilling, the distributions of potential archaeological features and deposits can usually be established, even without any excavations in a large-scale area. Of course, such detection can damage valuable cultural remains or disturb related archaeological strata inevitably and irreversibly. In such case, geophysical methods are useful because they can accurately identify, image and map the spatial extension and geometries of near surface archaeological features or changes in the matrix of a site in an absolutely non-destructive and cost-effective way (e.g. Bevan & Kenyon, 1975; Wynn, 1986; Jiang & Zhang, 2000; Gaffney, 2008; Zhao et al., 2015a). They are also recommended as valid methods to optimise location and planning of excavations (e.g. Forte & Pipan, 2008; Drahor et al., 2011; Zhao et al., 2013a).

1.1 Embryonic Stage: 1950s–1980

The development of large-scale infrastructure construction since the 1950s, opens a doorway for field archaeology. Archaeological and cultural relic research institutes were established consecutively by numerous provinces and autonomous regions. Besides, universities established the subject Archaeology to educate students in formal and systematic archaeological theories and methods. New concepts and technologies were also introduced to China in this period. The first application of geophysical methods in archaeology was the survey at the Mausoleum of the Emperor Wanli of the Ming dynasty in the mid-1950s (Jiang & Zhang, 1997). However, this survey did not provide satisfactory results. In 1978, the geophysical team from the Geology and Mineral Resources of Henan Province invited by the Museum of Henan Province, performed electrical resistance and magnetometer surveys at the Hougudui tomb in Gushi County. The subsequent excavations confirmed the geophysical results with the actual location of the main tomb chamber (Wu et al., 1988).

1.2 Initial Stage: 1980–2000

With the active recommendation from geophysical community to National Cultural Relics Administration, a wide variety of geophysical methods have increased been applied in archaeology since 1980. Projects included the identification of possible buried remains in large areas (e.g. Yan et al., 1998), mapping residual building foundations (e.g. Zhang, 1999a), locating and imaging ancient burial tombs (e.g. Zhang, 1996, 1999b), and characterising the degradation of architectural remains (e.g. Zhong, 1991). It is worth noting that integrated geophysical method, including side-scan sonar, magnetometry, and sub-bottom profiler, was used to detect ancient shipwrecks underwater in the sea of Liaoning Province in 1991. Of course, the scale of geophysical surveys was relatively small, and most of them were experimental in nature during this period, even though the geophysical results were a benefit for archaeological investigations and excavations (Jiang & Zhang, 1997).

1.3 Development Stage: 2000–2010

In order to facilitate an engagement of archaeologists/geophysicists in archaeo-geophysical prospection, Professors Hongyao Jiang and Limin Zhang, from Chinese Academy of Sciences, wrote and published the first book on this field in Chinese in 2000, entitled “Archaeo-geophysics”, mainly including the theoretic fundaments, basic concepts of the related methods and techniques, and especially case studies and achievements in China. At the same time, a large national archaeo-geophysical project was performed by China Geological Survey (CGS), to evaluate the applicability and the effectiveness for prospection of the Mausoleum of Qinshihuang, i.e. the first Emperor of the Qin Dynasty, during 2002–2003. The methods used included gravimetry, magnetometry, electrical resistivity tomography (ERT), electromagnetic induction (EMI), seismic reflection, ground penetrating radar (GPR), and surface nuclear magnetic resonance. The available literature also indicates that other integrated geophysical explorations, involving electrical resistance, magnetometry, and time-domain electromagnetic methods, were tested as early as 1987 and 1992 at the Mausoleum of Qinshihuang (e.g. Xia et al., 2004). However, for a specific target area, the scale of detection and the types of methods used by CGS have been the largest in Chinese archaeo-geophysics so far, and related geophysical results can be found in the book "Geophysical exploration for the underground palace of Emperor Qinshihuang Mausoleum", published by Geological Press in 2005. Progressively, more and more geophysical projects have been applied to field archaeology (e.g. Xia et al., 2004; Su et al., 2007; Shen et al., 2008; Wang et al., 2008, 2010; Xu et al., 2008; Yu et al., 2009).

1.4 Internationalisation Stage: 2010–Present

Implementation of large scientific research project and publication of related monograph may imply that archaeo-geophysics was moving towards the vision of researchers as an independent subject in China. There were few international exchanges and presentations of geophysical results on this field before 2010 (e.g. Yuan et al., 2006). However, the situation has been changing dramatically in the past decade, as more and more case studies in Chinese Archaeo-Geophysics have been published in international journals and conference papers. These include the characterisation of ancient burial mounds using integrated geophysical methods (Zhao et al., 2019; Li et al., 2021), identification of buried earthen archaeological remains with GPR (Zhao et al., 2012, 2015b, 2021; Shi et al., 2015; Jiang et al., 2017; Zong et al., 2018), ERT (Zheng et al., 2013) and multi-frequency EMI (Tang et al., 2018) for large-scale site surveys, surface nuclear magnetic resonance for cultural heritage site protection (Lu et al., 2020, 2021), GPR characterisation of wooden cultural relics (Zhao et al., 2013b), and underwater archaeological investigation with GPR (Qin et al., 2018).

2 Geography and Soil Characteristics of China

From the perspective of macro-topography, China is surrounded by a series of natural barriers: woodlands, deserts and mountains are distributed in the north, west and southwest respectively, while the east and southeast are the sea. The northern border

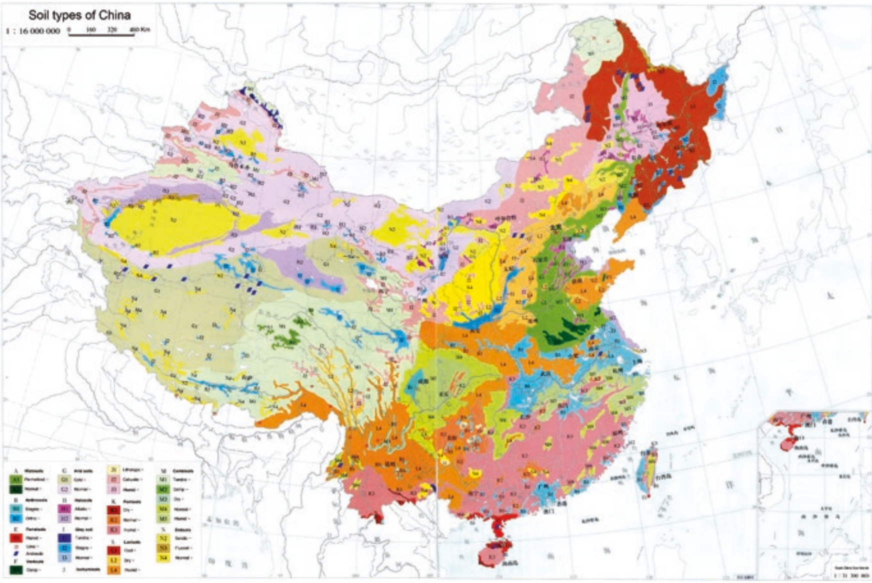

Fig. 1 Soil types of China. (Adapted from https://www.osgeo.cn/)

of China is open, as there are large gaps between the mountains, which have formed channels between China and neighbouring areas in ancient Chinese history. Besides, the topographic features of China are high in the west and low in the east. It is really rare that a country has both temperate and tropical zones, humid and arid areas, plains and mountains, and various types of natural soils and large areas of man-made soil (e.g. Fig. 1). According to natural conditions and current provincial boundaries, China can be divided into seven ecological regions: (1) North China in the middle and lower reaches of the Yellow River; (2) North-east China of the temperate zone; (3) the arid north-west region, including most Inner Mongolia; (4) Central China located in the middle and lower reaches of the Yangtze River; (5) humid subtropical and tropical South China; (6) humid subtropical and tropical south-west China; (7) and the Qinghai-Tibet Plateau at the west (Gong et al., 2014). Moreover, China has a wide variety of landforms and complex geological structures, made by internal forces such as geological foundations and neotectonics movements and external forces such as complex and changeable actions from climate, hydrology, and biology. For the land area of China, mountains account for about 33%, plateaus account for about 26%, basins account for about 19%, plains account for about 12%, and hills account for about 10%. In addition, other different types of landforms are developed, including mountain glaciers, frozen soil, aeolian sand dunes, loess, red soil, karst land, volcanoes, and coastal zones.

The subsurface sediments and soil conceal the tangible cultural remains of past societies that are fundamental as a source of information for archaeologist. In geophysical prospection, the differences in the physical properties of such soil, sediments and other buried interfaces such as archaeological remains are also very important to be able to select the best suite of detection methods. For example, soil moisture is a critical factor to be considered for GPR survey, as electromagnetic wave propagation is sensitive to attenuation that can be related to soil water content. From the perspective of soil moisture, associated with natural conditions and soil characteristics, the spatial distribution of Chinese soil can be divided into three major regions: moist soil in the east, sub-moist soil in the middle, and dry soil in the north-west. The north-west is a large area that can be cold and dry under the control of the north-west airflow in winter. The climate in the east is humid as it is affected by the south-east and south-west monsoons in summer. The north-western region is located in the interior of Eurasia, coupled with the influence of the Qinghai-Tibet Plateau and high mountains, resulting in drought and water shortage.

It is worth pointing out that China is a large agricultural country with a long history. Therefore, the depth and intensity of buried archaeological remains are considerable if compared with other countries in the world. In addition, the process of modern urban development has created a great deal of disturbance of the original soil and other deposits. During such construction work natural humus layers are stripped, some soil strata are inverted, and multiple anthropogenic deposits of different periods can be mixed and result in "multi-structured soil".

3 Significant Case Studies of Archaeo-geophysics in China

3.1 Ancient City Sites and Ancillary Building Remains

The scale of remains related to ancient cities is quite rich in China given its complex and long history. Therefore, there are many potential targets to be detected by geophysical methods such as ash pits, ditches, ancient kiln sites, ancient roads, and building remains with different materials, like masonry, brick, or rammed earth. Electrical resistance, magnetometer and GPR surveys are used for rapid surface scanning, always accompanied with a positioning measurement by Real Time Kinematic Global Positioning System (RTK-GPS) or terrestrial Laser Scanner. Other less conventional geophysical methods have been also used in China to detect specific potential archaeological interests.

The location and detailed characterisation of rammed earth sites in Chinese archaeology is an important topic due to the large temporal and spatial distributions of such type of sites. These include ancient city walls, large mausoleums, and building foundations. Yan et al. (1998) successfully surveyed the ancient city walls built during the Eastern Zhou Dynasty in Shangqiu, Henan Province using with ERT. The top of the wall remains were located at 2–4 m depth with a bottom 10–12 m deep. These great depths were caused by frequent flooding and diversion of the Yellow River at the site. A MCOHM-21 resistivity-meter system was used to acquire the data. The ERT results indicated that the apparent resistivity of the rammed soil layer was about 35–42 Ωm, while the apparent resistivity of the surrounding soil was about 15–25 Ωm. A similar ERT survey, performed with a DUK-2 resistivity-meter system, was carried out at the archaeological site of Sanxingdui Ancient Ruins, a very famous Neolithic-Bronze Age site located in the Southwest China (Su et al., 2007).

Moreover, the near-surface geophysical group from Zhejiang University has carried out a large number of experimental surveys at the Liangzhu site in recent years (e.g. Zhao et al., 2015b). This is a famous Neolithic site that was the centre of jade culture centre in south-east China. The buried remains of the ~40–60 m wide rammed earth ancient wall at the Liangzhu site, were discovered in 2007 (Zhejiang Institute of Cultural Relics and Archaeology, 2008). Figure 2 provides two examples of geophysical results around the wall, i.e. an ERT survey results showing the north wall. This was generated from 24 parallel ERT survey lines and a magnetometer survey map outside the east wall, performed with a Benteng resistivity-meter system and a Caesium optical pumped magnetometer G858, respectively. The continuous high resistance, associated with the rammed earth remains underground, is cut off by the low resistance part, which can be inferred as the location of the gate in the Liangzhu Period, besides, the continuous low resistance is associated with the water system, validated by drillings. In addition, the anomalies in the magnetometer survey map are associated with the distribution of cultural accumulations during the Liangzhu Period, which are roughly the same as the drilling results.

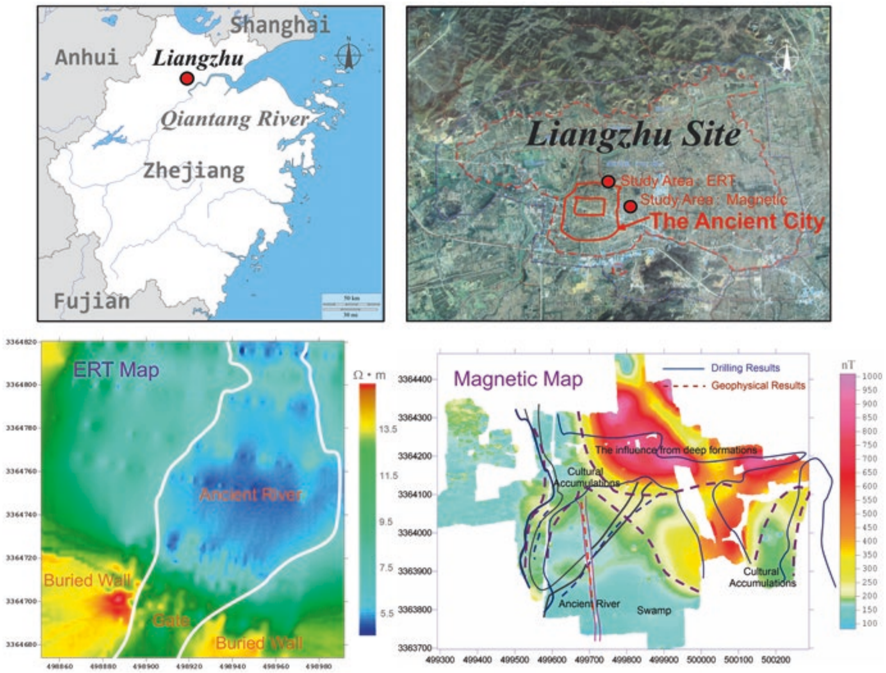

Fig. 2 The location of study area at Liangzhu site, Hangzhou, the ERT map of about 1.5 m depth acquired at the north wall and the magnetic map acquired outside the east wall

3.2 Ancient Tombs

Ancient tombs (burial mounds) with individual or collective funeral chambers have worldwide distributions. Such kind of detection objects is one of the most important archaeological interests, as they may contain important findings of great historical and economical values and they have great archaeological significance. However, the characterisation of burial mounds is an especially challenging geophysical problem, due to uneven topographical terrain, complicated surface environment, and complex distributions of the burial archaeological features (e.g. Dai & Xie, 2015; Zhao et al., 2019). Archaeo-geophysical characterisation at the Mausoleum of Qinshihuang was carried out combining different methods and this survey strategy has also been used at other burial sites such as the noble tomb of Chu State during the Spring and Autumn Period (Zhang, 1996), the cemetery of Marquis Haihun of the Han dynasty (Li et al., 2021), and masonry family tomb during the Han and Wei Period (Zhang, 1999b). Figure 3 shows the ERT result of the survey conducted at the burial mound of Hepu Han in South China were ~1200 tombs were excavated by archaeologist since the 1950s (Chen et al., 2018). A Trimble 5800 RTK-GPS was carried out to obtain high-resolution Digital Elevation Models (DEMs), while a Geopen E60D resistivity-meter system was used to acquire the ERT data. The iso-resistivity surfaces can emphasise temporal and spatial variations in data volumes, and detailed features such as tomb passage, robbing hole, brick facade, archway, chamber, rear chamber, and two side rooms were characterised obviously and effectively.

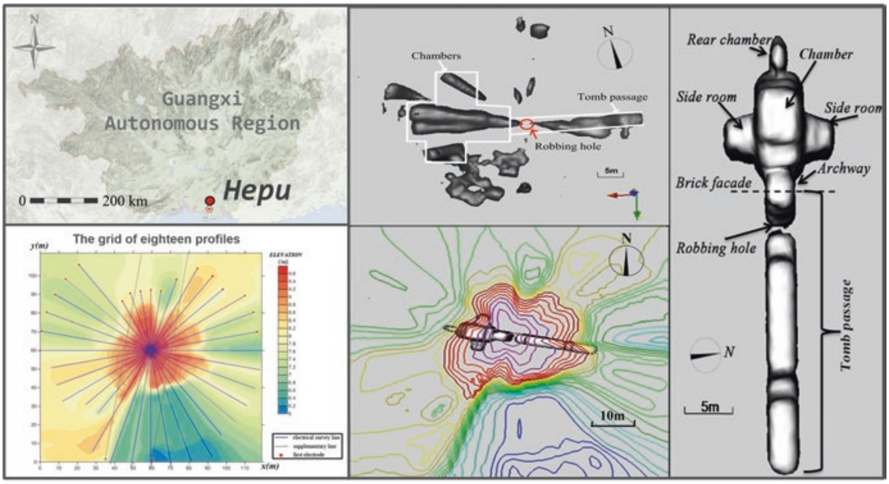

Fig. 3 The location of ERT example at the Hepu Han Tombs, the grid of 18 profiles overlapped on the digital elevation map, and the 'pseudo-3D' interpretation of the burial mound. (Adapted from Chen et al., 2018)

3.3 Cultural Heritage Protection

Geophysical methods can be used to evaluate states of cultural heritage structures such as grottoes, stone carvings, and murals (e.g. Lu et al., 2020). There are obvious physical differences between weathered rock vs un-weathered rock, and strongly weathered rock vs weakly weathered rock. Besides, the original resistivity/dielectric constant of the rock can change after anti-weathering coating liquid penetrates the repaired cultural heritage. Therefore, GPR and ERT have been used to assess the efficacy of rehabilitation of cultural heritage, as well as weathered interface and in-fill of cracks/voids, although such geophysical applications are still very limited in China. Figure 4 provides an inspection example of Leshan Giant Buddha with 71 m high, the tallest Buddha in the world (Zhong, 2002). The geophysical surveys were performed by the Research Institute of Railways in the 1990s. The result is an interesting plane contour of moisture content on the face of the Buddha. Although the author mentioned that resistivity and sonic methods were used, unfortunately, he did not describe the specific process of how to get the final result. Besides providing the plane contour of moisture content, the author only mentioned that their results can locate the potential cracks and the weathering depth of the statue subjectively.

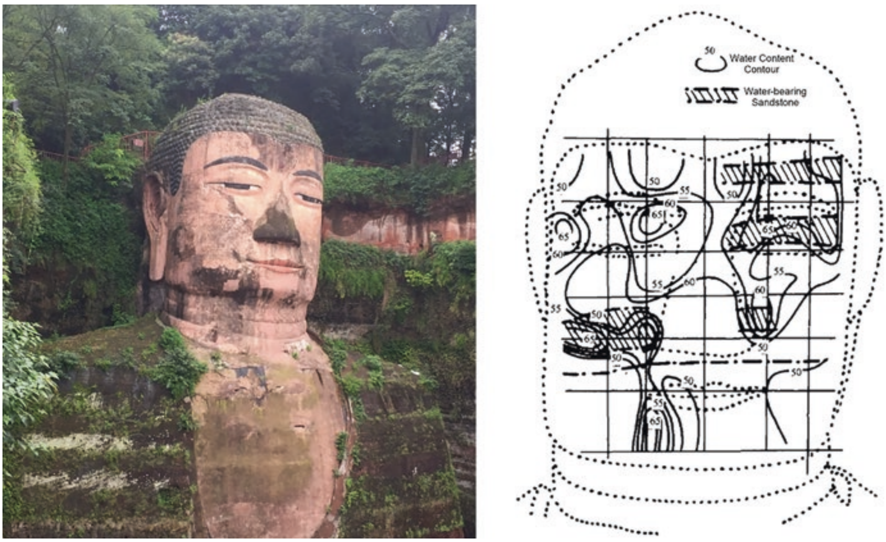

Fig. 4 The photograph (from Miss Suyu Qian) and the plane contour of moisture content on the face of the Leshan Giant Buddha. (Adapted from Zhong, 2002)

3.4 Urban Underground Remains

When ancient remains are buried underground in modern cities (e.g. Gan & Yao, 2021; Zhang & Wang, 2021), commonly used magnetic, electromagnetic and shallow seismic methods are ineffective due to the interference of a large amount of environmental noise. Moreover, the dense asphalt road network and hard cement ground make the traditional ERT with plug-in electrodes become unrealistic. In such case, besides GPR (e.g. Science and Technology Archaeology Centre, Institute of Archaeology, Chinese Academy of Social Sciences, and Qicheng Cultural Relics Scenic Area Management Office, 2017), more new technologies such as capacitive-coupled resistivity method need to be considered in the urban site. Figure 5 provides inversion results of two survey lines performed with an OhmMapper TR2 capacitive-coupled geo-electrical mapping system in the city centre of Hangzhou (Bie et al., 2017), where the high resistivity values are associated with the buried seawalls, built with blocks or stones to resist tides and waves during the Wu-Yue Kingdom period (about 910 AD), which are widely distributed in the southeast coastal area of ancient China.

3.5 Underwater Archaeology

The underwater investigations of antiquities, ancient ruins, and ancient tombs, attract strong attentions from archaeological experts and public, with its unique cultural charm. It's difficult to perform underwater archaeological surveys only by divers, geophysical explorations are more and more important, especially with the

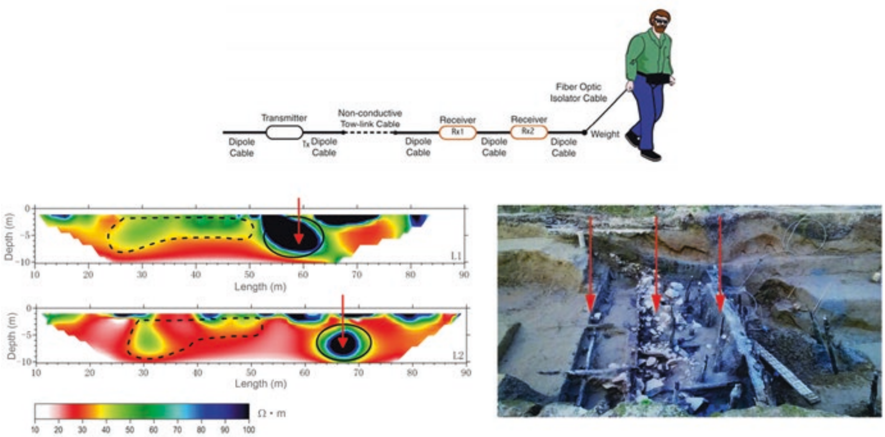

Fig. 5 The schematic diagram of capacitive-coupled resistivity system, the inversion results of two survey lines performed in the city centre of Hangzhou, and the photograph of the excavation for verification. (Adapted from Bie et al., 2017)

gradual improvement of marine equipment. Due to the different working environments between underwater and land, particularly influenced by the underwater visibility and currents, archaeo-geophysical methods on water are totally different and are used as follows: side-scan sonar, magnetometer for water use, multi-beam sounding system, sub-bottom profiler and GPR (e.g. Yang, 2014; Hu et al., 2016; Ma et al., 2016; Qin et al., 2018), equipped with diving equipment and corresponding logistical supports. The investigations of ancient shipwrecks, including wooden ships and ironclad warships (e.g. Wei, 2008; Zhou, 2020), have provided rich cultural relics for the study of ancient Chinese social history, greatly promoting the research of ancient Maritime Silk Road and the dynamic process of overseas trade history and relationship history (e.g. Underwater Archaeology Research Centre, National Museum of China, and Ningbo Institute of Cultural Relics and Archaeology, Zhejiang Province, 2020). As previously mentioned, integrated geophysical methods were used to detect ancient shipwrecks underwater in the sea of Liaoning Province as early as 1991, besides, more ancient shipwreck detections have been performed since then, like the No. 1 shipwreck of Pingtan Wanjiao from Qing Dynasty, in the East China Sea, the No. 1 shipwreck of Huaguangjiao from Song Dynasty, in the Paracels, and the No. 1 shipwreck of Nan'ao from Ming Dynasty (e.g. Yang, 2014; Ma et al., 2016).

Moreover, underwater archaeology in China has also some applications on rivers and lakes, for example, Yu et al. (2009) detected the distribution of famous buried-silver site in the Minjiang River with ERT, hidden here by Zhang Xianzhong, the peasant rebel leader of the Daxi Army in the late Ming Dynasty, which were recorded by many documents (e.g. the historical documents Shubi and Shunanjishi, both written in Qing Dynasty), and Qin et al. (2018) investigated underwater cultural relics of Yue kiln buried beneath Shanglinhu Lake, Zhejiang Province with GPR. Figure 6 provides a 3-D imaging of underwater ancient city, acquired with Simrad EM 3000 multi-beam sounding system on the Qiandao Lake, Zhejiang Province (Liu et al., 2005). The ancient city (i.e. the Suian County, also called Lion city) was submerged in the lake water due to the construction of Xin'anjiang Hydropower Station in 1959. As can be seen from the figure, the ancient city walls, streets and buildings are clearly displayed, providing preliminary quantitative information for the research and protection of the underwater ancient city.

4 Conclusions

Archaeo-geophysics can accurately identify, image and map the spatial extension of near-surface archaeological features or changes in the matrix of a site, so they are recommended as valid methods to optimise location and design of excavations. Throughout the past 70 years, researchers and practitioners witnessed the rapid development of geophysics in the field of Chinese Archaeology. This chapter has shown the historical development of the discipline of archaeo-geophysics, as well as some successful case studies in China which reached the peer reviewed literature.

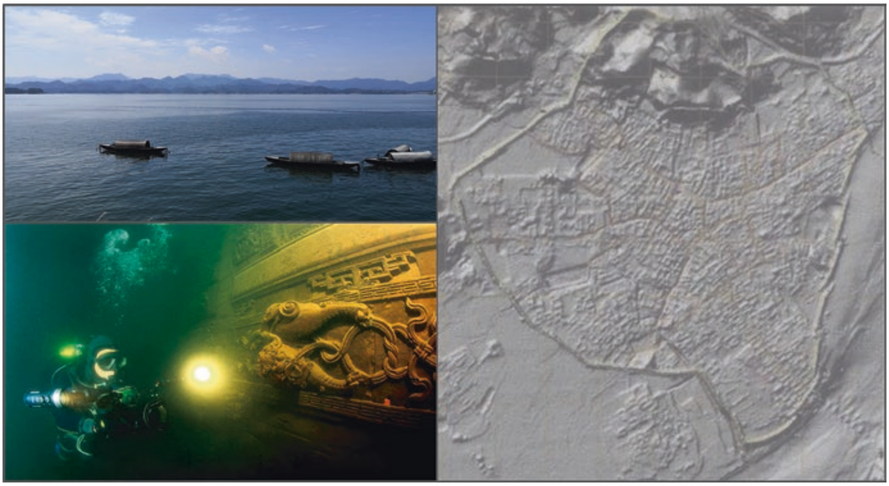

Fig. 6 Photographs above (2019, from the first author) and below (from the website of Chinese National Geography, 2009) the Qiandao Lake, and a 3-D imaging of underwater ancient city, acquired with Simrad EM 3000. (Adapted from Liu et al., 2005)

These included ancient city sites and ancillary building remains, ancient tombs, cultural heritage protection, urban underground remains, and underwater archaeology. However, failure is normal in reality. Our experiences suggest that failing to meet expectation is far more common than the successes reported. This observation is common for all near-surface geophysical applications and not restricted to archaeological prospection.

Without any doubt, geophysical methods are progressing from traditional location and experimental surveys in small scale to detailed imaging and diagnosis nowadays. However, interpretation of both 2D and 3D data are highly subjective and depend greatly on the user experience and understanding. Objective guidelines for survey data collection and data imaging are yet to be further explored in China. This work should involve preliminary available synchronous archaeological information as much as possible.

The development has paved the way to large-scale and regular use of the geophysical methods in almost all types of potential archaeological sites in future. Of course, we have to acknowledge that visual inspections via excavations and drilling cores are still the most common methods to reveal the truth on filed archaeology at present in China. It is probably not because of the unavailability or unpopularity of the geophysical methods, but the lack of necessary awareness between traditional field archaeologists. Given the large increase of wider applications, we stay positive with the development so far and expect a much wider use of geophysical methods on Chinese field archaeology in future.

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Part V
Cyprus

Sensing the Cultural Heritage from Above. The Case from Cyprus

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Abstract This chapter addresses the different remote sensing methodologies that have been applied for the study of the Cultural Heritage in Cyprus. Ground based geophysical prospection, aerial and satellite remote sensing, in tandem with soil analyses of cores, have been applied for the mapping of the archaeological sites and the reconstruction of the archaeoenvironment, but also for addressing issues related to the risk assessment of sites and monuments. Taking into account the different geological conditions of the island and some of its peculiarities (such as metamorphic and iron-rich geological formations), the success of these methods varies significantly. The past experiences can be used as a guideline for the wider and more successful application of the remote sensing techniques.

1 Introduction

Cyprus is one of the first localities in the Mediterranean world which made use of non-invasive research for archaeological studies. Since the 1970s, several studies employed geophysical surveys, remote sensing, and GIS application to investigate archaeological settlements, necropolis, and landscape. Other studies aimed at restituting the environmental context and its evolution in relation to ancient human occupation.

The range of geophysical methods developed to investigate the archaeological sites included ground penetrating radar (GPR), magnetometry, earth resistance

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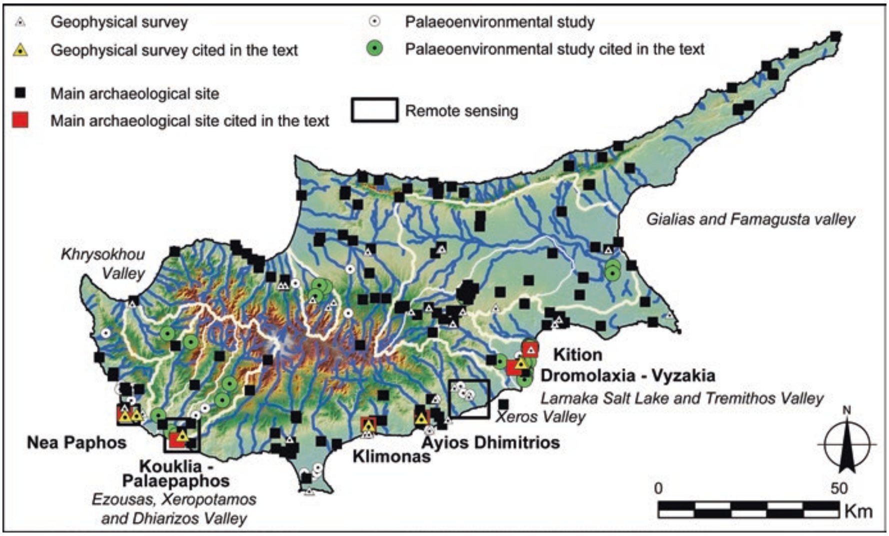

Fig. 1 Archaeological sites and case studies mentioned in the text.

mapping and electrical resistivity tomography (ERT), electromagnetic induction (EMI) and chemical analysis. Some specific limitations have been identified for each method and some archaeological features were better delineated when several methods were employed together and when the soil conditions and geological background allowed. Concerning the reconstruction of environmental evolution, cores, natural outcrops, and trenches were studied using multidisciplinary methods that included granulometry and magnetic susceptibility measurements associated with dating.

On a larger scale, aerial imagery and satellite remote sensing employing a large variety of space sensors have been used for the detection of archaeological sites and cultural heritage management, sometimes in tandem with ground-based prospection techniques. In many cases, the above have also been incorporated in Geographical Information Systems (GIS), and spatial analysis was used for a further assessment of the settlement patterns in different periods of antiquity.

The aim of this chapter is to present a condensed review of what has been done in terms of geophysical surveys, coring, and satellite remote sensing for archaeological applications in Cyprus until today (Fig. 1).

2 Environmental Background

Cyprus is the third largest island in the Mediterranean. The island belongs to the Mediterranean climate zone and therefore, experiences mild winters and hot dry summers. The wet season extends from November to March, with most (approx.

60%) of the rain falling between December and February (Pashiardis, 2002). The Troodos Mountain rage represents the dominant source of hydrologic activity where major rivers of the island originated. Among these we can cite the Pediaios and the Gialias that originate from the eastern part of the Troodos Mountain, drains the Mesaoria plain and end within the Mediterranean Sea in the eastern part of the island. Approximately two third of the island is covered with mountains. Its topography, which is related to the geological history of the island is mainly composed of two mountain range (Zomeni, 2012). The Pentadaktylos (Keryneia) mountain range is located to the north and is composed of recrystallised sedimentary deposits (limestone, dolomites and marbles). The southern part of the island is characterised by the Troodos Mountain range. It is composed of volcanic and metamorphic rocks related to the ophiolithic sequence. In the southwestern part of the island, the Mamonia formation, has been formed during Upper Triassic-Cretaceous and is composed of sedimentary rocks and basalts. Circum Troodos geological formations are mainly composed of marine and continental deposits. Between the two main mountain range, the Mesaoria plain is composed of conglomerate formation related to Pliocene and Pleistocene alluvio-colluvial fan (Harrison et al., 2013).

In a few cases, the metamorphic geology and the iron-rich deposits have created problems with respect to the efficient application of remote sensing techniques, especially in magnetic prospection. Furthermore, the compacted clay soils that exist especially in the valleys has created a strong compacted soil context that does not allow the clear identification of subsurface targets through the GPR surveys. The above are further attenuated from the deep ploughing and the intensive agricultural practices that sometimes have scratched the cultural horizon, diffusing in a large degree the past anthropogenic traces, which creates certain difficulties in the identification of the underneath architectural relics by the airborne and satellite sensors.

3 Ground Based Geophysical Surveys and Geochemical Analysis

The existence of a physical heterogeneity between the underlying archaeological targets and the surrounding natural sub surface (soil, geological bedrock, etc.) is the basic principle of main types of geophysical survey (Aitken, 1974; Nishimura, 2001; Scollar et al., 1990). Mineral and chemical composition of the sub-surface can be obtained respectively from measurements of the magnetic susceptibility and pXRF, in situ or from soil samples analyses in the lab. When cross combined with excavation, the shape, the geometry and the depth of these anomalies can be related to specific archaeological features. However, outcrops of the geological bedrock, intense sources of noise or small contrasts between the archaeological features and their soil environment can hide or make invisible the targets.

For more than 50 years, some of the most important archaeological sites of Cyprus have been studied through ground-based prospection techniques (Aitken, 1971; Fischer, 1980; Hesse & Renimel, 1978; Parhas et al., 1979). Limitation of geophysical surveys are mostly linked to climate (high temperatures) and geology. In the eastern part of the island, GPR measurements were strongly influenced by clay and salt rich sediment from Larnaca Salt Lake. Arid conditions in the western area of Cyprus induced very low readings in the resistivity surveys (Graham et al., 2013; Boutin et al., 2013; Gibson et al., 2013). Copper slag piles formed from copper extraction processes during Chalcolithic to Bronze Age period (and continued until recent historical period) together with very magnetic geological formations prevent the extensive use of magnetic methods near the Troodos Mountain range. Although some limitations still exist, several techniques have been implemented in order to depict the archaeological settlements and necropolis of the island from the Neolithic to the Medieval period. The most often used method remains the GPR, magnetic and electrical surveys. The ERT technique and EMI method are still only applied at a limited number of sites in Cyprus. Most of the investigations involved more than one method of prospection in a "manifold" geophysical approach (Sarris, 2013; Kalayci et al., 2017). Although the geomorphological context can be considered as a limitation, some geophysical survey techniques allowed to locate the sectors of extensive distribution of architectural relics with a better resolution of the archaeological filling. Best examples are illustrated at Klimonas—Agios Tychonas (Benech et al., 2017a) and at Kition (Benech et al., 2017b).

Just to present a few representative examples, excavations at the site of Klimonas—Agios Tychonas (Fig. 1) yielded the remains of a Pre-Ceramic Neolithic A (PPNA) village with mud-brick circular structures dated to the beginning of the ninth millennium BC (Vigne et al., 2017). Geophysical surveys (Fig. 2a) allowed to highlight structures that are more complex to identify due to the low contrast between the architectural elements and the surrounding soil. Although the magnetic response was weak in amplitude and small in size, several discrete structures like pits and raw earth architectural remains have been identified. The EMI survey was rather indicative of the geological substrate due mostly to the rough geomorphology and the dry environment (weak signal registration). The recognition of the geophysical signatures met a number of difficulties due to the rough geomorphology, the outcrops of the bedrock, the lack of sufficient thickness of soil, the dry environment (weak signal registration) and the intensive soil corrosion phenomena (lack of signal distinction) (Benech et al., 2017a).

Dromolaxia—Vyzakia (Hala Sultan Tekke) is a large Bronze Age city located on a Quaternary alluvial fan near the palaeo-depression of the Larnaca Salt Lake (south-east coast of Cyprus, Fig. 1) (Devillers et al., 2015). Since the first settlements ca. 1600 BC, the site was probably the most important harbour in the entire Eastern Mediterranean during Late Bronze Age (ca. thirteenth–twelfth c. BC). Around 1200–1150 BC, several layers of destruction have been also identified with the "crisis years" at the end of the Bronze Age in the Mediterranean. The extensive surveys using magnetometer (Fig. 2b) indicated large architectural compounds intersected by streets and tombs from the necropolises (Fischer et al., 2020; Trinks, 2015). The mineralogical and chemical analysis on soil samples allowed to

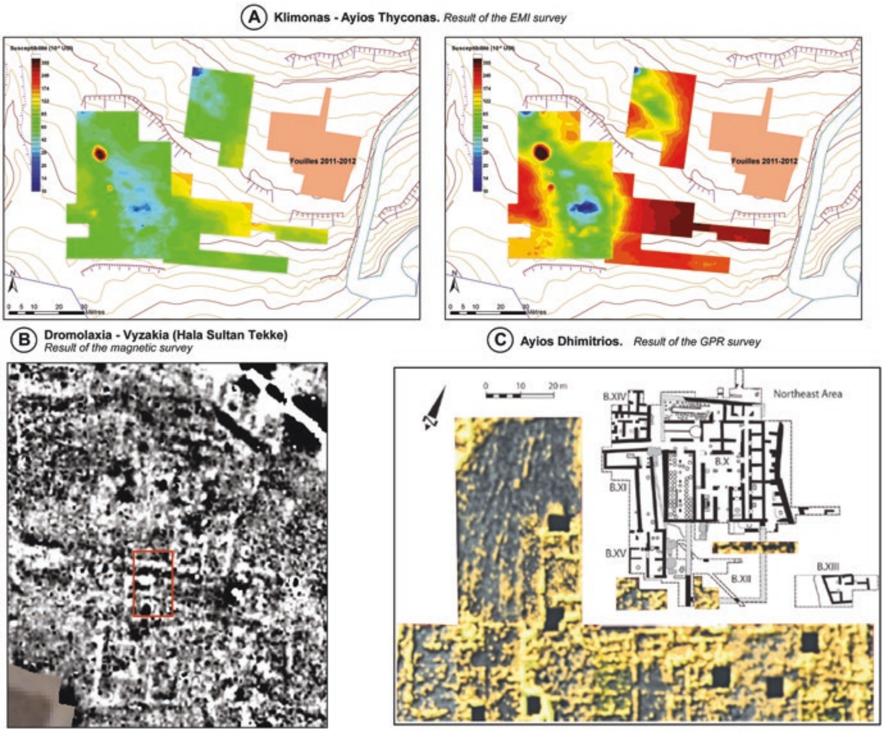

Fig. 2 Example of archaeo-geophysical surveys. (a). **Klimonas—Ayios Tychonas.** Left: Magnetic susceptibility map (in 10^{-5} USI) resulting from an electromagnetic survey with a CMD Mini-Explorer for a 71 cm coil gauge (drawing A. Tabbagh; topographic base R. Touquet). Right: Magnetic susceptibility map resulting from an electromagnetic survey with a CMD Mini-Explorer for a 118 cm coil gauge (drawing A. Tabbagh; topographic base R. Touquet). The geophysical anomalies are mostly linked to the geological bedrock rather than to architectural remains or ancient human activities. However, high values (in red to orange on the map) are obtained on the terraces of the archaeological site of Klimonas. (From Benech et al., 2017a, b). (**b**). **Dromolaxia—Vyzakia (Hala Sultan Tekke).** Magnetometer map of the archaeological site. The colour scale is presented in Black (negative anomaly) and white (positive anomaly). The red rectangle indicates the area of excavation CQ4. The interpretation of the magnetic survey was confirmed by excavation and highlight several buildings organised in large compound. (From Fischer et al., 2020). (**c**). **Kalavasos—Ayios Dhimitrios.** Time slice at depth of 60–80 cm. Light colours indicate high amplitudes and dark colours low amplitudes. Black rectangular voids are locations of extant olive trees. B. = building number (drawing by T. Urban and K. Fisher). The interpretation of the GPR survey was confirmed by excavation and highlight several buildings organised in large compound. (From Fisher et al., 2019).

highlight distinct characteristics between interior and exterior of structures, which can be related to by-products of domestic or industrial activities (Cuenca-Garcia et al., 2015; Hafez et al., 2017). GPR survey was limited to the uppermost parts of the archaeological and natural deposits due to the salty clay-rich soil inducing a strong electromagnetic radar attenuation.

Kalavasos—Ayios Dhimitrios (Fig. 1) is a significant regional centre, well-positioned site at a confluence of routes that link the eastern part of the island to the west, the copper mines from the Troodos Mountains to the north and the coast to the south (South, 1980). Previous archaeological studies suggest that during the Late Bronze Age period (ca. 1450–1200 BC), the site likely covered 11 ha, built around an urban centre (Keswani, 1993; South, 1997; Todd, 2004). The site's administrative centre is characterised by a 30.5 × 37 m court-centred monumental structure with ashlar masonry dedicated to the production and storage of olive oil and elite feasting activities (South, 1997; Fisher, 2009). The GPR survey (Fig. 2c) detected a complex of large quadrangular structures with apparent partitioned spaces in the South and in the West part of the site (Fisher et al., 2019; Rogers et al., 2012; Urban et al., 2014). Complementary EMI survey identified an area of remnant salts from organic matter in a central room or court that could possibly be related to by-products of feasting activities (Fisher et al., 2019). The same building exhibits an area of high magnetic susceptibility that might be related to some intense burning processes such as cooking. The lack of contrast between the magnetic properties of the calcareous soils and the limestone and sandstone building materials that were used to construct Late Bronze Age buildings limited drastically the magnetometry survey (Fisher et al., 2019).

Kouklia—Palaepaphos (south-west coast of Cyprus) is recognised as an UNESCO (United Nations Educational, Scientific and Cultural Organization) World Heritage site (Fig. 1). It has been one of the most significant sites of the island with a constant human presence from the Chalcolithic period to recent times (Maier & von Wartburg 1985). During Late Bronze Age (around the thirteenth c. BC), Kouklia Palaepaphos grew into one of the island's first regional polities and during the Iron Age, the site is considered as one of the ten blooming city-kingdoms of Cyprus (Iacovou, 1994, 1999; Maier, 1999). Along the fourth c. BC, when port facilities and administrative functions were transferred to Nea Paphos (18 km to the West), the urban landscape began to shrink. Only the open-air sanctuary to Aphrodite and its direct environs continued to receive attention during Hellenistic and Roman eras until the advent of Christianity. Previous hypotheses of the extension of the urban sectors and the fortification walls at Kouklia—Palaepaphos were confirmed and even rejected by systematic and extensive geophysical surveys in tandem with GIS spatial analyses (Iacovou et al., 2009; Sarris et al., 2005; Sarris & Papadopoulos, 2010; Stamatis et al., 2007). The multi-method survey (GPR, magnetic and electric) was able to identify monumental, domestic buildings and allowed to reconstruct section of the temenos wall of the sanctuary area. Some anomalies that were suggested by all methods proved to have been caused by geological processes (iron enriched bedrock or residues of past lightings, Fig. 3a).

Nicosia (Fig. 1), the capital of Cyprus since the tenth century (Papacostas, 2012), is located in the Mesaoria Plain, at the central part of the island. Ancient Nicosia has been occupied since the Late Chalcolithic period (Pilides, 2004; Hermon et al., 2014) but the modern city completely overlies architectural remains assignable to the early Christian period until the sixteenth c. AD. The Venetian fortification and the moat (1489–1570) have a circular shape containing eleven pentagonal bastions

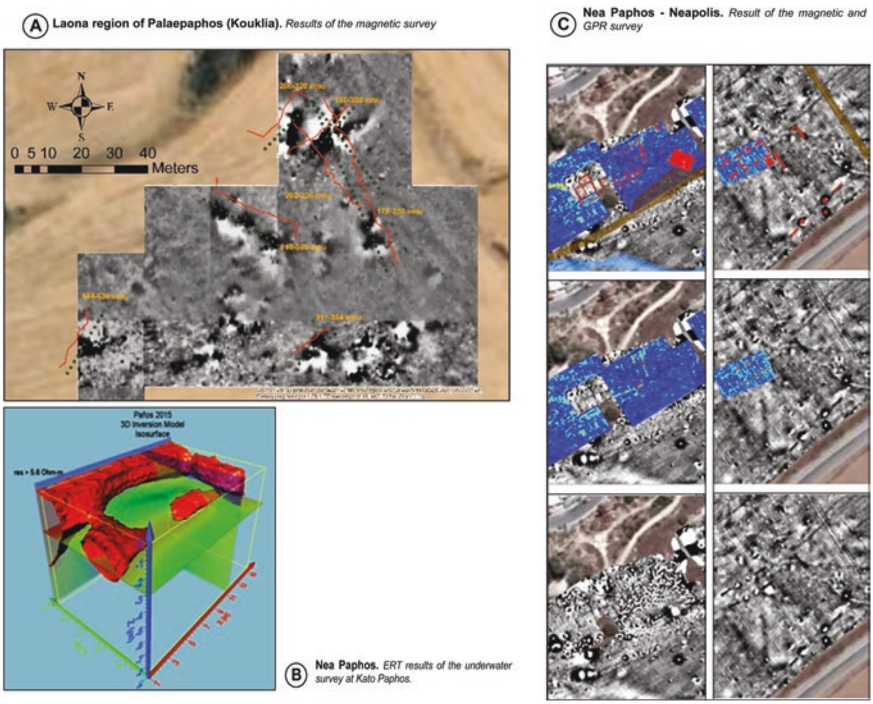

Fig. 3 Supplementary examples of archaeo-geophysical surveys. (**a**). **Laona region of Palaepaphos (Kouklia)**. Results of the magnetometer survey. Measurements with both Bartington G601 and Geoscan Research FM256 came show several extreme magnetic anomalies (>+/−3000 nT, Black (negative anomaly) and white (positive anomaly)) of relatively large dimensions (~5–10 m). Subsequent excavations did not result any kind of recent or ancient anthropogenic feature. Soil susceptibility analysis indicated a relative high level above the specific anomalies. The intensity of the magnetic anomalies and their amorphous shape is most probably related to the effect of lightings that hit the area. This may be related to the rich copper-bearing outcrops of bedrock that exist in a low depth below the ground surface. (From Sarris et al., 2014). (**b**). **Nea Paphos**. ERT results of the underwater survey at Kato Paphos. 3D isosurface of the resistivity values more than 5.8 Ohm-m showing the extend of the submerged wall structure related to the antic harbor up to 1.5 m below the seabed. (From Simyrdanis et al., 2017). (**c**). **Nea Paphos—Neapolis**. Result of the magnetic and GPR survey. The colour scale is presented in Black (negative anomaly) and white (positive anomaly) for the magnetometer survey and the intensity of the GPR signal is highlighted by hot (yellow to red) colours. Potential candidates to represent architectural features registered on the magnetic and GPR measurements. (From Sarris & Papadopoulos, 2019).

and three gates (Bakirtzis, 2017; Grivaud, 1992; Jeffery, 1907; Panciera, 2010; Violaris, 2012). The multi-method geophysical survey (ERT, EMI and GPR) allowed to reconstruct a section of the Venetian wall and of D'Avilla bastion (Cozzolino et al., 2020). Best results were obtained with the ERT method as EMI and GRP measurements were mostly related to modern underground structures (pipe, electric cabin). Some resistive anomalies detected by the ERT were verified by excavation and attested to a perfect correspondence between the geophysical previsions and the Venetian wall found in the subsoil (Cozzolino et al., 2020).

The archaeological site of Nea Paphos (southeastern coast of the island, Fig. 1) revealed important edifices related to the Classic Antiquity (House of Dionysos, the House of Orpheus, the Villa of Theseus and the House of Aion; the Agora, composed of an Odeon and the Asklepieion; the Theatre and the necropolis of the "Tombs of the Kings") and is inscribed on the World Heritage List of UNESCO since 1981. The city was founded at the end of the fourth c. BC when port facilities were transferred from Kouklia—Palaepaphos (Bérard, 1954; Michaelides, 1991; Papageorghiou, 1983). While disastrous earthquake ravaged most important cities on the island, the city became the central administrative centre of the Ptolemaic kingdom on the island around the third c. BC. The city began to shrink after the Arabs incursion of the seventh c. AD but continued to play an important role in the island during following centuries, especially during the Byzantine (eleventh c. AD) and Medieval period (around 1500 AD) (Altinok et al., 2011; Fokaefs & Papadopoulos, 2007). The ERT method implemented at the Hellenistic to Roman harbour of "Kato Paphos" (Fig. 3b) was able to provide solid evidence on possible building walls buried 2 m under the seafloor (Simyrdanis et al., 2017; Papadopoulos, 2021). In the Agora, preliminary results of the magnetic survey realised in 2015 indicated several rectangular anomalies that have been related to diamagnetic slabs of limestones, probably used for the pavement of the pathway. High amplitude magnetic signals were related to some granite column (in the form of concentrated dipoles) and low amplitude readings to architectural remains, filled pits, double canal made of limestone and clay pipes (Seifert et al., 2020). Around the city centre, two survey aimed at identifying ancient architectural remains. Multi-technique survey (GPR and magnetometry, Fig. 3c) demonstrated that most of the area is without significant ancient occupation (Sarris & Papadopoulos, 2019). Some exceptions are consisting of a number of linear anomalies and round features. The particular features are obvious in both the magnetic and the GPR data, although the magnetic measurements are obscured from high levels of noise (Sarris & Papadopoulos, 2019). A second study investigated four different sectors in the archaeological park and in the modern city (Benech, 2014). All sectors were polluted by superficial disturbances from neighbouring modern construction. The results delivered interesting magnetical anomalies whose organisation and orientation are in good correlation with the Roman villa discovered during excavation in the area by the French mission.

4 Coring and Reconstruction of Archaeoenvironment

The geomorphology and the landscape of Cyprus is mostly linked to the geological bedrock and to the climate of the island. Human activity is considered as a factor of transformation of the landscape (canals, rock extraction, urbanisation, etc.) in dynamic equilibrium with climate changes. The proximity of the main archaeological site with coastal, lacustrine and fluvial sectors is in relation with their evident benefit for the ancient societies' activities. As a counterpart, climatic events seemingly influenced on socioeconomic changes by impacting sowing and growing seasons and irrigation capacity.

Landscape reconstruction of these areas is obtained through the analysis of stratigraphic profiles from natural context or from core extraction. Several parameters are used on regularly distribute samples extracted along the profiles in order to reconstruct the ancient landscape and human activity (Fig. 4). Magnetic susceptibility measurements (low and high frequencies) can distinguish different sediment sources (Ghilardi et al., 2015; Sarris, 1992; Vella et al., 2019), soil formation (Dearing et al., 1996), firing events (Oldfield & Crowther, 2007) and pottery production or other workshop activities (Dearing et al., 1996; Jordanova et al., 2003). Grain size determinations (laser analysis for the fraction below 2 mm and sieving for coarser fraction), organic matter and $CaCO_3$ content (loss on Ignition) are generally used to quantify the depositional and erosional processes (Vella et al., 2019). Pollen and charcoal analysis contributes further to the reconstruction of the composition of the vegetation. Finally, the chronological control of the environmental evolution is obtained mostly through AMS radiocarbon (charcoals bones and shells) and OSL (sherds) dates.

Although well developed at the scale of the Mediterranean, multi method analysis of subsurface samples extracted from coring is still limited in Cyprus. The most studied area is represented at the south-eastern sector of the island in the vicinity of the Larnaca Salt Lake (Fig. 4). Two major archaeological sites are excavated for more than 100 years by French, British, Swedish and Cypriot groups. The particular

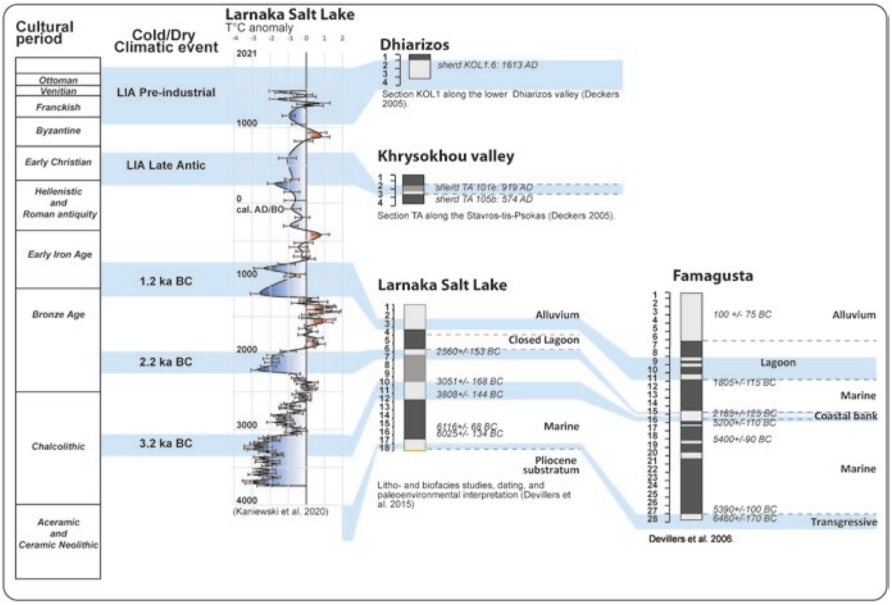

Fig. 4 Paleoenvironmental reconstruction based on cores extraction and pollen and sedimentological analysis. Dates are obtained through ^{14}C and OSL dating

studies at Dromolaxia—Vyzakia (Hala Sultan Tekke) (Bronze Age, ca. 1600 BC to ca. thirteenth–twelfth c. BC) and Kition (Cypriot Iron Age to the Hellenistic period) indicated that the area was continuously inhabited for the last 3500 years. The Larnaka Salt Lake delivered two continuous undisturbed sediment cores, with chronological (^{14}C dates), sedimentological, and paleoecological (pollen analysis) correlations allowing to create a unique sequence covering the period ~4000 ± 20 BC to 1500 ± 50 cal year AD (Kaniewski et al., 2013). Several cold and dry periods were recorded at 3.2 ka BC, 2.2 ka BC, 1.2 ka BP, 800 AD and 1200 AD in concordance with cooler phases in Europe (Kaniewski et al., 2020). Some other cores in the sector could identify several natural channels between the Salt Lakes lagoon and the open sea. Coastal progradation, associated to siltation of important naval routes of communication, participated to the abandonment of the large sheltered anchorage of Dromolaxia—Vyzakia (Hala Sultan Tekke) during the early twelfth c. BC. The canal, which was excavated during the later second millennium BC, could be a response to the siltation during the Iron Age. At Kition, cores extraction and paleoenvironmental reconstruction are systematically employed for the last 40 years. At around ca. 900 cal. BC and 500 cal. BC (Iron Age) the site overlooks a sea bay evolving into a lagoon and then into an increasingly enclosed marsh land following the formation of a coastal bank (Bony et al., 2016; Gifford, 1978; Morhange et al., 2000; Nicolaou, 1976). Thus, the military port was founded in the classical period in a lagoon environment, the coastal bank of pebbles having favoured the installation of a port activity in the most protected part of the lagoon. To the west of the Larnaka Salt Lake, within the Tremithos Valley, 8–10 m of fluvial sediments are recorded between ca. 4800 cal. BC (Sotira Neolithic Culture period) and ca. 2500 cal. BC (Late Chalcolithic) (Ghilardi et al., 2015). Around 3200 cal. BC, the river incised into the alluvial formation, probably in relation with flash-flood events during cold and dry climatic events centred on 3.2 ka BC (Bar-Matthews et al., 1997; Roberts et al., 2011).

The Gialias valley is the second area investigated to study the Holocene fluvial reconstruction in Cyprus (Devillers et al., 2006). The geomorphological study of the median sector of the valley has identified a first alluvial terrace which presents several paleosols dated to 9300, 7400, 4400, 3800 cal. BC. Downstream, marine vases fill the lower Famagusta valley. All the watershed region experienced very high sedimentation rate with a negligible human influence on detritism. Between 3500 and 2000 cal. BC, the first major incision phase was linked to low water intake and/or relatively high temperatures. This event can be reasonably related to the cold and dry periods of the 3.2 ka and 2.2 ka BC events identified by Kaniewski et al. (2020) at Dromolaxia—Vyzakia (Hala Sultan Tekke). Downstream, the presence of shell sands testifies to the establishment of a coastal barrier. Between 2000 cal BC and 1250 cal. AD, a new significant alluvial period and two phases of pedogenesis are identified (between 4400 cal. BP and 1400 cal. BC; 800 cal. BC). During the Middle Ages (300–1250 cal. AD), a new fluvial incision affects the middle valley corresponding to the cold and dry event of 800 AD identified by Kaniewski et al., 2020 at Dromolaxia—Vyzakia (Hala Sultan Tekke). The sedimentation rates of the

Frankish, Venetian and Ottoman periods (1250–1900 cal. AD) are important and characterised by sands with lenses of pebbles. The raising of the alluvial floor between (4 and 5 m) causes significant changes in the morphology of the alluvial plain during the LIA. The developments related to the fluvial network (mills, bridges, dams, etc.) then become unsuitable and are quickly become buried. Incision 3, could not be precisely dated but could be attributed to the first half of the twentieth century.

In western Cyprus, several studies aimed at the reconstructing the chronology of the alluvial erosion and filling phases since Holocene. The Khrysokhou, Ezousas, Dhiarizos, and Xeropotamos River terraces have been analysed through grain size and soil analysis (magnetic susceptibility, OM content and pH), the chronological control of samples been obtained with OSL datings (Deckers, 2005). Although early to mid-Holocene fluvial sediments may have been eroded in most cases, Byzantine to modern period have been more documented. Within the Khrysokhou valley (PITSI/Section TA-TB), two period erosion phases were identified around 574 AD and 920–1571 AD. The Ezousas valley presented evidences of possible early to mid-Holocene alluviation (EZA) and flood events around 1050–1060 AD (EZA and EZD respectively), 1297 and 1329 AD (EZG). Near Kouklia—Palaepaphos archaeological site, the lower valley of the Dhiarizos River delivered 3.1 m of rounded gravels overlied by fine silt (KOL1). OSL dating is estimating the age of that fluvial deposits at 1600 AD. Farther inland, fluvial sediments have been dated to 1200 AD (MB) and 1400 AD (PR1). Upstream, OSL datings on sherds attest to the presence of a sediment deposition shortly after 920 AD (KIS1). At the mouth of the Xeropotamos River, the sequence of deposits is dated sometime after 1760 AD (XA-XE). Finally, the Mitsero Basin in western central Cyprus showed a very similar absence of fluvial sediments dating between the early Holocene and the Medieval period (Given & Knapp, 2003). The incision phase identified in the Khrysokhou valley can reasonably be related to the other one identified between 300 and 1250 cal. AD at the Gialias valley (Devillers et al., 2006) and the cold/dry event at 800 AD in Larnaka Salt Lake (Kaniewski et al., 2020). Medieval to modern fluvial deposits (1297–1760 AD) are most probably linked to the LIA event.

5 Satellite Remote Sensing, Aerial Photography, and Ground Spectroscopy

Scientific literature related to satellite processing for supporting archaeological research (Luo et al., 2019) has been growing around the globe. This increase implementation is directly linked with the availability of meter and sub-meter satellite sensors, which took place at the end of the twentieth century, as a result of the release of the first commercial high-resolution IKONOS satellite sensor in 1999. Since then, several other high-resolution commercial satellite sensors have been set into orbit (Agapiou & Lysandrou, 2015).

In Cyprus, satellite remote sensing, aerial photography and ground spectroscopy have been only recently introduced. Hereunder, are briefly presented some examples of archaeological projects that implemented in their research process satellite and/or aerial investigation methods, tools, and data. Also, some examples of basic scientific research fulfilled within the framework of funded research projects are given. All presented examples were accomplished as part of the multidisciplinary research group of the Archaeology and Cultural Heritage section (ARCH), Remote Sensing and Geo-environment research Lab, established at the Cyprus University of Technology.

One of the first integrations of multitemporal satellite archives with higher resolution aerial datasets was implemented under the Palaepaphos Digital Atlas (2002–2003) and the Palaepaphos Urban Landscape Project (PULP) (2006–today) (Iacovou et al., 2009; Iacovou, 2008). For these projects, high-resolution multispectral satellite data like the GeoEye, IKONOS and QuickBird, along with multitemporal orthophotos provided by the Department of Land and Surveyors of Cyprus, were processed. Also, compressed RGB images from the Google Earth digital Globe were extracted and elaborated. At the same time, the above-mentioned geodataset was used to provide background information on the landscape through the GIS environment.

An integration of archive aerial images with recently acquired high-resolution satellite datasets was carried out in the case of Graz Amargeti Survey Project, directed by Dr. Gabriele Koiner and Dr. Gabriele Ambros (For preliminary reports refer to (Amargeti Survey Project, 2021) and (Graz Amargeti Survey Project, 2021). Specifically, a WorlView-2 multispectral image and archive aerial orthophotos provided by the Department of Land and Surveyors of Cyprus (1963, 1993 and 2014) were used. Linear features (cropmarks) were extracted in specific plots of the case study area before the ground geophysical investigations. Despite the limited spatial resolution of the aerial data, results were found very encouraging. These, along with the geophysical prospection's outputs, will be used to support and guide future archaeological field investigations.

A recent project concerned the mapping of the ancient monuments (declared as such and protected by the Antiquities Law), in the Paralimni Municipality (Agapiou et al., 2020). To geolocate the monuments and sites under question, archive aerial images and cadastral maps (provided by the Department of Land and Surveyors of Cyprus), were used. Given the recent land-use changes in the area, the exact geolocation of the protected monuments was achieved through the interpretation of aerial photos, cadastral maps, and archaeological records. As the cadastral plans of Cyprus have changed over the last decades, and the plan, sheet and plot numbers have been modified, the detection of the monuments—especially of those that have been declared protected decades ago—through the archival, archaeological information required confirmation from the historic aerial datasets to match the plots with the protected zones of the monuments.

Another recent example was the investigation of the Xeros valley, under the auspices of the Settled and Sacred Landscapes of Cyprus (SeSaLaC) project (directed by Associate Prof. Thanasis Vionis), through aerial photographs. Despite the limitation of the spectrum resolution (analysis was conducted only in the visible part of the spectrum), the results were found very promising as they were aligned with the results of the geophysical prospection surveys. Several hot spots were identified and mapped in GIS environment through image enhancement techniques, including histogram stretching and filtering. Based on the findings, hot-spot analysis and clustering was applied to group the detected archaeological proxies.

A more methodical approach towards the integration of satellite, aerial remote sensing and ground spectroscopy for archaeological studies, was initiated in 2012 with the first related PhD thesis (Agapiou, 2012) the core of which was the use of satellite, middle range and ground remote sensing techniques, along with geoinformatics towards archaeology and built heritage monuments. In Agapiou (2012), the use of satellite remote sensing datasets was investigated to detect cropmarks, which were used as archaeological proxies for subsurface archaeological remains. Such proxies are detected due to their unique spectral signatures and the distinct contrast that they provide in relation to the existing cultivations. The optimum temporal and spectral resolution for supporting these types of investigation in the Eastern Mediterranean region was identified (Agapiou et al., 2013). The processing of hundreds of ground spectral signatures obtained from simulated test fields indicated that the 760 and 900 nm spectrum regions are the best wavelengths to support the interpretation of cropmarks and their semi-automatic extraction from the images. It was also found that the period between the mid-March and the beginning of April is the optimal temporal window for observing and detecting cropmarks over cultivated areas in Cyprus.

A challenging task was the study of the optimum spatial resolution for supporting landscape archaeology, especially in areas with spectral heterogeneity. The optimal spatial resolution (OSR that is the ground spatial resolution or the pixel size of the images), for two different cases studies, a simulated archaeological environment in Alampra village test field and the archaeological site of "Nea Paphos", were investigated (Agapiou, 2020). The local spectral variance of a given area of interest (e.g., archaeological proxy) is minimised without losing key details necessary for an adequate interpretation of the cropmarks. The spectral range was limited to the visible and near-infrared part of the spectrum (400–900 nm). The OSR was estimated for each spectral (RGB), and near-infrared bands. The study was also expanded to include vegetation indices, such as the Simple Ratio (SR), the Atmospheric Resistance Vegetation Index (ARVI), and the Normalised Difference Vegetation Index (NDVI). Based on these findings, the OSR for the above case studies was defined (Fig. 5). The outcomes indicated that the OSR could minimise the local spectral variance, thus minimising the spectral noise, and, consequently, better support image processing to extract archaeological proxies in areas with high spectral heterogeneity.

In parallel, another study was performed in environments with spectral heterogeneity. In these areas, interpretation and detection of cropmarks can be problematic even after applying sophisticated image enhancement analysis techniques due to the phenomenon of mixed pixels. To overcome this problem an image-based methodology over specific case studies in Cyprus where the vegetation is suppressed

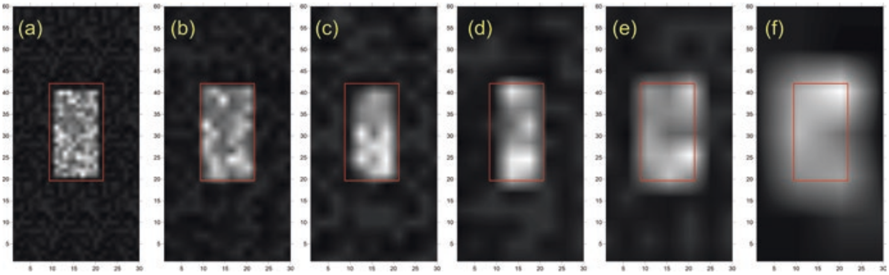

Fig. 5 (**a**) Simulated simple ratio (SR) datasets pixel size 1; (**b**) simulated SR datasets pixel size 2; (**c**) simulated SR datasets pixel size 3; (**d**) simulated SR datasets pixel size 4; (**e**) simulated SR datasets pixel size 5; and (**f**) simulated SR datasets pixel size 10. (Agapiou, 2020)

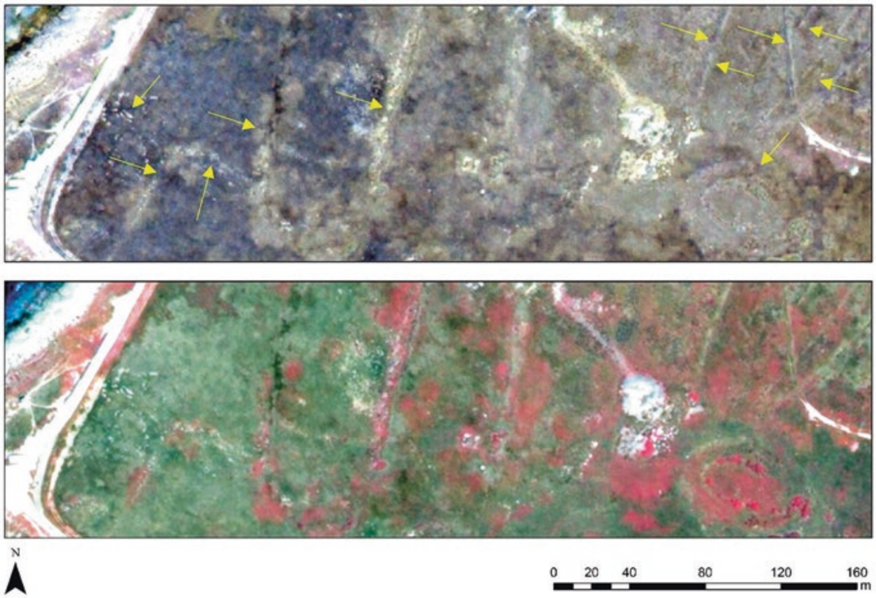

Fig. 6 Vegetation suppression (NIR-R-G composite, top) and pansharpened multispectral image (NIR-R-G composite, bottom). (Agapiou, 2019)

following the "forced invariance" method, was proposed (Agapiou, 2019). The promising results of this study were evaluated in the archaeological site of "Nea Paphos" in Cyprus using a WorldView-2 multispectral image (Fig. 6).

The use of aerial photography as an investigation tool for archaeological purposes in a more systematic basis has only lately started in Cyprus. A recent study gathered all known archive and new aerial photographs over Paphos area, to examine its burial grounds (Lysandrou & Agapiou, 2020). In that study, specific aerial datasets were elaborated, and blended with archaeological and topographic data, investigating the Hellenistic (-Roman) eastern necropolis of Nea Paphos boundaries and tombs. Some of the aerial data were produced before the excavation of the site, and therefore were of valuable utility. This investigation was based on metrics extracted from known Hellenistic tombs of the necropolis (Lysandrou, 2020). Thereafter, more archaeological features, possible other tombs, were detected and interpreted through the aerial images (Fig. 7). The use of multitemporal archives enabled the reconstruction of the landscape of Paphos before the modern urban expansion, revealing at the same time various soil and cropmarks that share common characteristics. All archaeological remains and proxies have been introduced into a Geographic Environment System, for a solid visualisation and interpretation on a landscape level.

Important issues related to the risk management of monuments and archaeological sites in Cyprus are earthquakes, and urbanisation. Several studies that integrated satellite imagery and geo-spatial modelling have been carried out for the examination of the specific hazards. An example from a recent earthquake (2015) held in Paphos is reported by Agapiou and Lysandrou (2020). That study presented the results from the exploitation of a big-data cloud platform (Hybrid Pluggable Processing Pipeline-HyP3), for detecting ground displacement after a 5.6 magnitude scale earthquake in 2015. Ascending and descending pairs of Sentinel-1 images, acquired before and after the event, were processed through the HyP3 platform, revealing small relative ground displacements near the 'Tombs of the Kings' necropolis, and the Nea Paphos archaeological site (Fig. 8). As shown in Fig. 8, each estimated fringe corresponds to a change in range of λ/2, where λ is the

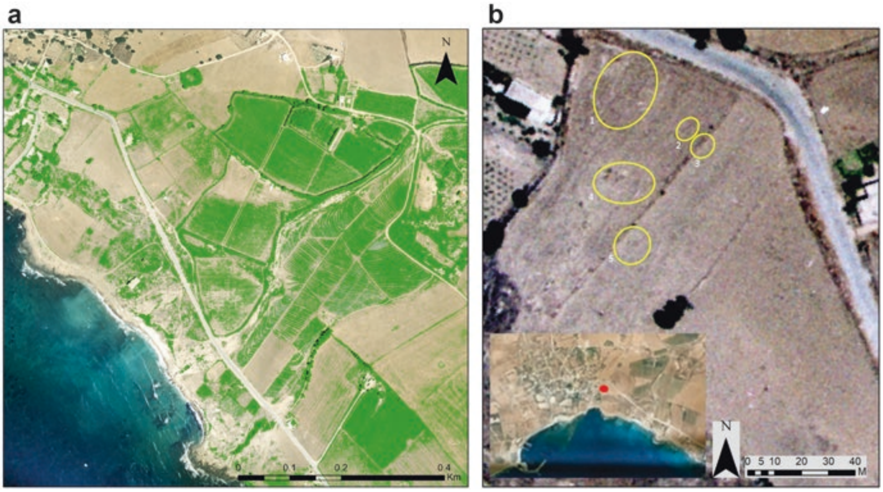

Fig. 7 (Left) 1968 aerial photograph: red dot on bottom left view indicates a specific area within the Eastern necropolis of Nea Paphos, with notable archaeological proxy concentration. A closer view of this area is shown in the background image. Yellow circles denote archaeological proxies. (Lysandrou & Agapiou, 2020); (Right) Arable areas and dense vegetation zones within the Eastern necropolis of Nea Paphos are shown in green colour. From the inspection of the area and concerning the GRVI values, a threshold was set to defined vegetated areas. (Lysandrou & Agapiou, 2020)

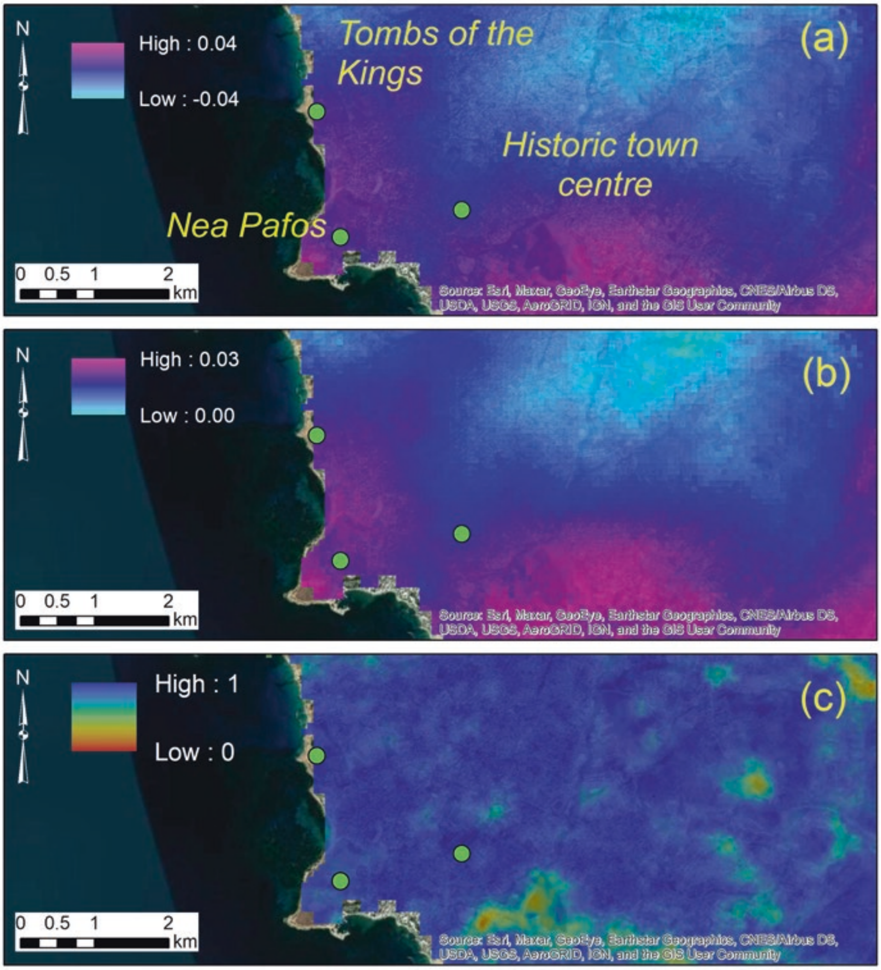

Fig. 8 (**a**) Unwrapped interferogram. (**b**) Vertical displacements. (**c**) Coherence map, enveloping important archaeological sites of Cyprus. (Agapiou & Lysandrou, 2020)

Sentinel-1 radar wavelength (estimated to 5.54 cm for the Sentinel-1 radar satellite). The closer the fringes are together, the higher the deformation on the ground.

Urbanisation processes in Cyprus were documented through remote sensing sensors. For instance, in the Paphos District an increase of 300% of the urban footprint was mapped after analysing Landsat 5 TM and Landsat 7 ETM+ images. A supervised classification analysis covering the period 1980–2010 was examined by Agapiou et al. (2015). The expansion was recorded in the western part of the Paphos city; however, the rest of the island cities have shown a similar trend (Fig. 9). During this period, archaeological rescue excavations revealed significant archaeological records, like the Hellenistic and Roman tombs in Paphos (Lysandrou & Agapiou,

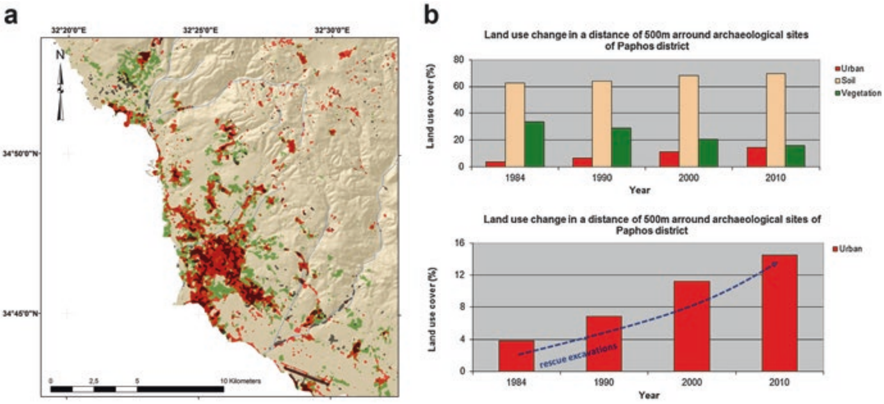

Fig. 9 Left: Urban expansion of the Paphos city from 1984 to 2010. Black colour indicate urban areas back in 1984; orange colour the urban areas of 1990; red colour the urban areas of 2000 and green colour the urban areas of 2010. Right: Land use change (%) from 1984 until 2010. Areas calculated from the Support Vector Machine (SVM) classifier and the Landsat images (top). Urban expansion (%) from 1984 until 2010. Areas calculated from the SVM classifier. During the last years, rescue excavations by the Department of Antiquities have been increased according to the yellow line shown in the graph (bottom)

2020; Lysandrou et al., 2018), underlining the numerous subsurface wealth of archaeological findings of the island.

Since then and after the economic crisis that hit Cyprus in 2012, the construction industry was considered a central pillar for the country's future economic growth. Since 2015 land development was supported through large constructions and extended infrastructural works beyond human scale. This is a phenomenon known in the literature as vertical sprawl. Agapiou (2021) implemented a quick, automatic detection method using radar medium resolution Sentinel-1 images (Fig. 10). The approach was to capture the urbanisation process of the city of Limassol that has been initiated during this period due to recent large construction projects.

6 Discussion and Final Remarks

The scope of this chapter was to summarise the contribution of various remote sensing sensors used in Cyprus over the last years, related to landscape archaeology and built heritage. Different prospection methods have been implemented through the years all over the island, spanning from ground-based techniques, aerial investigations, and satellite observations. Despite the number of projects that have been carried out, the employment of the specific techniques has been carried out in a non-systematic way and without specific planning, mostly based on the needs of the individual archaeological research campaigns. Furthermore, most of the programs that involve remote sensing techniques in the cultural landscapes have been realised

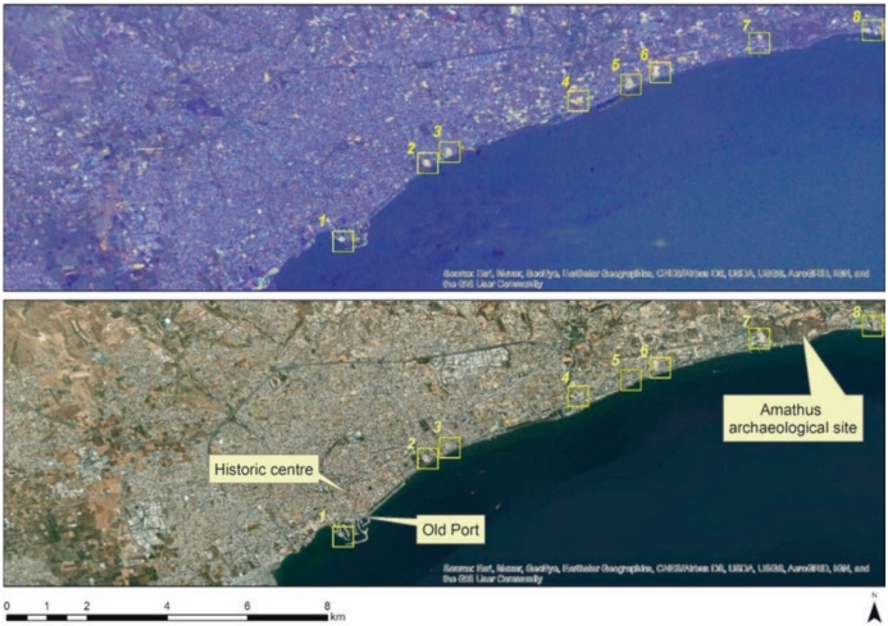

Fig. 10 Top: Radar polarisation visualisation change detection during the period 2015–2020 over Limassol city. Bright colours indicate areas of changes during this period. Bottom: The same are using as a background a high-resolution satellite image. (Source: ArcGIS Basemap)

at the southern part of the island, whereas almost none of them has been experienced in the northern Turkish occupied part of the island. Only the very early use of magnetometry at the Late Bronze Age site of Enkomi (Aitken, 1971) before the invasion has been recorded within the occupied part of Cyprus.

Most of the geophysical surveys have been carried out from foreign research teams, which most of the times were not aware of the soil or geological conditions of the area under study. The metamorphic geology and the rich in iron content soil deposits create limitations in some of the methods and this has been obvious at the results obtained. The lack of extensive soil analyses and the metadata (many of the surveys have not created extensive reports or have not been published) did not allow for the further enhancement of the methods. Early explorations were primarily aimed at recognising the extent of occupation of the sites rather than defining their detailed mapping. Advances in geophysical instrumentation now allow the detection of small structures, such as post holes, and can provide evidence for the presence or absence of archaeological structures, their depth and geometry with a much better resolution than in the past.

In a number of times, past human interventions have polluted the areas of them with modern debris which creates problems in the acquisition of quality geophysical measurements. In general, most of the geophysical surveys indicated increased levels of noise originating from the intense cultivation practices. At Idalion, the cultivation activities may have seriously affected the conservation of the ancient architecture in various parts of the site. Very few architectural structures remain in good preservation within the disturbed layers (Sarris, 2020). At Yeroskipou—Ayioi Pente, the area was severely disturbed due to modern human interventions in the area (agricultural activity, road and earthworks, mausoleum construction, etc.) (Sarris & Papadopoulos, 2010). Ancient architectural remains at Ayia Marina—Mavrovouni might have been dismantled by posterior clearance for agricultural purposes (Graham et al., 2013).

Similarly, the economic development on the island has followed an exponential growth since the 1980s. The emphasis on the tourist development, the large constructions all over the island, in the cities, villages and the coast, accompanied by the urban and population growth, easily depicted by the satellite imagery, had noticeable effects on the cultural archaeological sites and historical monuments (Agapiou et al., 2015). The intense cultivation, expansion of urbanisation and large construction works have been responsible for the destruction and bad preservation of archaeological remains. Taking into account the projection of the United Nations that about 69% of the population will be confined in urban centres by the year 2050, it is obvious that there will be an increased pressure for further expansion of the urban fabric and thus a higher level of threat in the enclosed and surrounding cultural monuments (Kiruthiga & Thirumaran, 2019) and this will also affect the cultural assets of the island.

Despite the few cores and soil analysis that has been conducted aiming towards the reconstruction of palaeoenvironmental conditions of the islands, such studies remain very limited. Most of the work has been conducted at the salt lakes of Larnaka and Lemesos (Akrotiri). The most recent studies deal with the palaeogeographic evolution of the closed lagoon of the Akrotiri Salt Lake based on the sedimentological and micropalaentological analyses of cores (Polidorou et al., 2021a) and the use of beachrock development as an index of the coastal changes in the past 2000 years (Polidorou et al., 2021b). From a much wider GIS and Remote sensing perspective, Agapiou et al. (2017) has considered the risk assessment of the coastal heritage landscapes within the marine spatial planning, but without taking into consideration the coastline evolution. Similarly, Andreou et al. (2017) and Andreou (2018) addressed the issue of the impact of the coastal erosion on the archaeological sites of Cyprus using the DSAS model for classifying the coastal erosion sections in a small section along the south-central part of the island (between Pyla and Tochni-Lakkia), with emphasis at Tochni-Lakkia and using a combination of historical aerial photos of the Department of Lands and Surveys, laser scanning and geophysical techniques.

These past advances indicate the accelerated momentum that has been achieved in the application of remote sensing and GIS techniques in the archaeological context of Cyprus. This has driven to some latest developments that are expected to have a major impact in the research and Cultural Heritage management (CHM) of the island. The first concerns the establishment of devoted laboratory research units at the University of Cyprus (UCy) and the Cyprus University of Technology (CUT). At the University of Cyprus, the Laboratory of Digital Humanities GeoInformatics

(DigHumanities GeoInfo Lab—http://www.ucy.ac.cy/geoinfolab/the-lab), supported by the "Sylvia Ioannou" Chair for Digital Humanities at the Department of History and Archaeology is dealing with the application of cutting-edge technologies (Geographical Information Systems (GIS), Geoinformatics, computational and statistical methods, etc.) in Landscape Archaeology, Environmental Archaeology, Monument Monitoring, and Cultural Heritage Risk Assessment and Modelling. The Lab has already participated in a number of projects in Cyprus (Palaepaphos, Xeros valley, Fraggisa, Idalion, Paralimni, Petounda), Greece (Pylos, Thouria, Rethymno, ancient Corinth, ancient Halos) and Kosovo (RAPID project), emphasising its research in the Eastern Mediterranean and the Balkans. At the same time, a new graduate program on Digital Heritage and Landscape Archaeology (http://www.ucy.ac.cy/mscgidh/) has been initiated at the University of Cyprus aiming to provide training to international students on the application of Spatial Technologies and GeoInformatics in the wider domain of Digital Humanities. Similar is the case of the former Archaeology and Cultural Heritage section (ARCH) of the Remote Sensing and Geo-environment research Lab (http://www.cyprusremotesensing.com/) at the Cyprus University of Technology, the research of which emphasises the 2D/3D documentation of archaeological sites, the aerial and satellite remote sensing applications, the GIS management of cultural heritage sites, and geoinformatics for archaeological analysis (Archaeology and Cultural Heritage section, 2021). The group has been active in a number of research projects in Cyprus (Kataliondas-Kourvellos, Pano and Kato Pyrgos Tillirias, Mansoura Tillirias, Ayios Sozomenos, Palaepaphos, Nea Paphos, Politiko, Sotira, Paralimni, Xeros valley) and Greece (Malia). Also, is organising several training courses and workshops. The group has made clear that in Cyprus, integrated remote sensing state-of-the-art techniques have been implemented, also following the recent trends of related to the Copernicus European Space Programme with the Sentinel missions, as well as the exploitation of big data and earth cloud platforms.

It is obvious that though the collaboration of the above groups, as this joint paper indicates, there will be more systematic engagements expected in the domain of remote sensing techniques in archaeology, which is taken positively by the Department of Antiquities of Cyprus, as it will be able to exploit the above resources in the best possible way. Furthermore, the above action will improve the scientific capacity to support the various needs from the archaeological research and heritage management perspectives, creating a roadmap for the more systematic use of these technologies by the local and foreign academic and research institutions.

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A modified version of the figures in the section "Ground Based geophysical surveys and geochemical analysis" is included at an article that has been submitted at Archaeological Prospection by Marc-Antoine Vella and Apostolos Sarris (Vella & Sarris, 2022).

The Laboratory of Digital Humanities GeoInformatics (DigHumanities GeoInfo Lab—http://www.ucy.ac.cy/geoinfolab/the-lab) was established based on a starting grant of the University of Cyprus.

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Part VI
Denmark, Finland, Iceland, Norway and Sweden

A Review on the Development and Current Role of Ground-Based Geophysical Methods for Archaeological Prospection in Scandinavia

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Abstract This chapter provides an extensive overview of the use of geophysics in archaeological research and cultural heritage management in Finland, Sweden, Norway, Denmark and Iceland. It discusses the current status, role and acceptance of geophysical methods in each country, and outlines the state-of-the-art based on a synthesis of existing knowledge and experience. The authors consider the past, present and future of archaeo-geophysics in the individual regions, taking into

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account the academic, curatorial and commercial aspects of their use. This, in turn, serves as the basis for a discussion of the reasons for the varying degrees of acceptance and integration of the methods in each country, and aid the distribution of knowledge and experience gained across Scandinavia and beyond. The practical experience, application and general acceptance are not similar in the different Scandinavian countries. There is a general lack of integrating geophysical (and by extension non-intrusive methods) within the archaeological practice and guidelines. The case studies presented here show a range of archaeological applications of geophysics in Scandinavia, demonstrating how geophysical methods should by no means be considered "new" or "untested". While there is a need for targeted research, there has also been a challenge in disseminating the already generated knowledge and experiences to other actors within the archaeological community. Some of this can be explained by a lack of trained personnel, domestic competence and archaeological institutions undertaking research into the applicability of geophysical methods, and data-sharing and making reports accessible.

1 Introduction

Near-surface geophysical prospection methods have proven, under suitable conditions, to be valuable tools for archaeological researchers and cultural heritage managers (Clark, 1990; Gaffney & Gater, 2003). Commonly used methods such as

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magnetometry, earth resistance (ER), ground-penetrating radar (GPR) or electromagnetic induction (EMI) can reveal buried archaeological remains without exposing them, where geophysical contrast characteristics may contribute with knowledge such as depth and volume information, evidence of burning or refuse deposits, state of preservation in situ etc. permitting their non-invasive discovery, mapping, documentation, investigation, and preservation. This by itself or in combination with other minimally invasive investigation, contribute with cultural-historical knowledge beyond merely pinpointing the most promising excavation sites. Technological and methodological developments over the past two decades have resulted in considerable progress concerning the extent of surveys and imaging resolution, thereby increasing the potential of the methods for minimally invasive archaeological research and heritage management. This development has been particularly noticeable in Scandinavia, where concerted efforts have been made to integrate prospection into routine archaeological activities since the mid-2000s (Cuenca-García et al., 2020).

The shared archaeological material culture, and the glacially dominated surface soils and often shallow depth to bedrock serve as preconditions for the use of geophysical prospection methods in large parts of Sweden, Norway, Denmark, Finland and Iceland. With buried cultural heritage predominately expressed in the form of pits, postholes, hearths, overploughed burial mounds, iron production sites, and only rarely solid features such as stone foundations or deep ditches, these often faint traces require particularly careful data acquisition, processing and interpretation—especially with regard to sample density and resolution, as well choosing the geophysical methods best suited to the prevailing geological and expected archaeological conditions.

With comparable archaeological features and common geological and environmental conditions, a review of the development, role and status of archaeo-geophysical prospection in Scandinavia is prudent. A first analysis was provided after the *Sensing Archaeology in the North* workshop in 2020, where experts working in ground-based/marine geophysics and remote sensing met to discuss the state-of-the-art of these methods in Scandinavian and North Atlantic archaeology (Cuenca-García et al., 2020). This chapter goes beyond the results of this meeting and expands on the particular achievements of ground-based geophysical methods and individual country analysis. Our goal is to define the current role of ground-based geophysical methods for archaeological prospection in Scandinavia and describe trends to explore in future work.

2 The Past-historical development

Sweden

A comprehensive overview of the history of archaeo-geophysical prospection in Sweden has been compiled by Viberg et al. (2011), and demonstrates how geophysical prospection methods for archaeological applications were not widely

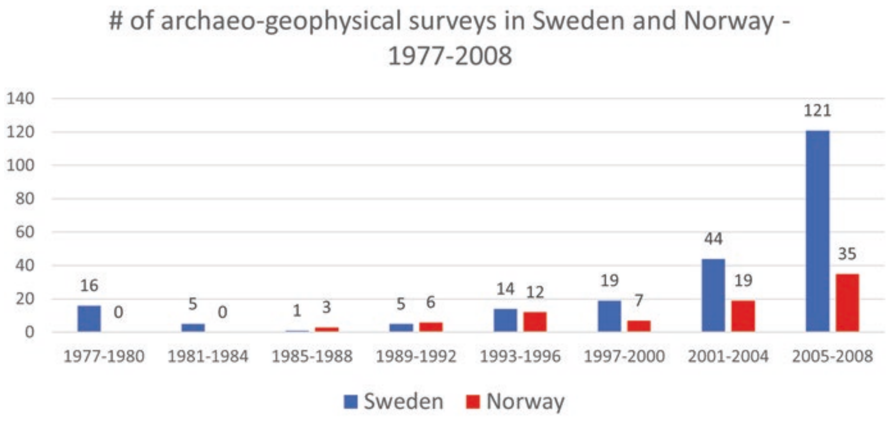

Fig. 1 The number of archaeo-geophysical surveys in Sweden and Norway between 1977 and 2008. (From Viberg, 2012; Stamnes & Gustavsen, 2014; Stamnes, 2016)

adopted in Sweden until the mid-2000s—a development comparable to what was seen in Norway (see Fig. 1).

The first text describing the potential benefits of electrical and magnetic methods in the Swedish archaeological literature was published as late as 1971 (Rausing, 1971). These methods would not, however, be practically evaluated in Swedish archaeology until the late 1970s, e.g. (Ahlbom et al., 1981; Fridh, 1982; Furingsten, 1985). Geophysicist Bengt Fridh from the Geology Department of Chalmers University of Technology in Gothenburg carried out several surveys in collaboration with the Swedish National Heritage Board but, unfortunately, these initial surveys were challenging from a practical and collaborative perspective. The challenging collaboration with the field archaeologists and the disappointing results are well documented and well worth reading (Fridh, 1982). Despite the limited success of these surveys, Fridh concluded that geophysical methods could indeed be employed successfully in Swedish archaeology. However, he also argued that combinations of methods should be used, that archaeology needs professionally trained geophysicists for the job, that over-confidence in the potential of geophysical prospection methods can be as damaging as no trust at all, that a failure in the application of a method can lead to its complete rejection, and that archaeologists should be educated in geophysics (Fridh, 1982).

The first short thesis on archaeological prospection in Sweden was written in 1980 by archaeologist Peter M. Fischer who, working on Cyprus in the late 1970s, demonstrated that GPR could be a valuable archaeological survey tool in the future (Fischer, 1980). The first GPR surveys in Sweden were carried out during the late summer of 1979 (Wihlborg, 1980) and several other GPR surveys soon followed in other parts of Sweden (Bjelm & Larsson, 1980, 1984; Burenhult & Brandt, 2002). Seismic refraction methods have so far only been used once for archaeological prospection purposes in Sweden. The method was tested at the Viking Age settlement of Birka and was able to estimate the thickness of the extensive cultural layers of the site (Andrén et al., 1997).

The beginning of the 1990s also saw the first EMI survey for archaeological applications in Sweden being carried out by Kjell Persson from the Archaeological Research Laboratory (ARL) at Stockholm University (Persson & Olofsson, 1995; Persson, 2005). Laboratory measurements of magnetic susceptibility of soil samples were first conducted in Sweden in 1980 (Freij, 1980), and field and laboratory measurements of magnetic susceptibility has been used extensively by the *Environmental Archaeology Laboratory* (MAL) of Umeå University (Engelmark & Olofsson, 1999, 2000).

Despite the many examples of archaeological geophysical surveys in Sweden from the late 1970s onward, archaeo-geophysical prospection methods have often been regarded as ineffectual in Sweden. In many cases, the unsatisfactory results could be explained by imprecise survey methodologies, coarse sampling spacing, and the coverage of too small survey areas. These issues were often confounded by unrealistic archaeological interpretations of the collected data. This led to a widespread scepticism of the methods' validity, and this situation did not begin to change until the mid-2000s (Viberg et al., 2011).

Denmark

The first example of the use of a magnetometer in Danish Archaeology is a study of a Roman Iron Age iron-smelting site at Drengsted in 1965 (Abrahamsen, 1965). Later, a series of case studies conducted between 1978 and 1983 were reviewed by Møller et al. (Møller, 1984). They included off-shore and on-shore methods and metal detection and provided outlooks for the future of the method in Danish archaeology. The first prospected sites included mainly Iron Age sites, with notable examples such as the rich weapon sacrifice site in Illerup Ådal (Sørensen et al., 1980), the famous Himlingeøje burial mound, Celtic fields and a settlement at Heltborg, Thy, a Medieval tile oven, and two sites in Jutland with Bronze Age roads beneath peat bogs (Jørgensen, 1993). A total of 18 sites were listed in the review, and methods applied until 1984 were GPR (n = 12), magnetometry (n = 4), and resistivity (n = 3).

From 1984 to the early 1990s, few studies of geophysical applications in archaeology are known. Since early in this period archaeo-geophysical interest was primarily focused on archaeomagnetic investigations. Gram-Jensen et al. (2000) and Abrahamsen et al. (2003) provide overviews of these studies. During the 1990s, the methods were basically the same as previously deployed. The abilities of existing software seem to be a constrain in properly processing and visualising the data for archaeological purposes. Palaeolandscape studies were also carried out in this period. Two studies of palaeochannels around the Medieval monasteries at Gudenåen (Voer and Vissing Kloster) by Møller (1984), and the likely palaeo-opening to the North Sea (Kristiansen et al., 2021) west of the Viking Age ring fortress Aggersborg were studied by seismics (Andreasen & Grøn, 1995; Møller, 1986). Other prospection studies include a gradiometer survey at Kalø castle (Koppelt et al., 1999), and several Iron Age and Neolithic sites investigated through geomagnetics (Smekalova & Voss, 2001; Smekalova et al., 2005). An overview of early GPR studies at the Viking Age bridge at Ravninge Enge and the multi-period wetland crossing at Sjellebro is given by Jørgensen (1993).

From 2000 to the early 2010s the use of geophysics as an archaeological tool is only mentioned sporadically in national archaeological methodological guidelines (Breuning-Madsen & Kähler Holst, 2003; Kulturarvsstyrelsen, 2012). At the same time, electromagnetic and transient electromagnetic (EM and TEM) software and instruments were developed intensively, but mainly applied outside archaeology. In archaeology collection of EM data became viable when the EM38 (Geonics Limited) instrument became available for cost-efficient larger scale mapping, and a few surveys were carried out at Jelling (Greve et al., 2008), Nr. Vosborg (Henningsen et al., 2014) and Fyrkat (Torp, 2011). Magnetic susceptibility and magnetometry were increasingly used from 2000 to 2010. Examples combining both methods include studies at the Iron Age to Viking Age site at Rispebjerg and Sorte Muld, Bornholm (Jørgensen, 2009; Joslin, 2014; Stümpel, 2010; Watts, 2009), and the Iron Age site Hoby on Lolland (Klingenberg et al., 2010).

Mapping by magnetometry alone was performed at sites such as Store Krusegård on Bornholm (Bornholms Museum, 2010; Smekalova & Bevan, 2011); settlements close to the Viking Age ring fortress Trelleborg on West Zealand (Voss & Smekalova, 2006); the Iron Age site Rønninge Søgård on Funen (Prangsgaard, 2014); three sites on the island of Samsø (Smekalova et al., 2008); an Iron Age settlement near Horsens (Grabowski & Linderholm, 2014); and an Iron Age settlement and harbour site at Stavnsager near Randers (Loveluck & Salmon, 2011); iron production sites around Varde, West Jutland, e.g. Yderik (Peters et al., 2008). Smekalova et al. (2008) further provides an overview of investigations of iron production sites, Neolithic cooking pits, flint mines, megalithic graves, settlements, fortifications and abbeys.

From 2000 to 2010 GPR was used at Lodbjerg, Thy, in a combined geoarchaeological study on Iron Age fields and aeolian sand activity (Clemmensen et al., 2001; Pedersen, 2003). Around the castles at Hald Ege, Viborg, a combination of GPR, EMI and magnetic susceptibility was applied to non-destructive prospection of the Medieval site (Larsen & Hjermind, 2010). At more than 10 sites on Djursland, combined GPR and fluxgate gradiometry were carried out to study potential Neolithic enclosure sites (Klassen & Klein, 2014), and GPR was applied at sites at Frederiksborg Castle, Esrum Abbey, and Kronborg Castle by small private companies (e.g. Falkgeo). However, reports or data from these surveys have not been made available.

It should be noted that many scientific reports and much data collected by local museums, international universities and private companies during the 2010s are very difficult or impossible to access today. Moreover, a number of unpublished studies using resistivity methods are known from the period, but the reports could not be found for this review (B.H. Jakobsen, pers. comm.). More mapped sites are mentioned in other contexts, but neither data nor reports have been located, e.g. Vordingborg Castle (Svannevig, 2004), Ribe and Kås (Husted, 2014).

Studies until the 2010s seem to suffer from a general mismatch between, or poor communication of, the archaeological needs and the spatial resolution of the deployed instruments and software. For example, when the largest Bronze Age burial mound in Denmark, Hohøj near Mariager, was investigated by GPR in 1998, the data were never convincingly processed or interpreted for the archaeological end-user (Bech, 2000). Miscommunication, likely combined with a lack of adequate software and computer-power, may be a reason for a perceived general resistance by the Danish archaeological community towards applying geophysical prospection during this period.

Norway

The introduction of geophysical methods to Norwegian archaeology can be divided into three broad phases. The first is characterised by rudimentary surveys undertaken between the 1960s and 1970s. Relying on analogue proton magnetometers and conductivity meters (SCM/'Banjo' EMI instrument), these small-scale investigations proved successful in mapping sub-surface archaeological features, but were limited to a handful of surveys (Myhre, 1968; Farbregd, 1974), and can mostly be regarded as experimental. The second phase, between the late 1980s and 1990s, saw the introduction of digital survey instruments and a broader spectrum of systems in use. In connection with the Borre Project in Vestfold, for instance, GPR profiles were collected over the large burial mounds there in 1988 and 1989, and magnetometer data and other remote sensing techniques were used for investigating the surrounding landscape (Myhre, 2004). From the 1990s onward, a steadily growing number of surveys were undertaken (Fig. 1), particularly by geologist Richard Binns, who carried out over 71% of all geophysical surveys of Norwegian archaeological sites between 1990 and 1999. The earliest surveys of this period are generally of relatively low resolution, often presented as dot-density maps. While the data quality might have been up to standard for the time, the relatively poor spatial resolution and possibilities for adequate georeferencing limited the archaeological applicability of the results. Also, some of the interpretations were generally over-optimistic, creating the impression of better archaeological results than the data quality really allowed for (Stamnes, 2016, p. 25).

The early 2000s saw the extensive and successful use of magnetometer scanning of iron production sites in upland areas (Risbøl & Smekalova, 2001). This period also saw the first use of multi-antenna GPR arrays and multi-sensor magnetometer systems exemplified by the investigations of Iron Age mound cemeteries at Gulli and a burial mound at Rom in Vestfold (Gjerpe, 2005). While the surveys failed to indicate the presence of ring ditches and boat burials at Gulli, presumably on account of the undulating top surface, the investigations at Rom showed a very clear picture of the mound's interior (Gjerpe, 2005; Lorra, 2003).

The first truly successful geophysical archaeological prospection surveys in this respect, however, were the outcome of a pilot study conducted by the geophysical archaeological prospection unit of the Swedish National Heritage Board (Riksantikvarieämbetet—UV Teknik) in collaboration with Vestfold County Council. Here the necessity of using a higher-than-normal spatial sampling resolution in order to be able to detect small archaeological features such as those commonly encountered in Norwegian archaeology was demonstrated (Trinks et al., 2010a). Further catalysts for the increased use of geophysical prospection in archaeological research and management, were two initiatives that coincided in time: Firstly, the collaboration of the Norwegian Institute for Cultural Heritage

Research (NIKU) and Vestfold County Council with the Vienna based Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro) which, from 2010 onward aimed at investigating the applicability of motorised large-scale, high-resolution geophysical prospection surveys on a landscape-scale in Vestfold county. This had a major impact on the heritage management practices in this county (see Sect. 3.2). Secondly, the investment in geophysical survey equipment and expertise at the Norwegian University of Science and Technology (NTNU), which from 2009 undertook field research and provided geophysical surveys as a service to partners within the cultural heritage management in Norway (Stamnes, 2016).

From the early 2010s until the present, archaeological geophysical prospection has matured as part of the available toolbox of field methodologies, and increasingly been used both in research and rescue archaeology. The field has become professionalised, and involves several local prospection experts with a firm understanding of Norwegian archaeology. Archaeologists trained in geophysical archaeological prospection undertake the fieldwork, post-processing and interpretation, a combination essential for ensuring a high level of quality of data collection, data interpretation and the delivery of reliable results. The professionalisation of the field is a result of targeted initiatives by research groups at NIKU, NTNU and Vestfold County Council, where high-fidelity surveys have been developed and deployed since 2010 (Nau et al., 2017a, b; Stamnes, 2016; Cuenca-García et al., 2020; Schneidhofer et al., 2022).

Finland

There has been some testing of geophysical techniques in Finland, but primarily on a very small scale. The use of archaeo-geophysics was introduced here in the early 1980s, even though applied geophysics had been actively practised in other fields since the 1950s (Leino & Pesonen, 1984). The first survey was performed at an Iron Age settlement site in southwest Finland in 1983, which included magnetometry, spontaneous and induced polarisation and ER (Pernu & Helkka, 1983). Tests involving GPR also commenced in the late 1980s, for example, at the medieval Kastelli castle site in Oulu, northern Finland, to locate underground stone structures near the visible castle remains (Toikka & Toikka, 1989). The survey results were not verified, but the site was re-surveyed in 2010. It was concluded in both surveys that modern land use and the complex topography of the site hampered the successful performance of the survey (Museoviraston, 2021). In 1988–1991, a group of fieldwork directors at the Finnish Heritage Agency (former National Board of Antiquities) used geophysical techniques at their larger fieldwork projects, where magnetometry, ER and GPR were tested at several rescue excavations (Julkunen, 1988; Lavento, 1990, 1991; Schulz, 1991; Seppälä, 1992; Ruonavaara, 1992) (Fig. 2). Typically, modern pipelines, landfills and iron objects hampered the surveys, but ER functioned satisfactorily at certain sites and facilitated the detection of archaeologically relevant underground structures and features (Lavento, 1990, 1991). In the old town of Helsinki in 1989–1990, GPR was used for locating older church foundations and other types of underground objects (Lavento, 1992). A few Stone Age hunter-gatherer sites on podzol soils were also surveyed. For example, at

Fig. 2 GPR survey in progress in 1988 at the Neolithic settlement site of Tyttöpuisto in Eura, western Finland. (Photo: Anne Vikkula/University of Helsinki)

Pirittävaara in Rovaniemi, southern Lapland, GPR was tested with various antennas, and 500 MHz worked adequately for the shallow stratigraphy (Lavento, 1992).

Several geological features, including ancient shore formations and sediments, were identified, but the archaeologically relevant targets were not detected. Instead, at the Typical Comb Ware site Pispa, western Finland, a gradiometer survey successfully detected cooking pits filled with fire-cracked stones (Julkunen, 1988; Ruonavaara, 1992). However, it has to be acknowledged that most of the early surveys were performed with inadequate transect spacing (c. 2 m), and their results may thus be considered as approximate.

Magnetic prospection was also applied at Stone Age red ochre graves in the 1990s, which also involved soil sampling and laboratory analysis of mineralogical and magnetic characteristics of natural deposits and red ochre graves from six sites. Vertical gradient and total field measurements (at 0.25 m spacing) at the Neolithic burial site of Hartikka, central Finland, were performed in 1997 (Kukkonen et al., 1997). At Hartikka, several anomalous reflections were detected on sandy podzol, suggesting hitherto unknown grave pit features. However, a number of the previously known grave pits did not produce anomalies, possibly due to low susceptibility.

In general, GPR has been most commonly used in Finnish archaeology in the 1980s and 1990s. In addition to the examples given above, it has been used at historical mansion sites, the garrisons of the Häme Castle, the medieval church of Valmarinniemi in Keminmaa, and (from ice) at the suggested naval port of the Olavinlinna Castle (Koponen, 1992; Museoviraston, 2021). In the early 2000s, EMI and GPR (Vaara, 2006; Haarala & Helminen, 2011) were occasionally applied at known archaeological sites before excavations, but most of the prospection campaigns were conducted solely with metal detectors (Museoviraston, 2021). At the multi-period settlement site of Hiidenniemi, eastern Finland, GPR was tested at an overgrown bay in front of a dryland settlement area (Forsberg et al., 2009), and wooden structures from the Bronze Age were revealed at the bottom of an overgrown bay via test trenching (Koivisto, 2011). Unfortunately, the GPR data was collected with a too low spatial resolution to resolve the sought features. EMI was applied on mineral soil at the same site, but the survey suffered from the same resolution problem.

Iceland

The first Icelandic geophysical survey connected to archaeological research involved use of a proton magnetometer at the farm site Svalbarð in 1988 (Amorosi, 1992). Prior to 1999, most subsequent investigations employed GPR and were conducted by the Reykjavik-based engineering company, Línuhönnun hf. Their first survey was undertaken in 1992, and investigated the remains of a monastery at Viðey as part of a larger excavation (Árbæjarsafn, 1992). Over the next decade they conducted surveys at around 30 archaeological sites (Horsley, 2005). Earth resistance survey was first used at Nes in Seltjarnarnes in 1995 (Vésteinsson, 1996).

In addition to these early applications, a few noteworthy projects have impacted the use of geophysics in the Icelandic context. These projects advanced the knowledge of Icelandic subsurface material and helped demonstrate geophysics' potential—and limitations in Icelandic archaeological investigations. Research undertaken by Tim Horsley fully explored the processes and factors that affect magnetometry (fluxgate gradiometer) and ER (twin probe array) for archaeological prospection in Iceland. Between 1999 and 2004, Horsley (1999, 2005) undertook investigations at 40 sites across the country to comprehensively assess the various geological, geomorphological, and archaeological factors that affect the outcomes of such surveys (Fig. 3).

The work characterised the types of geophysical anomalies produced by a range of igneous geologies (basaltic bedrock, various glacial deposits, and tephra deposits), as well as by andosols and periglacial phenomena that are commonly found throughout the country. It also evaluated the effectiveness of these two complementary geophysical methods for locating and characterising typical archaeological features. With structures commonly built from turf with little to no stone, their buried remains present some novel challenges for these techniques. One outcome of Horsley's research was to develop methodologies for data collection, processing, displaying, and interpretation of data, all of which differ from approaches routinely adopted in other parts of the world. Subsequent excavations at sites including Gásir, Skálholt and Hofstaðir demonstrated the usefulness of combining magnetometry and ER surveys for archaeological investigations in Iceland, especially when integrated with earthwork surveys, aerial photography, and targeted excavation (Horsley & Dockrill, 2002; Horsley, 2005).

Each of these early projects has helped to demonstrate the potential of non-invasive geophysical methods to the archaeological community in Iceland. They

Fig. 3 Collecting earth resistance data at Steinastaðir on Iceland in 2001. (Photo: Tim Horsley)

have shown that these surveys are clearly a reliable way of identifying features, cultural layers, and structures that can allow archaeologists to make informed decisions in advance of excavation. Despite clear limitations regarding suitable ground conditions, improvements in equipment and software led to GPR becoming preferred over other geophysical survey techniques.

3 Recent Status and Developments

3.1 Geophysical Prospection in Archaeological Research

Sweden

From 2005 onward, several important steps were undertaken to change the perception of geophysical archaeological prospection methods in Sweden. A major step was the establishment of a dedicated unit for geophysical prospection within the technical group of the archaeological excavation department—UV Teknik—of the Swedish National Heritage Board. This unit developed a strategy for the professional use of the most suited geophysical prospection technology for archaeological and geological conditions encountered in Sweden, modelled on the example of the highly successful Ludvig Boltzmann Institute group for Archaeological Prospection and Virtual Archaeology (LBI ArchPro) in Vienna. The Viennese experts had conducted several successful prospection test surveys in Sweden in 2004. While UV Teknik started with manually operated single-channel GPR systems and fluxgate gradiometer as well as caesium magnetometer arrays, the declared goal had been from the beginning to render geophysical archaeological survey methods more efficient by involving sensor arrays mounted on—or towed by—motorised systems equipped with automatic data positioning solutions. First such test surveys were conducted from 2006 onward.

Aside from a number of research and development surveys, conducted to gain experience and representative data, contract archaeological projects were soon offered and realised in Sweden, Norway, the Netherlands, and Cyprus. In particular, the collaboration with archaeologists from Vestfold County Council and later NIKU in Norway proved to be very fruitful, paving the way for the establishment of the LBI ArchPro in 2010. The impact of the prospection team from UV Teknik, which closely collaborated with the Austrian expert Alois Hinterleitner on specialised processing of the prospection data, on Swedish and Norwegian archaeological research has been significant. In particular, the geophysical archaeological prospection research and development surveys conducted at the UNESCO World Heritage Site of Birka have been exceptionally successful (Trinks et al., 2010b, 2013b, 2014), and led to the major LBI ArchPro case study running from 2010 at Birka and Hovgården. This pioneering work, conducted with the support of GPR manufacturer MALÅ Geoscience, paved the way for the extensive use of motorised high-resolution GPR array systems for archaeological prospection in Scandinavia. Further outstanding geophysical archaeological prospection surveys among the over 50 sites explored by UV Teknik between 2005 and 2010 were those conducted at Old Uppsala (Trinks & Biwall, 2011), Ales stenar, and Borre in Norway. From 2010 onward the *Uppåkra* LBI ArchPro case study, which with its 197 ha magnetometry coverage, is as extensive as it has proven successful (Biwall et al., 2011; Trinks et al., 2013a; Gabler, 2018).

In parallel with the surveys and research and development carried out by the prospection unit at the Swedish National Heritage Board and the LBI ArchPro, numerous geophysical archaeological prospection research surveys were carried out by the Archaeological Research Laboratory (ARL) of Stockholm University. This laboratory has since the 1990s offered the possibility for master's students to study geophysical archaeological prospection methods within an archaeological context (Kristiansson, 1996; Stavrum, 1997; Wåhlander, 1997; Stålberg, 2000; Vaara, 2004; Sabel, 2006; Viberg, 2007). From 2008 onward, several articles were published on surveys carried out across Sweden with different geophysical methods (Viberg & Wikström, 2011; Gustafsson & Viberg, 2012; Viberg et al., 2013, 2014, 2016; Rundkvist & Viberg, 2015; Kalmring et al., 2017). These surveys were predominately carried out using single-channel GPR, fluxgate gradiometry and different EMI methods and instruments. However, more recent surveys have also included multi-channel array GPR systems and mobile mapping systems for large-scale high-resolution surveying of Iron Age and Medieval ringforts on the Island of Öland (Fig. 4) (Viberg & Larson, 2015; Viberg et al., 2017, 2020).

ARL remains one of the few academic institutions in Sweden offering the opportunity to work with archaeological geophysical prospection methods. Apart from the ARL, occasional archaeological prospection courses are also provided at other

Fig. 4 Collecting of GPR data at the fortress of Gråborg. (Photo: Magnus Larson)

universities in Sweden (e.g., Gothenburg University), but opportunities for more extensive training is currently limited. Possibilities exist to apply for courses and programs in geophysics at several universities in Sweden, but very few students choose to work specifically with the archaeological geophysical application.

A notable research project where large-scale GPR and magnetometry is utilised to detect and identify buried Stone Age sites of importance is currently ongoing at Gothenburg University. This project has involved gathering magnetometer data of about 600 ha in collaboration with DAI from Frankfurt in Germany (Tony Axelsson, pers. com). No articles have of yet, to our knowledge, been published.

Denmark

In the last decade, a steadily increasing number of geophysical surveys have been undertaken in connection with archaeological research projects, but not all of these have been published. Investigations where towed or handheld fluxgate gradiometers have been employed seem to be the most common approach. Examples include the following sites: a number of sites in western Jutland (Fuglsang, 2015; Olesen, 2019b); Iron Age sites near Odense River and Kertinge Nor on Funen (Fuglsang & Kristiansen, 2018), a Viking Age settlement near Toftum near Viborg (Fuglsang, 2015), Lusehøj on Funen (Merkyte & Albek, 2011), and a Neolithic burial site near Østerbølle i Himmerland (Nielsen & Johannsen, 2014). Brown et al. (2014), and Goodchild et al. (2017) have applied fluxgate gradiometry surveys to the two Viking Age ring-fortresses at Aggersborg and Borgring respectively.

Recent gradiometer developments includes examples of large-scale, cost-efficient mapping using towed 3D fluxgate gradiometers (tMAG) at an Iron Age site near Fæsted, Southern Denmark (Grundvad et al., 2021) and Aggersborg (Kass et al., 2021), where no archaeological interpretations have been published as yet. Recently, successful mapping by a handheld magnetometer inside a dense forest canopy was achieved at a Neolithic long barrow site in Ringelmose Skov, East Jutland (Stott, 2021).

Large-scale mapping by EMI has been possible since the early 2010s with towed commercial instruments (Christiansen et al., 2016; Sandersen et al., 2021). One example of the method's archaeo-geophysical development is the prospection of the Iron Age site Alken Enge near Skanderborg, where the focus was on inversion and better data treatment processing in a geoarchaeological context only (Christiansen et al., 2016). A lake-based seismic study was included at Alken Enge in an attempt to create a seamless palaeo-landscape model of this palaeocoastal spit to understand this unique Roman Period martial event and post-battle corpse manipulation site better (Holst et al., 2018; Soe et al., 2017; Søe et al., 2018). Viking Age ring-fortresses, and its palaeo-surrounding in a landscape with loamy soil, have been mapped by EMI (DUALEM421s) at Borgring near Køge (Petersen & Christiansen, 2016) with the archaeological aim of understanding the foundation and rampart construction (Kristiansen et al., 2022). Mapping by EMI (DUALEM) have also been carried out at a few sites in Region Midtjylland where data only are available: Gl. Åkjær, Kokholm, Sallingholm, De Tre Hald-er, and Celtic fields at Fur (M.H. Greve, pers. comm.)

Early investigations using GPR surveys were generally undertaken collecting only a few sparse radar profiles until a few years ago. Early examples of studies containing GPR amplitude maps (time- or depth-slices) from 2010 exhibit substandard data presentation and interpretation (Larsen & Hjermind, 2010). The results of several larger and more successful GPR prospections have been published in the last 10 years. These include mapping archaeological sites such as Sorte Muld on Bornholm (Museum, 2010), the Viking Age ring-fortifications at Aggersborg, Fyrkat, Nonnebakken (Brown et al., 2014; Nordjyllands Historiske Museum, 2020), characterisation of Viking Age settlements at Stadil Mølleby and a medieval village at Rysensten—both located on sandy soils in northern Jutland (Filzwieser et al., 2017a), and at the site of Skovborglund near Hadeslev with highly truncated burial mounds (Rambøll, 2019).

Studies that combine GPR and fluxgate gradiometer have been carried out at several Viking Age and Medieval sites (Stadil Mølleby and Rysesten) in Western Jutland (Nau et al., 2015; Filzwieser et al., 2017a, b), and a Viking Age landing site at Havsmarken on Ærø (Odense Bys Museer, 2019). Recently, a minor Late Glacial kettle hole at Tyrsted near Horsens was studied by a combined shear-wave seismics, GPR, 2D ERT and EMI before a total excavation of this Bromme Culture site (Corradini et al., 2020).

In 2019, the Danish Technical University (DTU), in collaboration with the Danish National Museum in Copenhagen, received funding for a project entitled "Archædrone" to investigate the applicability of a patented drone-operated magnetometer- and EMI system on a series of archaeological sites (Nationalmuseet, 2020). The Drone-towed controlled-source electromagnetic instrument is tested at one site on Falster (Vilhelmsen & Døssing, 2022) but further case studies from this project are yet to be published.

Norway

The use of ground-based geophysical prospection in Norwegian archaeological research can be loosely grouped into three categories: research focusing on geophysical techniques as a primary investigation tool, research concentrating on methodological development, and research integrating them as part of minimally-invasive multimethod approaches (e.g. combining these techniques with other sensing methods or targeted soil analyses).

An encompassing summary of the development of the use of geophysical prospection in Norway is given by Gustavsen and Stamnes (2012), Stamnes and Gustavsen (2014), and Stamnes (2016). Worth mentioning during these early times is an interesting GPR study conducted in 1997 by Davis et al. (2000), which targeted victims of the Spanish flu in permafrost on Svalbard. After that, dedicated archaeo-geophysical research began to substantially increase from 2007 onward, which coincides with collaborations between the Swedish National Heritage Board and Vestfold County Council and, subsequently, a partnership between NIKU, Vestfold County Council and the LBI ArchPro (Trinks et al., 2010c). The first doctoral thesis focusing on geophysical prospection at a Norwegian university (Stamnes, 2016) contributed to that development, as well as a PhD awarded within the framework of the LBI Archpro (Schneidhofer, 2017).

Notable among the research studies during this time are magnetic and GPR surveys to map Iron Age graves (Trinks et al., 2010a), an investigation of a substantial cooking pit site with >1000 pits at Lunde (Gustavsen et al., 2018), a multi-methodological study of Iron Age burials and boat-houses at Gustad (Stamnes, 2010), the investigation of a metal working site at Sem (Gustavsen et al., 2019) and five iron production places (Stamnes et al., 2019; Stamnes & Rødsrud, 2020). The detailed interpretation of two Iron Age hall buildings discovered in 2007 at the royal burial site of Borre, and an additional hall discovered by large-scale motorised GPR survey, (Tonning et al., 2020) received a considerable amount of attention, only eclipsed by the discovery of the Gjellestad ship burial in 2018 (Gustavsen et al., 2020a).

The rising interest in archaeological prospection since 2010 has increasingly translated into considering GPR surveys in particular already in the planning stage of a project as an important comparative part, rather than a stand-alone survey or an experimental application without any concrete research questions. The investigation of the Rom burial mound (Martens, 2009; Lorra, 2003) presents an early example of a project with a comparative geophysical component. Other important and more significant projects followed, such as the Kaupang excavations (Pilø, 2007), the *Gokstad Revitalised* project (Bill et al., 2013), and recently, the on-going *Viking Nativity* project at Gjellestad.

Since the onset of geophysical prospection, an interesting development is the focus on methodological questions and improvement. This includes survey design and approach (Stamnes, 2010; Stamnes & Gustavsen, 2018), the use of motorised geophysics for large-scale areas (Gustavsen et al., 2013b; Nau et al., 2017a; Trinks et al., 2018; Cuenca-García et al., 2020), the use of geophysics in cultural heritage management (Stamnes & Gustavsen, 2014, 2018; Stamnes, 2016) and the effectiveness of GPR for archaeological prospection on snow-covered areas and in wetlands (Gabler et al., 2019, 2021).

Another focus lies on specialised approaches for specific research areas, such as the investigation of iron production sites (Risbøl & Smekalova, 2001; Rundberget, 2007; Stamnes et al., 2019), the use of large-scale geophysical data sets for palaeoenvironmental investigations (Schneidhofer et al., 2017b; Draganits et al., 2015), the combination of geophysical prospection and metal detection surveys (Tonning et al., 2017; Fredriksen & Stamnes, 2018; Gustavsen et al., 2019; Sand-Eriksen et al., 2020), and the minimal-invasive study of grave sites (Cannell et al., 2018). Research in Norway also increasingly pursues the issue of how varying environmental factors can influence contrast in the data and consequently efficacy and reliability of a survey—an interest that is driven by the increasing use of GPR as a primary investigation tool in cultural heritage management (Fig. 5). (Gustavsen et al., 2018, 2020b; Gabler et al., 2019, 2021; Schneidhofer et al., 2017a, b, 2022; Schneidhofer, 2017). The end result is a continuously growing body of published research and reports (Fig. 8).

Fig. 5 Soil moisture monitoring as part of the Vestfold Monitoring Project (Schneidhofer et al., 2022). (Photo: Petra Schneidhofer/Vestfold and Telemark County Council)

There are also some examples of palaeoenvironmental analysis, and combinations of soil scientific analyses and geophysical data performed to enhance the understanding of the source of the geophysical observations made and increase the understanding of formation processes of the cultural landscapes. While the soil sampling strategy and analysis is not always performed as an integrated part of the analysis of the geophysical data (e.g. Stamnes & Bauer, 2018), there are case studies where this is has been done (Draganits et al., 2015; Schneidhofer et al., 2017b; Stamnes & Bauer, 2018; Cannell et al., 2018; Gustavsen et al., 2018).

Finland

Among a number of research-based investigations in the 2010s, there have been testing of the applicability of geophysical techniques in varying settings and types of archaeological sites. GPR, magnetometry and EMI (with slingram) were also tested at the Neolithic fishery site of Lamminoja, north-west Finland, in a wetland environment for cross-verification between surveys and ground-truthing data (Fig. 6) (Koivisto et al., 2018).

At Lamminoja, insufficient physical contrast between waterlogged wood and the surrounding sediments and the targets' burial depth and small size hampered the survey. In addition, complex sediments affected by drainage, uneven terrain and dense vegetation rendered most of the geophysical techniques ineffective. However,

Fig. 6 Magnetometer survey carried out at the Neolithic fishery site of Lamminoja in Haapajärvi in 2012. (Photo: Satu Koivisto/University of Helsinki)

it became apparent that the magnetometer responded to remanent magnetic structures even underneath saturated peat.

In 2020, an extensive geophysical dataset was collected using GPR and magnetometers to characterise an area of archaeological potential at Lake Lepinjärvi in Karjaa in south-west Finland. The surveys were supported with a Short-Term Scientific Mission (STSM) by COST Action SAGA as part of an ongoing Norwegian-Finnish collaboration between NTNU, the University of Helsinki and University of Turku, which aims to facilitate knowledge transfer and training between the three institutions. It constituted the first large-scale and high-detail archaeo-geophysical prospection ever conducted in Finland. The data was collected using the NTNU University Museum's multi-channel equipment. The target area at Lake Lepinjärvi comprises long-term continuity in the utilisation of archaeological sites spanning from the Late Neolithic to the Late Iron Age, and in some cases even to the Medieval Period (Vanhanen & Koivisto, 2015). The geophysical data have been analysed in 2021, and the magnetic anomalies and GPR reflections of potential archaeological interest will be verified in 2022 through targeted excavations.

To date, major geophysical projects and PhD dissertations focusing on archaeo-geophysics are still pending. Some methodological testing has been integrated into a few recent PhD studies (Hakonen, 2021; Koivisto, 2017), and Knuutinen and Kinnunen are in progress. A number of master's theses concerning geophysical techniques in archaeology have been finalised, for example, the utilisation of GPR at the historic monastery of Naantali (Somerharju, 1999), the medieval castles of Raasepori (Kalmari, 2014; Knuutinen, 2012) and the historic cemeteries in northern and southwest Finland (Heikkinen, 2014; Gustafsson, 2014).

Iceland

In the past, the use of ground-based geophysical prospection in Iceland in archaeological research has mainly been undertaken by universities from abroad in collaboration with Icelandic researchers. A notable geophysical survey using GPR was conducted as part of the *Skagafjörður Settlement Survey project*. The objective was to identify, catalogue and assess the Viking Age and Medieval structures of a Northern Icelandic fjord valley (Damiata et al., 2008). This was followed by The Skagafjörður Church and Settlement Survey project, where GPR was again used with great success (Damiata et al., 2017, 2008). In both projects, the GPR data were compared with subsequent excavation data, providing the opportunity to make direct comparisons between the radar results and the archaeological record (Damiata et al., 2017).

In 2010 the *Institute of Earth Sciences* and the *Department of Archaeology* (University of Iceland) invested in a GSSI SIR-3000 GPR system with three different antenna types. This changed the possibilities to do geophysical prospection in Iceland dramatically. The first large Icelandic project equipped with this system was *Finding the Medieval Monasteries* where 14 monastic sites were surveyed (Kristjánsdóttir, 2017). In addition to GPR, magnetometry and ER surveys were also carried out. A GPR survey was also implemented during the excavations at Skriðuklaustur, another monastic site in Eastern Iceland. Here, numerous surveying experiments were conducted before and during the excavations with varying results (Jónsson, 2011).

A new GPR survey was undertaken at Viðey as part of a bachelor's project in geology as a comparison to an older survey (Friðriksson, 2012). Coolen and Mehler conducted an ER and topographic surveys at Þingeyrarin Austur-Húnavatnssýsla to identify the court circle (dómhringur) and other structures associated with this assembly and monastic site (Coolen & Mehler, 2015). In addition to mapping the former cemetery enclosure and possible burials, the survey revealed the buried remains of the church that may indicate the site of an earlier stave church within the circular dómhringur earthwork.

The Leiruvogur Harbor Research Project was a multi-disciplinary research project that aimed to locate and excavate Viking Age harbours in Leiruvogur (Byock et al., 2015). One aspect of this study was the use of geophysical surveying to help map and reconstruct the Viking Age harbour landscape. Using a combination of GPR, magnetometry, EMI and ER, as well as both terrestrial and marine seismics, this investigation revealed what was interpreted as two inner harbour areas dating to around the Settlement Period. Another aspect of this project focused on a nearby mound referred to as Skiphóll, or Ship Mound. GPR was employed along with coring and excavation to help conform the anthropogenic origin of this mound (Wilken et al., 2016).

In 2016, GPR surveys were conducted at four important trading sites, Gautavík, Gásir, Maríuhöfn, and Kumbaravogur, in a joint campaign by the Centre for Baltic and Scandinavian Archaeology and the LBI ArchPro, within the project *HaNoA Harbours in the North Atlantic (800–1300 AD)*. Except for Gautavik (Mehler et al., 2020), the results of this campaign have not been published at the time of writing.

More recently, GPR surveys have been carried out as part of a three-year project, *Monasticism in Þingeyrar* as well as part of a master project (Jónasson, 2019a, b, c, 2021).

3.2 Geophysical Prospection in Rescue Archaeology

Sweden

Geophysical prospection in Swedish rescue archaeology can be characterised as sporadic rather than systematic. One reason for this could be the way geophysical archaeological prospection methods were initially pitched by heads of the largest contract archaeology unit to the rescue archaeology community: it was claimed to be able to replace traditional archaeological methods such as trial trenching. However, the archaeologists working in rescue archaeology primarily saw geophysical prospection as an extra cost, when reducing the overall costs for archaeology was the primary goal for the decision makers in the county administrations. Since 2010, only a handful of geophysical archaeological prospection surveys have been carried out in rescue archaeology each year, mostly with single-channel GPR systems, directly linked to ongoing or upcoming major archaeological excavation projects. One such example is Västlänken, a railway tunnel being built through the city of Gothenburg, where the geophysical prospection using single-channel GPR started already in 2011 (Biwall et al., 2012). Other early examples are Nibble in Uppland in 2007 (Trinks et al., 2007), Gamlestaden in Gothenburg (Karlsson & Westergaard, 2013) and Kvarnholmen in Kalmar (Trinks et al., 2011). However, a recent development has opened up for geophysical prospection to become an integral part of the archaeological field evaluation method in combination with the traditional digging of trial trenches. The county administration in selected areas of Sweden is willing to give geophysics a fresh opportunity to evaluate what the latest technology has to offer. With this, larger fields will be available, multi-channel systems will be used, and more data will be produced. There is, however, still room for small-scale geophysical prospection using single-channel GPR in the world of the county administrations, exemplified by the discovery of parts of a monastic church in Scania in 2020 (Westergaard & Ericsson, 2020), a project financed through the county administration in an attempt to locate the monastery under the castle before a planned expansion of its buildings.

Denmark

In Denmark, mitigating the impact of development and land use falls under the jurisdiction of local museums as defined by Chapter 8 of the Museum Law (Kulturministeriet, 2014), which is administered by the State Heritage Agency *Slots og Kulturstyrelsen* (SLKS). There is no requirement to include geophysical or other prospection methods in advance of development under Chapter 8. The requirement for intensive trial excavation (circa 20% of the impacted area) means it can be challenging to convince archaeologists at the museums of the need for additional means of prospection. Despite this, magnetic prospection has been employed increasingly in advance of development over the last decade. Museum Midtjylland used magnetic prospection extensively in advance of motorway construction and has tested magnetometry for extensive housing development projects in east Jutland in collaboration with Moesgaard Museum (Stott & Fuglsang, 2016). Other methods are less commonly applied in under the Chapter 8 mitigation, although, as an example, the Erritsø Viking Age fortified settlement near Fredericia was mapped by EMI (Ravn, 2019) with promising archaeological results.

The impact of forestry and agriculture on archaeological features is not covered under Chapter 8. For the former, up to 5% of the expense of archaeological mitigation is covered by the landowner. For the latter, the state heritage agency provides funds for recording archaeology threatened by cultivation. In both cases the limited financial resources make geophysical prospection an attractive proposition for the museums, as large-scale trial excavation is economically unfeasible. Examples include extensive iron production at Neder Julianshede and Moesbo as mentioned in Olesen (2019a), and magnetic surveys of plough damaged barrows undertaken by Felding (2015). In addition, two large-scale GPR surveys were undertaken in Denmark by the NTNU University Museum from Norway in 2021. The first of these at the presumed henge monument of Overdrevsbakken for the Museum Vestsjælland in 2021 (Stamnes, 2021; Claudi-Hansen & Stamnes, 2023), and the other at Rye Kirke over a medieval manor in collaboration with the Museum of Roskilde. Both surveys were financed partly by SLKS.

Two cases where private landowners have paid for archaeological prospection by GPR are known, respectively at Kærby Fed on Funen (Schmidt, 2016), and of a burial mound near Kalundborg (Tiirkainen, 2020), but reports and data from these surveys are unpublished.

Norway

By investigating the archaeo-geophysical surveys conducted between 2000 and 2017, a steady increase in the number of management surveys can be observed. Apart from a small surge of surveys related to mapping the spatial organisation of iron production in the Gråfjell-region in 2002 and 2003, the annual amount of surveys are generally low (Risbøl & Smekalova, 2001). There is, however, also a definite change around 2013. From then on, management-initiated surveys in Norway became the majority (Stamnes, 2016). Still, in 2017, less than 2% of all archaeological investigations involved using geophysical methods in one way or form.

There are reasons behind this: the collaboration between Vestfold County Council, the LBI ArchPro and NIKU. A significant value lay in enabling knowledge transfer, thus building competence by directly involving local partners in methodological development and application of geophysical prospection surveys and data interpretation. Eventually, the Vestfold Case Study demonstrated the potential of motorised prospection approaches and initiated a paradigm shift in the acceptance and perception of non-invasive methods in the Norwegian archaeological community. Concerning heritage management purposes, the use of non-invasive methods in archaeological site assessments and registrations, as conducted at county council level, opened up new opportunities compared to the traditionally applied method of trial trenching. It was now possible to use non-invasive and invasive methods comparatively to increase the understanding of a site while minimising the destruction of the archaeological remains, making the process more efficient.

A research collaboration between NIKU and the National Road Authority (Statens vegvesen) called *Arkeologi i veien?* aimed to evaluate the potential of geophysical survey methods early in the planning process of major road developments (Gustavsen et al., 2013a). This particular project demonstrated a political will to investigate the feasibility to use geophysical methods in the planning process.

In 2015, Vestfold County was the first county in Norway to systematically implement geophysical prospection (primarily GPR) into its cultural heritage routines; a development that has since progressed with geophysical prospection being increasingly considered on this administrative level all across Norway.

Similarly, the research efforts of NIKU and NTNU has led to the compilation of a complete database of all known geophysical surveys performed up to 2017 (Gustavsen & Stamnes, 2012; Stamnes & Gustavsen, 2014; Stamnes, 2016), as well as a large corpus of published reports and case studies. In particular, NIKU, NTNU and Vestfold County Council and their collaborators have published the majority of peer-reviewed articles on geophysical prospection of Norwegian archaeological sites. For example, NIKU has undertaken the most extensive continuous archaeo-geophysical mapping in advance of major infrastructure development in Northern Europe. This includes several tens of hectare-sized projects in advance of railway construction in the former counties of Hedmark, Akershus and Østfold, as well as an InterCity project in Vestfold, where a total of 85 hectares out of all 105 hectares of agricultural fields along the planned development were surveyed with total coverage GPR, and later followed by a targeted trenching scheme (Nau et al., 2017c).

The NTNU University Museum has legal responsibilities for all excavations (both development-initiated rescue archaeology and research initiated investigations) in mid-Norway and, since 2009 has developed an important infrastructure of geophysical instrumentation not only for ground-based geophysical surveys but also for aerial and marine explorations. As with Vestfold County Council, being an integrated part of both a research environment and centrally placed within the heritage management has facilitated the establishment of in-house competence since 2011 and knowledge transfer on the benefits of adopting these methods as part of cultural heritage management. This has led to the implementation of several surveys in advance of larger development-initiated excavation projects, where the interpretations and geophysical imagery has been used to focus excavation efforts, avoid critical infrastructure and plan more accurate budgets. NTNU has also performed surveys on behalf of other regional archaeological museums and county councils and has been involved in various research collaborations in Norway and abroad. One of these projects was in collaboration with NIKU and funded by the Norwegian Directorate for Cultural Heritage, and focused on directly comparing the results from test trenching performed by the county councils, interpretations and imagery from large-scale, high-resolution GPR surveys, and excavation data. This project provided important information on the accuracy and potential of this methodology of two particular case studies. Certain features, typically cooking pits and burnt remains, had almost similar detection rates independent on methods, while smaller features such as postholes were more elusive in the GPR data. Still, a comparison of delineation of sites based on detected features in both trial trenching and GPR was comparable (see Fig. 7) (Stamnes & Gustavsen, 2018; Gustavsen et al., 2020b).

Finland

In commissioned archaeology in Finland, conducting proper archaeological prospection with the help of geophysics and evaluating the results is usually still considered as too time- and money-consuming by the contractors and heritage management officials. Even though this option would be economically and practically beneficial (for both parties and especially for the sake of archaeology), proper geophysical surveys have not yet taken root in the heritage management system of Finland. Especially in urgent rescue projects, there is not enough time for any preceding phases other than excavation. Therefore, geophysical surveys are not integrated into the early planning and budgeting phases. The faint increase in the use of archaeo-geophysics in contract archaeology in the 1990s and early millennium

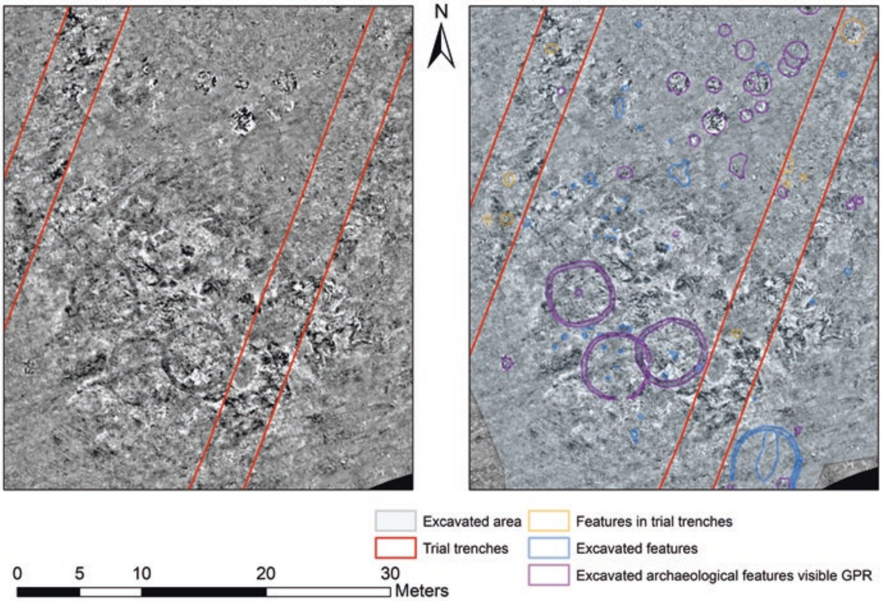

Fig. 7 Comparison of a high-resolution GPR depth slice and excavation results and the position of trial trenches illustrating how important archaeological features might easily be missed in traditional archaeological evaluations. (From Stamnes & Gustavsen, 2018; Gustavsen et al., 2020b)

was merely an outcome of individual interests of certain fieldwork directors and the time when commissioned archaeology was not yet outsourced (and compromised) as it is today in Finland (Finnish Heritage Agency, 2021).

Iceland

Apart from a few unpublished surveys in the 1990s, geophysical techniques have not been employed as part of an archaeological evaluation ahead of a development project. Archaeo-geophysical surveys have always been related to research projects. There are many reasons why geophysical methods have not been commonly used in rescue archaeology. One of the reasons is that private companies do all rescue archaeology, and they lack funding and incentive to build up expertise and equipment. The reason also lies in the archaeology and landscape; it is not so common to take test trenches in a big open/flat area. In the case of magnetometer surveys, the volcanic nature of the bedrock in most parts of Iceland introduces a very strong background magnetic response, hampering the interpretation of such data. Also, there have only been a few large rescue-projects in the last 20 years, so the cost to build up expertise is considered by some decision making actors to be too high compared to the benefit.

3.3 National Legislative Situation

Sweden

The Swedish Heritage Conservation Act of 1988, revised in 2014, is designed to protect and preserve the historic environment in Sweden, which is considered a national concern. The changes made to the act in 2014 move the focus from monuments to environments and state that the law applies to all traces of long-abandoned human activity older than 1850. This applies to all ancient monuments, and an undiscovered monument has the same legal protection in the same manner as a well-known monument. Under the act, it is prohibited to alter, remove, damage or cover an ancient monument. Regarding archaeological fieldwork, this is tendered for, and it is the Country Administrative Board that decides who gets to perform the work. The evaluation should be of high scientific quality and at a cost proportional to the circumstances. However, it is not stated exactly how the work is to be conducted, although recommendations from the National Heritage Board exist. As for the use of geophysical methods, the legislative situation in Sweden is simple; if one excludes metal detectors, geophysical prospection does not require a permit from anyone apart from the landowner's acceptance. This is simply because they are considered to be non-invasive methods. This also applies to planned geophysical surveys of a registered ancient monument. The Swedish National Heritage Board furthermore encourages the usage of non-intrusive methods, suggesting that geophysical prospection might be an important way of evaluating a larger area than what is possible to cover by ordinary test trenching (Riksanvikvarieämbetet, 2012).

Denmark

The legal requirements to perform geophysical surveys in Denmark are simple on non-protected cultural heritage land, only requiring permission of the landowner, while protected nature areas can be challenging to access depending on the type of nature. In protected cultural heritage areas, permits must be obtained from SLKS. There are no legal requirements for storing the acquired data in any digital form, and this has been achieved by paper or pdf files with maps in most cases, rather than as raw and processed data. The ownership of these data is unknown in most cases, and only the geophysical company, a few museum specialists or university researchers have the capability to handle the raw data.

A free text search in the public Danish national archaeological database, "Fund og Fortidsminder" (www.kulturarv.dk/ffreg/) was performed for this paper. The following search terms resulted in these numbers of onshore sites: "geophys*" 20, "georadar" 19, "magneto*" 32, and "Elektro*": 2. No other likely search terms were successful, and overlap was also seen, so archaeo-geophysical methods had investigated approximately 40 onshore sites in total. Less than 10 of these cases had data or an archaeo-geophysical report attached in the database. A significant share of the prospection discussed above was not found in the database, while approximately 10 sites found herein have not been identified by a report (e.g. Nonnebakken, Gråbrødre Kloster, Esrum Kloster and Sæby Kirke). Personal contact with the local museum's archaeologist with interest in the single site helped us retrieve at least one report, but reports from older GPR prospection studies were particularly difficult for us to find. Therefore, the current "Fund og Fortidsminder" database practice seems unsuited for collecting and securing open-access archaeo-geophysical data and reports. A free-text search in the open-access geophysical database, GERDA (https://gerda.geus.dk/), a mandatory open-data repository for data collected for most Danish public authorities, did not reveal any datasets from archaeological sites.

Norway

In Norway, cultural heritage management follows the Norwegian Cultural Heritage Act (NCHA) of 1978, which states that all sites, monuments and portable antiquities older than 1537 are automatically protected by law. The legal protection remains even if the sites have yet to be recognised or discovered (Cultural Heritage Act – Act of 9 June *1978 NO.50 Concerning the Cultural Heritage – LOV-1978-06-09-50*, 1978). A development proposal triggers an archaeological evaluation if the site is considered of high archaeological potential. How this is to be done, is largely up to the county archaeologists in charge of evaluating the project and the area. However, it is in part regulated by recommendations issued by the Directorate of Cultural Heritage. According to the budget guidelines issued by the Directorate, geophysical survey methods are not considered a primary field method for archaeological evaluation (these are visual inspection, test pitting, trial trenching, monitoring of ongoing development work, metal detecting, and various forms of documentation).

Geophysical methods may be employed if deemed fruitful from a practical and/or professional point of view, but their use must be accepted by the developer if they represent added costs compared to conventional methods (Riksantikvaren, 2015). Generally, the total costs of a project need to be balanced against the extent of the planned activity. The initial archaeological evaluations should be thorough enough so that the regional archaeological museums can plan an investigation (i.e. excavation) based on the county authorities' assessment. If a site is under threat by development, the developer has to apply for an exemption from the NCHA. A site or monument can be removed following archaeological excavation if this is granted. The decision on how to do this, and what methods to include, is left to the professional judgement of the archaeologist handling that particular case. It has been noted that often archaeologists try to avoid higher costs in the early stages of development planning, but also that this might have ramifications for planning steps further along the way (Stamnes, 2016). It remains to be seen if increased acceptance of larger budgets early in the planning stages will be beneficial from a cost-benefit point of view.

In the latest governmental white paper on the new goals for Norway's cultural environment policies, geophysical methods have been granted a separate section for the first time. It concludes that geophysical methods can, in many cases, contribute to increased quality, overview and knowledge of cultural environments and that any limitations in the technology today should not stand in the way of the use of technology that can supplement the data that is already registered. It also states that there is still a need for method development (Ministry of Climate and Environment, 2019–2020). This particular document states a new official attitude with increased acceptance of the application of geophysical methods within Norwegian cultural heritage management.

Finland

The *Finnish Antiquities Act (295/1963)* dates to the 1960s and therefore has no references to or recommendations on the use of geophysical methods in archaeological fieldwork. Its long-awaited reform, however, is currently underway. In the quality instructions for archaeological fieldwork compiled by the Finnish Heritage Agency in 2020 (Finnish Heritage Agency, 2020), geophysics is regarded as an optional method in archaeological prospection (Finnish Heritage Agency, 2021). Geophysical surveys in the planning phases of archaeological fieldwork or site evaluation are thus scarce. Currently, there are few specialists in this field and only one fieldwork company, the Muuritutkimus Ltd., which conducts geophysical surveys for their own prospection and planning purposes (Muuitutkimus & Knuutinen, 2018). A number of geophysical companies also offer survey services for archaeologists, but usually, an understanding of archaeological soils, stratigraphy and target objects—as well as the needs of the archaeologists—require lengthy and profound immersion in this specific application of geophysics. Still, today, there are no commercial archaeo-geophysical services available in Finland. There is no national database of archaeo-geophysical results available, but published archaeomagnetic, sediment paleomagnetic and chronological data from Finland is included in the international GEOMAGIA50 database (Brown et al., 2015).

Iceland

In Iceland the *Cultural Heritage Agency* oversees the protection of Icelandic archaeological and building heritage. The current legislation on cultural heritage was passed in 2012. According to Act no. 80/2012 on heritage in Iceland, archaeological heritage includes both archaeological artefacts and sites. It states that all sites and monuments older than 100 years are automatically protected by law. There are legal requirements to perform geophysical surveys or use metal detectors. According to act No. 621/2019 and paragraph 36.2 a permission is needed from the *Cultural Heritage Agency*. There is a no database of geophysical survey permissions available today.

4 Discussion

4.1 General Observations

Generally, the tendencies and experiences from archaeo-geophysical surveys in Scandinavia are similar: Early surveys (i.e. prior to approximately 2005) were often conducted using unsuitable techniques, low spatial resolution, and over-optimistic expectations. Furthermore, there are numerous of examples where non-archaeologists collected very usable geophysical data but lacked the archaeological expertise to properly interpret or understand the results. On several occasions this led to interpretations that could not be verified by excavation, leading to the dismissal of the methods as useful for archaeological purposes. Also, survey strategies might not have been ideal for answering archaeological challenges or research questions. The lack of successful surveys led to a general perception that these methods did not work under Scandinavian archaeological and geological conditions, thereby preventing a sound acceptance and integration of geophysical methods within Scandinavian archaeology.

Additionally, the absence of domestic or in-house expertise and equipment resulted in a lack of development and knowledge gain. Initiatives such as at UV Teknik in Sweden, the employment and investment in equipment and trained personnel both at Moesgaard Museum and in Museum Midtjylland in Denmark, the collaborations between Vestfold County Council, NIKU and the LBI Archpro, recent research initiatives from archaeologists at the Turku and Helsinki Universities in Finland, or the efforts from the NTNU University Museum in Trondheim, Norway, has to some degree changed the situation within the last 10 years. In particular, the Scandinavian formula for change (at least as performed in Denmark, Norway and Sweden) has consisted of the acquisition of large-scale/high-resolution survey capabilities, powerful data processing solutions, and the long-term investment in specialised human resources. Obtaining useful archaeological information through geophysical methods anywhere depend on a sufficient geophysical contrast between the archaeological features and their immediate surroundings. Therefore, significant regional and intercountry differences in the performance of the geophysical methods are expected. In Denmark, as an example, the groundwater table is generally high; Approximately 25% of the land was wetland before the mechanisation of agriculture, around 7% is reclaimed marine sea- and lake beds. Furthermore, an overarching gradient in surface geology from fine-grained subglacial sediments in the eastern part of the country to coarser-grained pro-glacial landforms towards the west creates significant regional differences. Methods such as gradiometry and GPR, generally speaking, perform best in the western part of the country due to fewer natural stones and boulders in the soil, and the widely distributed well-sorted sandy parent materials.

High-standing groundwater table and peaty soils are nationwide issues in all the Nordic countries that may restrict the quality and depth of investigation of EMI and GPR instruments. However, these soil types are often very heterogeneous and hence a patchy problem. Very electrically conductive soil, typically marine clays and silts, might be very attenuating in regards to electromagnetic signals used for GPR surveys, and might pose a problem. However, experience from Norway shows that clayey subsoils are actually favourable, leading to homogeneous and geophysically "calm" backgrounds contrasting well with cut archaeological features such as cooking pits, postholes and ditches (e.g. Gustavsen et al., 2019).

In Denmark, geophysical archaeological prospecting has suffered from being fragmented since the very beginning. It has been and still is, conducted by many actors, including private and foreign companies, some Danish and foreign universities, and a few local museums. The archaeo-geophysical maps produced were, until a few years ago, of little help to the excavators, as the archaeological literature rarely draws on these for new conclusions. Some studies, however, have claimed that their excavations were based on the geophysical results (e.g. Nielsen & Johannsen, 2014). One thing these studies have in common, is that most of the collected data are either in non-accessible formats, are not open access, or are lost. No public repository has been created for archaeological geophysical data sets, while geophysical data from other publicly funded projects must be uploaded into the open-access GERDA database. Access to the technical and archaeological reports, if any, requires in many cases personal knowledge of the site or the local archaeologist who collected the geophysical data.

In Norway and Sweden, this situation is different, as databases of all known surveys from before 2017 in Norway, and before 2008 in Sweden exist. A complete list of all known published articles on the archaeological use of geophysical methods has been compiled and made available by researchers from the NTNU University Museum, NIKU and Vestfold and Telemark County in Norway. This includes mentions of surveys, published or unpublished reports, publications or projects identified through archival sources and media appearances. Reports, data plots and raw data might not be readily available, but compilations such as these might serve as a knowledge base and a source for demonstrating the methods' applicability for a wider area. A lack of access and overview has hampered the acceptance for, and knowledge dissemination of, the archaeological contribution demonstrated by past geophysical surveys. It is our hope that the historical overview provided from Scandinavia in this chapter, albeit not exhaustive, will improve this situation (Fig. 8).

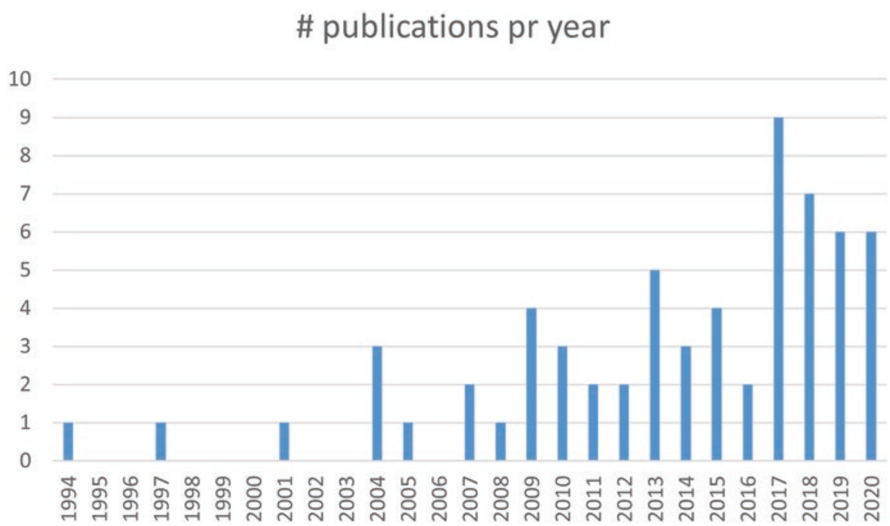

Fig. 8 Number of published articles involving geophysical survey methods on archaeological sites in Norway. 28 out of 62 are from the last 4 years

The application of geophysical methods in Finnish archaeology is random and sporadic and there are not many publications available (especially in English). Another problem is that, following the geophysical surveys, the results have seldom been verified through excavation or coring. Therefore, the viability of the methods tested on varying sites and soil conditions has been unverified. Because of this, many archaeologists and heritage managers are uncertain about the viability of techniques and how to make the most of them in site evaluations and land use planning procedures. In addition to these challenges, the number of specialists focusing on archaeo-geophysics alone is extremely small in Finland. The same applies to a large degree in Denmark. Several companies offer services in Sweden, and a growing number of experts in Norway, although centred around a few institutions.

In addition to the difficult landscape, soil conditions and vegetation hampering the full utilisation of archaeo-geophysics in Finland, there is very limited funding allocated to rescue archaeology. The budgets are constantly getting smaller because of harsh competition between excavating firms. Geophysical methods are very seldom demanded or recommended by heritage management officials in the pronouncements on construction or land development projects. The current state of affairs may be considered structurally unsound, and this causes grave consequences to archaeological heritage. It also produces large obstacles in developing and applying geophysical techniques in rescue archaeology. A more active approach, including systematic testing, comprehensive research, dissemination, and cooperation, are vital to improving the current situation and promoting the wise use of archaeo-geophysics and other non-invasive methods in archaeological fieldwork.

There are costs associated with performing geophysical surveys as part of any archaeological project, and their success and wider acceptance depends on their ability to detect archaeological features, preferably in an affordable manner. Methodological research in itself is important, and might provide knowledge of the applicability and performance of geophysical survey methods under different survey conditions and archaeological contexts. Still, pure foundational research often struggles with getting funding from large official funding bodies, as it easily becomes thematically too narrow for larger funding schemes. There are some honorary exemptions, such as the Vestfold Monitoring Project initiated by Vestfold County Council in collaboration with NIKU in Norway (Schneidhofer et al., 2022).

We also consider the early integration of non-destructive methods in archaeological projects as ideal, where a better integration is likely to lead to improvements at all stages of heritage management, including planning, site evaluation and budgeting. The archaeological time period and the site formation processes have to be considered before applying a particular geophysical method at a given site. For instance, many contemporary urban sites are extremely difficult to survey due to heterogeneous soils, disturbances, complex stratigraphy and abundant infrastructure. Activities from other periods can also be challenging as the remaining features, even when excavated, are often visible only as faint, organic-richer, stone-less postholes, and with little or no geophysical contrast. This is especially the case in glacial subsoil naturally rich in erratic stones (e.g. Stamnes, 2021), or where strongly deteriorating pedogenic processes such as groundwater redox or podzolisation are found. Knowledge of the local soil conditions is thus essential before commissioning a particular archaeo-geophysical method at a site. Indeed, practitioners overpromising the effectiveness of geophysical methods in challenging conditions have arguably contributed to the resistance to adopting these techniques among the wider archaeological community. Therefore, it is vital that we can, honestly and effectively articulate the limitations of the methods alongside showcasing their benefits.

The introduction of geophysical methods has had some impact on the archaeological community, but the geophysical methods are not a part of the everyday considerations and archaeological field practices in Scandinavia. The use of geophysical methods needs to gain additional acceptance, and knowledge of the possibilities and limitations of geophysical methods needs to reach the actors involved in archaeological research and cultural heritage management. The amount of geophysical survey reports, articles and knowledge on the use of geophysical methods is growing, and is helping to build a set of reference points and experiences that previously have been unattainable. Currently, geophysical instrumentation and trained staff are only in place at a few institutions in Scandinavia, and there are limited options for professional training involving the application of geophysical methods. Mechanisms of support for training, knowledge dissemination, experience and knowledge of the possibilities and limitation of geophysical methods and the potential gain for including them in the daily practice of cultural heritage management should be encouraged.

4.2 Future perspectives

Large-Scale, High-resolution GPR Mapping

While we notice an increased interest in geophysical prospection methods within Scandinavian archaeology, such methods still are not yet integrated into everyday considerations and archaeological field practice in the region. This is despite the by now substantial knowledge, experience and skills developed in, for instance, Norway, on conducting large-scale, high-resolution GPR mapping within a heritage management scheme at internationally outstanding quality, looked up to by many archaeological professionals worldwide. The smooth integration of very extensive high-resolution GPR surveys into infrastructure development projects (planning and construction of major road and railway corridors) with subsequent targeted trial trenching of selected areas that show anomalies of buried archaeology as well as those areas that did not show anomalies of archaeological interest has been developed into an exemplary, highly effective tool in Vestfold and Telemark County in Norway.

Methodological and Fundamental Research, Multi-method Approaches

Further methodological and fundamental research is necessary and encouraged. This might focus on the applicability of a wide range of geophysical prospection methods, on more efficient data collection, processing algorithms, automated or semi-automated means of data interpretation et cetera. Also, targeted research on well formulated archaeological research questions and cultural historical problems will aid in spreading the knowledge about the capabilities of various prospection methods at hand. The possibilities are almost boundless, and it is in essence only ones creativity, time and costs available that sets the limits. Widening the range of complementary geophysical survey methods applied would surely improve the quality of the results. For instance, GPR surveys have become the preferred archaeological prospection method in Norway. Increased research into the applicability of EMI methods might improve the detection potential for buried archaeological remains under survey conditions that are challenging for the GPR approach such as contexts with fine grain texture, high moisture content and/or in combination with high salt content (Conyers et al., 2008; De Smedt, 2013). Similarly, EMI and 3D ERT methods might prove beneficial in areas challenging for magnetometry, for instance when performed at sites with numerous erratic rocks with strong remanent magnetisation. To make sure one method does not become a "one size fits all" approach, it is vital to stay on top of novel developments and testing alternative approaches. More insight into best-practice scenarios for combining different large-scale, high-resolution geophysical data-sets and their interpretations with targeted minimum-invasive geoarchaeological soil sampling and trial excavations stand a great chance to increase and improve the prospection and archaeological interpretation result substantially. For instance, for enhanced and more robust integration of geophysical prospection methods within cultural heritage management frameworks. This will also shed more light on cost-benefit analyses, and how to best manage and preserve endangered and important buried archaeological heritage.

Data Archiving, Data Sharing, Open-Science, and Standards

Prospection data collected for archaeological purposes often can have considerable value for other fields of study, and subjects outside of archaeology, such as environmental mapping, soil management, agriculture, infrastructure mapping, geology and more. Learning how to best share, reuse and combine data-sets between different disciplines will become an advantage and will improve the benefits and acceptance of geophysical mapping in modern development schemes. The increasing speed and capability of data collection opens up for ever larger prospection approaches, than even those that we have already seen to be highly successful in Scandinavia and beyond so far.

This sharing of data will also require an open-data, open-science approach to archaeo-geophysics in Scandinavia, where most reports are available, but data are rarely shared openly. The present lack of a formal coordinated strategy for conducting, disseminating and archiving geophysical archaeological prospection surveys has, in some instances led to the loss of knowledge. This is clearly unacceptable, and is indicative that many of our existing infrastructures are unsuited to handling the proliferation of data, information and knowledge produced by geophysical archaeological prospection and other methods, such as 3D recording, intensive geochemical, geoarchaeological and palaeo-environmental soil sampling. It is hoped that this can be addressed in the future by facilitating open-access publication of data, processing workflows and reports without the barrier to entry imposed by formal publication in academic journals. Any such publications must include persistent object identifiers. They can be cited effectively and reliably and integrated with existing heritage management databases. Such an approach should also allow for embargoes to allow for analyses and publication and the censorship from public view of outstanding archaeological contexts that require protection from looting. The generated data can have an impact beyond archaeology, as they are adjacent to societal priorities, such as climate change adaptation. Furthermore, they could be essential to many vital aspects of environmental mapping, such as soil carbon storage and drainage. Such an "*open science, open data*" would be highly warranted if archaeological geophysical prospection is to play a more important role in the future. Of paramount importance is the access to data sets, allowing future commercial exploration archaeology and archaeological research to make full use of the potential offered by the data. Therefore, a discussion on the setup of either national or a Scandinavian open-access databases of geophysical archaeological prospection surveys and data is encouraged.

Geophysical prospection methods will likely be more frequent and more widely applied within rescue archaeology in the future. This will require the formulation of standards and the introduction of quality control mechanisms. But, it is important that standards respect the local and regional geological, archaeological and soil specific conditions prevalent in Scandinavia.

Dissemination and Training

The dissemination and training of students, scholars, young practitioners and future decision-makers within geophysics, archaeology and cultural heritage management is also vital. Presently, the possibilities for practical training and knowledge gain are minimal. While everyone can, in principle, obtain their own equipment, that does not equate to that one immediately can produce professional images of buried archaeology, nor that one is capable of interpreting the acquired data correctly. Developing these skills takes time and devotion. An increased effort in interdisciplinary training initiatives and the establishment of education courses for fieldwork, data processing and data interpretation is encouraged. They can act as fora where students and professionals working within the field of archaeological prospection can learn more about the possibilities, limitations and potential of geophysical archaeological prospection methods, allowing for better professional judgements within their line of work.

5 Conclusions

This chapter aimed to review past and current experiences with ground-based geophysical methods for archaeological prospection in Scandinavia, identify the current role of such field practises, and identify trends to explore in future work. By compiling an extensive overview of work undertaken in all Scandinavian countries, we can conclude that while the geological conditions and archaeological targets are mostly comparable, the acceptance of integrating geophysical surveys in archaeological work has been very different from country to country. It was not our intention to create a complete overview for all Scandinavian countries, but the historical overview provided in this book chapter, albeit not exhaustive, has improved our understanding of the development. Before this publication, the lack of access and overview has hampered the acceptance and knowledge of the possible archaeological contributions of past surveys. While the general acceptance of geophysical survey methods can be described as "reluctant", the vast body of case studies presented here show that geophysical methods by no means should be considered something "new" or "untested". Still, there is work to be done to investigate and demonstrate the possibilities and limitations of the various methods under the prevailing geological and archaeological conditions, for instance, by comparing excavation results with the geophysical data and publishing and disseminating the experiences gained. It is essential to articulate both the limitations and possibilities of the various methods as honestly and effectively as possible. The lack of competence and experience in the decision-making bodies, or skilled domestic practitioners driving research and knowledge transfer on-wards, open-access data transfer and the possibilities of training has hampered a proper integration of geophysical methods within the general heritage management in Scandinavia. There are some notable changes. The introduction and experience with large-scale, high-resolution GPR surveys currently being undertaken in the region have led to internationally leading research in the applicability of the method and the integration of such results in archaeological research and heritage management. This, in turn, in some cases trickled down into national heritage agency guidelines, although generally—geophysical methods are given little attention.

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Part VII
Egypt

Geophysical Prospecting in Egypt: An Overview

Tomasz Herbich

Abstract Among the methods of archaeological geophysics used to the study of Ancient Egypt, magnetometry is the most widely applied. This is due to the dry climate and geological conditions (a large part of the sites are located in a desert environment), which make electrical resistivity measurements difficult and time consuming. GPR and EMI were used sporadically so far, and with no convincing result. The good results provided by magnetometry is due to the magnetic properties of the mud deposited by the river Nile, which is the basic raw material for the production of sundried bricks, the basic building material in the Nile Valley to the present day. The results obtained so far have provided some excellent examples of the effectiveness of magnetometer surveys in revealing city and settlement plans, production sites, cemeteries, and cult places. These investigations have also provided extremely useful observations for the reconstruction of the development of settlement taking place not only on a site, but also on a wider scale (e.g. reconstruction of palaeolandscape).

1 Introduction

Geophysical research in Egypt has been dominated by magnetometry, by far the most popular of the commonly applied methods. Electrical resistivity and other electromagnetic method, including ground-penetrating radar (GPR) and electromagnetic induction (EMI), being used only sporadically. This preference derives, inter alia, from the nature of the architectural building material contrasted with the geological background. The sun-dried mud brick, which was the main material in use throughout Egypt, in the Nile River valley and Delta as well as on the desert fringes, was made of Nile silt, which has a high iron oxide content giving it a high magnetic susceptibility (Hesse, 1967). In the case of archaeological sites on the desert fringes of the Nile valley, the sun-dried bricks are in a high contrast with the diamagnetic quartz sand matrix, and this was the reason of successful tracing of

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mud structures even when using instruments of low resolution (like proton magnetometers of ±1 nT resolution, Herbich, 2015). Experience gained over the past quarter of a century—when using the fluxgate and caesium instruments of higher resolution (in range of ±0.1–0.01 nT) has broadened the base for tracing mud-brick structures in the alluvial matrix of the river valley and Delta (Herbich, 2003).

The sporadic use of electrical resistivity method is due to their low time-effectiveness when collecting data in a sandy matrix characterised by very low humidity. Outcomes are successful only in very specific conditions: when stone-made structures are embedded in a humid alluvial matrix giving a high contrast between the resistivity of the structure and that of the alluvium. It should be kept in mind that because stone building material was always at a premium (including limestone specifically for burning lime), ancient sites always used to be a ready source, hence so few preserve elements of stone architecture.

As for GPR surveys, the logistics of its use in Egypt have always been problematic, as well as other adverse effects related to the type of geology and overall substrate. The shallow water table—barely a meter below the surface as a rule—on sites with an alluvial base and intensive irrigation practices, discourages the use of this method. Its effectiveness has been proved on a few sites, mainly in the Sudanese part of the Nile valley, where it has demonstrated great potential for detecting mud-brick structures (Obłuski et al., 2021). It has also shown success in revealing settlements in alluvial areas with a low ground water table (Ullrich & Wolf, 2015).

Geophysical work done in Egypt can be divided into two periods with the turnover occurring in the mid-1990s. The change is observed primarily when looking at manner to conduct magnetometer surveys. It is due to several factors, the most important: the resolution and measurement speed, both of which are directly related to apparatus development; enhanced data processing methods; and a growing body of experience from different kinds of archaeological sites located in regions with a different geological and pedological characteristics. Archaeological verification of geophysical data has also allowed to test the results and interpretation provided by such geophysical surveys, building a store of knowledge about different applications. The border date is 1996 when instruments automatically recording measurements were first used in Egypt, alongside software for digital map processing (Fassbinder et al., 1999; Becker & Fassbinder, 1999; Abdallatif et al., 2003). A similar phasing also applies to the use of the electrical resistivity.

2 Period I (1973–1996)

Malkata near Luxor was the first archaeological site to be tested in Egypt (Fig. 1). In February and March 1973, Elizabeth Ralph from the Museum of the University of Pennsylvania, a pioneer in the use of caesium magnetometers to survey

Fig. 1 Location of sites mentioned in the paper marked on a satellite image of Egypt. (Google)

archaeological sites, carried out research at the site of the New Kingdom[1] harbour and settlement (Ralph, 1973). The measurements were made in a differential mode, meaning that the differences between the base magnetometer and the instrument

[1] Periodisation of the ancient Egypt (after Dodson & Ikram, 2008, pp. 314–317): Predynastic Period (P.) (5000–3000); Early Dynastic P. (3050–2660), Old Kingdom (2660–2190), First Intermediate P. (2190–2066), Middle Kingdom (2066–1650), Second Intermediate P. (1650–1549), New Kingdom (1549–1069), Third Intermediate P. (1069–656), Saite P. (664–525), Late P. (525–332), Hellenistic P. (322–30 BC), Roman P. (30 BC–AD 395), Byzantine P. (395–640).

moved along the traverses were noted and a total area of ~11 ha[2] was covered. Despite a rather loose sampling grid (2 m traverse interval) the survey traced the remains of mud-brick structures within the settlement, but the results were not sufficient to reconstruct the plan of the port expected in the area.

Proton magnetometers needed about 6 s to take a measurement with ±1 nT resolution, hence with one measurement per square meter it was not possible to cover more than 1000–1500 m^2 in a day's work. Most of these surveys were implemented over desert fringes of the Nile Valley, in Abusir, Giza and Saqqara, where the high contrast between the magnetic susceptibility of mud-brick structures and the matrix guaranteed the recording of structures invisible on the surface. At Giza, measurements were taken every 5–10 m in order to confirm the presence of structures without even thinking of tracing the layout (Dolphin et al., 1977). GPR and electrical resistivity surveys were also used at Giza within the framework of the same project. It was the first time that these geophysical methods were applied in Egypt and the objective was to trace stone structures around the pyramids and burial chambers (Dolphin et al., 1975).

The study carried out by Vladimir Hašek at Abusir for the Charles University (Prague, Czech Republic) expedition have been unduly forgotten and this study has not been cited neither in Egyptological nor in archaeo-geophysical literature. Fieldwork was preceded by a thorough laboratory examination of the magnetic and electrical properties of building materials used in mortuary architecture. Several magnetic anomalies were identified and interpreted as Late Period funerary shafts cut in bedrock with mud bricks lining their upper parts. The results of the surveys also served to draw a plan of the mortuary temple in front of the Raneferf pyramid. Verifying excavations in the following seasons fully supported Hašek's interpretations (Hašek & Verner, 1981; Herbich, 2024, pp. 387–390).

The next prospection with a proton magnetometer was carried out by the University of Warsaw at Saqqara, west of Djeser's Step Pyramid, in an area covered with sand bearing no evidence of human activity on the surface (Myśliwiec & Herbich, 1995). The surveys covered an area of ~1.5 ha, using two proton magnetometers in a differential mode over a one square meter grid. A few areas of anomalous values were identified and interpreted as clusters of mud bricks. The results were used to plan excavations. The largest anomaly turned out to be a tumble of mud bricks concealing the entrance to a funerary chapel cut in the rock of an unknown vizier named Meref-nebef from the reign of the late Old Kingdom king Teti (Herbich, 2003, pp. 16–18).

Among other studies using proton magnetometers, including Egyptian geophysicists (see Hussain, 1983), a survey carried out at Mendes, a site in the Nile Delta, stands out given the week magnetic contrast between subsurface mud-brick structures and the alluvial deposits. A square metre sampling grid was used with a measurement resolution of ±1 nT. The survey was effective in locating furnaces for pottery production, which were characterised by anomalies in the range of

[2] Surface area calculated based on Fig. 2, Ralph, 1973.

50–100 nT due to additional thermoremanent magnetisation, but it failed to resolve remains of settlement architecture (Pavlish, 2004, pp. 87–100). The scarce contrast between mud-brick structures and the surrounding matrix, typical of sites in the Nile Delta, weighed heavily on future of magnetometer prospection in Egypt.

In the mid-80s, there were some sporadic surveys were carried out mainly in the desert fringes of the Nile Valley where a high contrast between the values of magnetic susceptibility of mud-brick structures and the surrounding matrix was expected (e.g., Mathieson, 1995). The lack of conviction continued until early 1990s, at a time when high-resolution instruments (between ±0.1 and ± 0.01 nT) started being used in Europe. These instruments allowed short measurement time, denser sampling, and larger-areas coverage.

Electrical resistivity surveys were also sporadically used during this period. Three surveys have been noted in publications: Abusir, Amarna and Tell Atrib in the Nile Delta. In Abusir, electrical resistivity and magnetometer surveys were used simultaneously to obtain complementary information to determine which building material was used (stone or mud-brick; Hašek & Verner, 1981). The survey in Amarna helped to determine the original extent of the desert, now covered by Nile deposits and the location of wells inside the city (Mathieson, 1989). An architectural complex of mud and red brick material was discovered at Tell Atrib (Myśliwiec & Herbich, 1988; Myśliwiec, 2013).

3 Period II (After 1996)

New caesium and fluxgate magnetometers changed the attitude towards magnetometry in Europe in the 1980s, demonstrating the effectiveness of the method in tracing archaeological features (Herbich, 2015). Fluxgate gradiometers, produced then chiefly by Geoscan Research, measured the vertical gradient of the vertical component of the Earth's magnetic field (Gaffney & Gater, 2003, pp. 61–64), whereas the caesium system (by Scintrex) applied in uncompensated so-called duo–sensor configuration, measured the variation of the total Earth's magnetic field along two traverses (Becker, 1999). A team from the Bavarian State Department for Monuments and Sites in Munich, the Polish Academy of Sciences and National Research Institute of Astronomy and Geophysics (NIARG) in Helwan, Egypt, used the two types of instruments to survey the Polish concession in West Saqqara (Fassbinder et al., 1999; Abdallatif et al., 2019, pp. 149–150). The results clearly revealed square magnetic anomalies that typically corresponded to the response of mud-brick walls surrounding burial shafts in this area. The clarity of the image was the result of a dense sampling rate, with spacing between traverses equal to 0.5 m, in-line sampling 0.25 m for the fluxgate and about 0.10 m for the caesium instrument. The data were visualised as greyscale maps (256 shades, using Geoplot software).

Surveys in Dakhleh Oasis and the Nile Delta opened new perspectives for the use of these instruments. Fieldwork at the Old Kingdom settlement of ‘Ain al-Gazareen proved the great potential of magnetometry to trace mud-brick structures made of

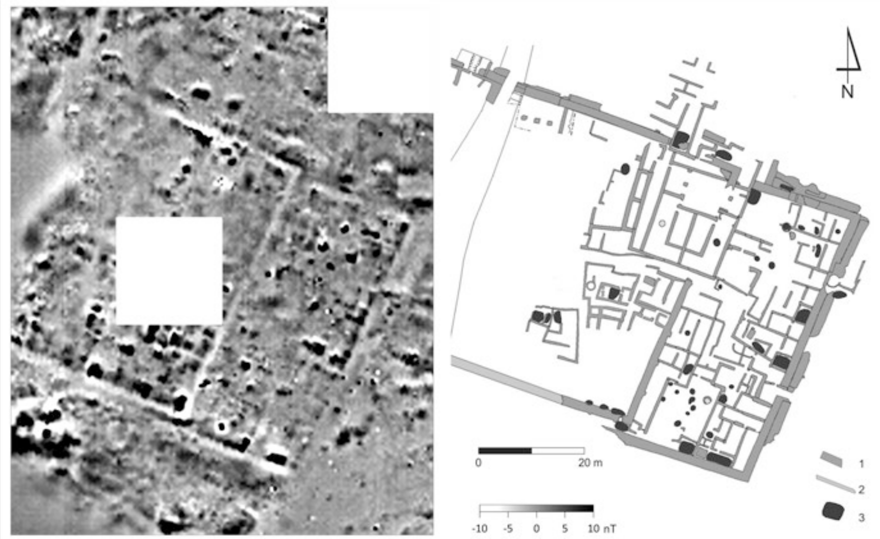

Fig. 2 ‘Ain al-Gazareen. Left: results of the magnetometer survey of the eastern part of the settlement. Right: map of the settlement after excavation (after Mills, 2012, p. 178). *1*—mud-brick walls; *2*—walls reconstructed based on the survey; *3*—fireplaces, hearths, kilns, ovens, ash dumps

local silts devoid of the magnetic properties (Fig. 2). A 10 times higher measurement resolution compared to the proton magnetometers and a denser sampling rate (four measurements per square meter) enabled these results. Digital greyscale map analysis also helped to image the shape of structures differing by a fraction of nanotesla. Buried structures showed up as negative anomalies (features with low magnetic values in a matrix characterised by higher values). Higher values for the layers constituting the matrix were due to concentrations of ash and organic remains typical of cultural occupational deposits (Herbich & Smekalova, 2001).[3]

Instruments with higher sensitivity, like the caesium system applied in Saqqara, were tested by the expedition of the Pelizaeus Museum in Hildesheim at the site of Qantir in the Nile Delta, the late New Kingdom capital of Egypt Pi-Ramesse. The instrument proved to be effective in mapping mud-brick architecture on predominantly alluvial site (Becker & Fassbinder, 1999). The surveys carried out in 1996–2003 covered an area of more than 2 km^2, mapping the city and distinguishing districts with chiefly palace architecture, residential, storage and religious areas, including the waterfront on the Pelusiac branch of the Nile (Pusch & Becker, 2017). The clarity of the mapping of mud-brick structures, in this case, usually as positive magnetic anomalies (characterised by values higher than those measured for the surroundings) is due, in part, to the fact that towns in the eastern Delta were frequently founded on sandy Pleistocene geziras not covered by Nile silt deposits in

[3] A Overhauser magnetometer was also used at Ain Gazareen; see Smekalova et al. (2003).

the Holocene (Sampsell, 2003, pp. 118–120). The lower magnetic susceptibility of the sand matrix provided a sufficient contrast to facilitate the identification of the archaeological remains as positive magnetic anomalies.

The successful outcome of the prospection in Qantir fomented interest in carrying out research on other sites in the Nile Delta. In 1999, the neighbouring site of Tell el-Dab[c]a (ancient Avaris, capital of Egypt in the Second Intermediate Period) started to be explored. More than 10 years of research at this site brought many significant discoveries, not the least a palatial complex from the Hyksos period, a New Kingdom royal palace, the dimensions and plan of which were verified, fortifications from the times of Horemheb, domestic architecture from the Middle and New Kingdoms. Magnetometer survey results verified the course of the Pelusiac branch of the Nile and the extent of the floodplain provisionally traced as a result of a study of site geomorphology (Forstner-Müller, 2009; Herbich, 2024).

Both Pi-Ramesse and Avaris are located today on intensively irrigated agricultural land, levelled from the beginning of the nineteenth century to increase the area of arable land; the levelling resulted in the removal of later occupational strata. Before the use of geophysical surveys to locate and map archaeological sites, potsherds concentrations were used as a proxy for the location of archaeological sites because of the plow pulling to the surface ceramics and other remains. Uncultivated sites in the Nile Delta are man-made mounds (“tells” or “koms” in Arabic) formed of accumulated cultural layers. These can be quite well preserved and be up to a few dozen meters high. Initially, their high/topography and the general low contrast between the magnetic properties related their buried archaeology and surrounding matrix discourage the implementation of magnetometer surveys. However, after the success of prospection in Qantir and Tell el-Dab[c]a, these sites were also tested.

First on the list was Buto (of Predynastic and Old Kingdom date in the lower parts and Late Period and Ptolemaic-Roman in the upper ones) in the north-western Delta. In 1999, the surveys gave a distinct image of the subsurface structures related to the later phases of the site. Characteristic tower houses from this period, with square plans about 10–15 m to the side, had wide foundations, no less than 2 m wide, which undoubtedly aided in their perfectly clear mapping and period determination. Prospection in the following seasons produced images of structures from different periods which were verified by archaeological excavations: an exceptionally clear picture of a Roman-age pottery production centre (more than 50 furnaces) overlying a deserted Late Period and Ptolemaic settlement (Hartung et al., 2003). Earlier deposits (Early Dynastic period) were not reached as these were far too deep.

In 1999, fieldwork began at the Red Sea harbour site of Berenike. The site is located at an area of limestone and sandstone deposits (originated by erosion processes of the adjacent Red Sea Mountains) overlaying magmatic granite rocks. The main building material, as attested in excavations, was fossil coral reef chunks and blocks of gypsum/anhydrite, neither of which have diamagnetic or week ferromagnetic properties. Effective mapping was possible thanks to the higher magnetic susceptibility of the deposits in which these remains were embedded, and the resolution of the instrument used (at least ±0.1 nT) as the contrast difference was quite subtle (Herbich, 2007).

These projects and achievements reflect the new perspectives for geophysics in Egypt that appeared in the last 5 years of the twentieth century. Geophysical prospection, mainly using magnetometry, turned out to be an effective tool for recording archaeological structures not visible on the surface on all categories of sites in Egypt regardless of region, whether in the Nile Valley or Delta, the Mediterranean and Red Sea coasts, the deserts, and desert oases. A growing awareness of the new possibilities resulted in a considerable intensification of research.

The examples presented below concern sites primarily from the Nile Delta showing the application of geophysical methods in areas with predominantly Nile alluvium deposits. The presentation follows a division of sites by functional categories, matching a recent publication of surveys at desert sites (Herbich, 2019). Examples of landscape reconstruction around ancient sites are discussed in the last section.

3.1 Cities and Villages

Considering the results of the past 25 years of research in Egypt, it is evident that geophysics in general and magnetometry, in particular, have provided researchers with an effective tool for the study of ancient urban layout. Measurements of large areas in short periods of time opened the way to studies of cities and villages with an area from a few to a few hundred hectares. Before that, few cities were actually excavated over larger areas, and even then, rather in the sacral and palatial districts. This enabled various extreme hypotheses to be formulated, like the one that unlike Mesopotamia, Egypt did not develop cities as such (Wilson, 1960).

Prospection at urban sites had the objective of establishing the layout of given districts and, in a few cases, of the settlement as a whole. Of the sites where just districts were surveyed, one should mention Saïs, where sections of the city with buildings demonstrating plans typical of the Late Period were observed (Wilson, 2006, pp. 151–175), and Kom Firin, where the full plan of a large late New Kingdom-period walled complex centred around the temple was established (Spencer, 2014, Fig. 4, pp. 17–46). Regarding tell sites, measurements gave a reasonable image of a small settlement at Kom el-Gir, tracing plans of individual buildings, a network of streets over an area of 13 hectares and beside that, the first Roman fort to be known from the Delta (Schiestl, 2016). In the case of larger tells, either close to or exceeding 1 km^2 in area such as Buto and Tanais, considerable parts of the cities were reconstructed, and urban layout analyses led to establish specific functions areas and even a chronology of development.

At Buto (Tell el-Fara'in), an important Pre- and Early Dynastic centre, abandoned around 2200 BC and reoccupied in the eighth century BC through early Islamic times, the objective of the surveys initiated by the German Archaeological Institute in Cairo in 1999, was to trace the remains of the first phase of occupation (Hartung, 2018). The structures did not show up well on the magnetometer survey results due to: the slightness of the contrast between the magnetic susceptibility of the walls and the surroundings; the unimpressive width of walls; and the depth at which the remains were found (usually more than 1 m). However, the later occupation phases were imaged perfectly and became a solid base for a program of excavations of the later phase of city occupation, especially the special role of a major pottery production centre from Ptolemaic and Roman times (Hartung et al., 2003, pp. 263–266; Ballet, 2018; Ballet et al., 2019). An area of 25.5 ha was surveyed in the western and northern parts of the site, recording a few dozen buildings on either side of a N–S street (Fig. 3). The buildings revealed typical casemate plans characteristic of the Late and Ptolemaic-Roman periods, with thick walls arranged in squares and a series of rooms observed at foundation level (see photograph in Fig. 3). The form of these multi-storied houses is known from iconographic representations and architectural models (Marouard, 2012). Analogous structures excavated in the city district dated to Ptolemaic times prove the continuity of building traditions independent of changing power models. The remains of two enclosures were traced, polygonal on the northeast, where walls were up to 5 m thick and the structures, of Late Period date and unknown function, covered an area of 8000 m^2. Furthermore, a fragment of a wall 12 m thick, total length 400 m, located in the south-western part of the site, possibly surrounding a temple complex from Ptolemaic times. The different magnetic values demonstrated by the various structures inside the complex were explained by the different composition of the bricks. Once archaeological fieldwork had established the date of selected structures, the settlement chronology could be read from the magnetometer results, including the functional changes occurring in the different districts over time. The western part, inhabited until Ptolemaic times, was turned into a burial ground, while the northern part, also abandoned by the residents, was turned into a flourishing pottery production centre—both these functional changes were reflected in the results of the magnetometer survey (Hartung et al., 2007, 2009).

At Tanis (Sân el-Haggar), close to a third of the 200 ha of the tell in its northern part was occupied by a sacral district, which was excavated. The rest of the site was expected to be of a residential nature, an idea supported by satellite imagery showing up in a few places the outlines of buildings typical of the Late Period (Leclère et al., 2016, pp. 41–42). The results of the magnetometer survey showed that there are two clearly different districts, both in terms of layout and the kind of building material used (Fig. 4). On the western side of the central part of the tell and in the southern part the architecture, consisting of casemate buildings, follows an irregular street grid typical of the first millennium BC (Marouard, 2012). Stable values of the readings indicate dried mud-brick as the building material (Fig. 4a). In the eastern district, the architecture is predominantly of an insular kind separated by a regular network of streets, close to a square in shape. A series of high-magnetic anomalies is typical of the magnetic response of walls made of red brick (Fig. 4b). The layout suggested a Roman date for this district, and this agreed with the chronology of surface pottery (Defernez, 2015; Leclère, 2015). The analysis also confirmed the settlement chronology: Late Period and Ptolemaic ceramics on the surface are an indication of the district with Late Period architecture not being inhabited after Hellenistic times; and the settlement retreating to the highest central part of the tell around the religious enclosure (Leclère, 2019).

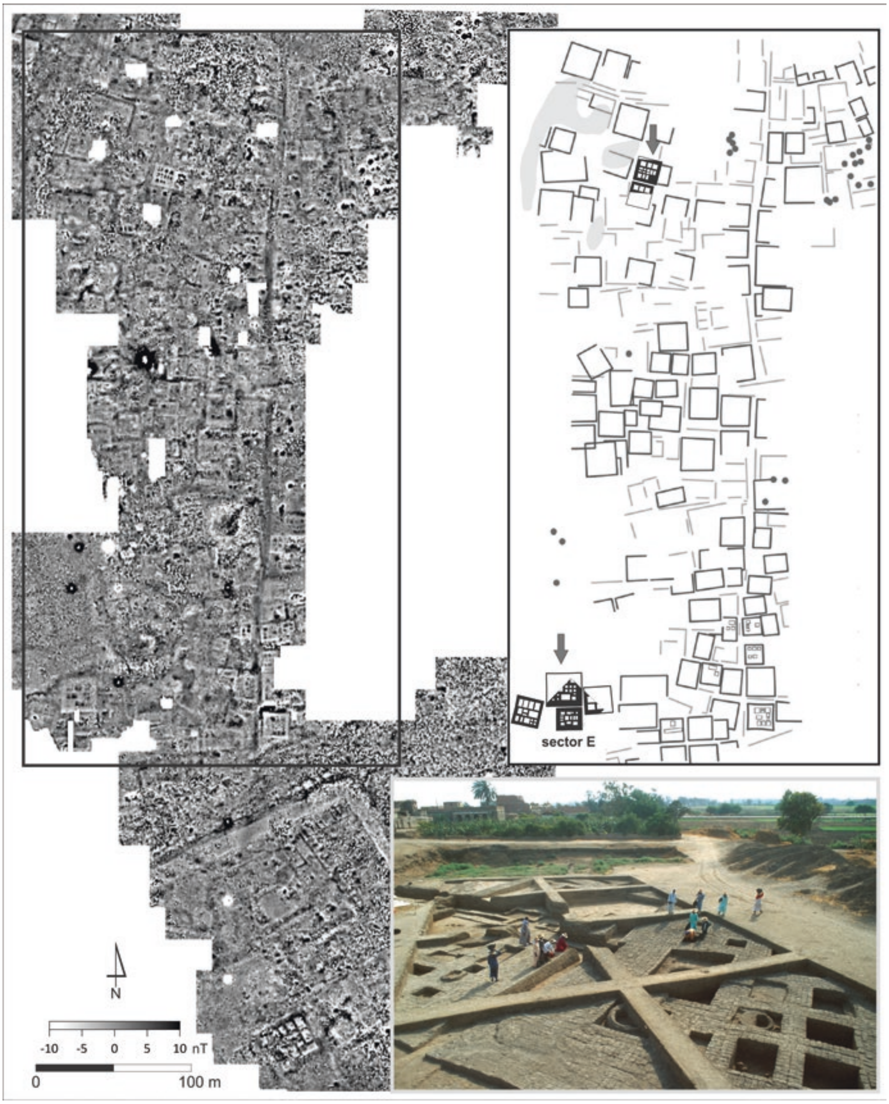

Fig. 3 Buto/Tell el-Fara'in. Left: results of the magnetometer survey of the western part of the site; the box marks outline of the reconstruction map. Right, above: reconstruction map (after Marouard, 2012, p. 107), the arrows mark the Late Period houses with plans verified by excavation. Right, below: foundations of the houses excavated in sector E (courtesy of DAI, phot. Ulrich Hartung)

The study at Pelusium (Tell Farama), a Graeco-Roman town at the mouth of the now defunct Pelusiac branch of the Nile where it flows into the Mediterranean, is an example of the integration of magnetometer and electrical resistivity surveys. The area east of the Byzantine-period citadel was surveyed, between the foundations of

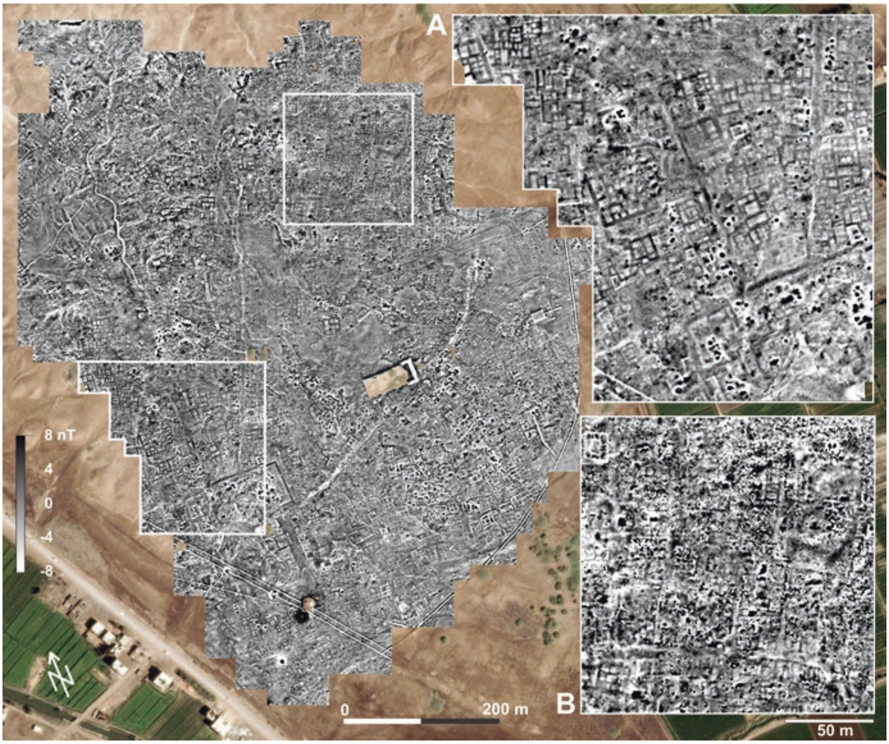

Fig. 4 Tanis/Sân el-Haggar. Results of the magnetometer survey of the central and southern part of the site. White lines mark the extent of the survey areas A and B (*A*: dynamics −6/+6 nT; *B*: dynamics −4/+4 nT)

a Roman theater and the old lagoon shoreline (today the site is 4 km from the sea) (Jakubiak, 2009). The magnetometer results enabled a reconstruction of city quarters with streets and established the orientation of the architecture (Fig. 5). However, the red brick used as building material, characterised by high magnetic susceptibility, made difficult to reconstruct the plans of individual structures apart from the outer shape. The bulk of the walls were recorded in the negative: trenches where walls were dismantled down to the brick foundations (used in the Byzantine fortress) (Herbich, 2021). The electrical resistivity results often produced more detailed plans of streets and buildings (or confirmed those revealed by magnetometry, e.g. a circular building interpreted as a bouleuterion), possibly thanks to the good contrast provided by the soil high humidity and salinity against the building materials. The use of two methods concurrently allowed the type of building material to be distinguished (whether red brick, mud brick or stone). This was the case of a round feature in the western part of the map (red arrow in Fig. 5), characterised by low magnetic susceptibility and high resistivity, the combination of which suggested stone which has diamagnetic or weak ferrimagnetic properties of its own as the building material of choice (Herbich, 2020).

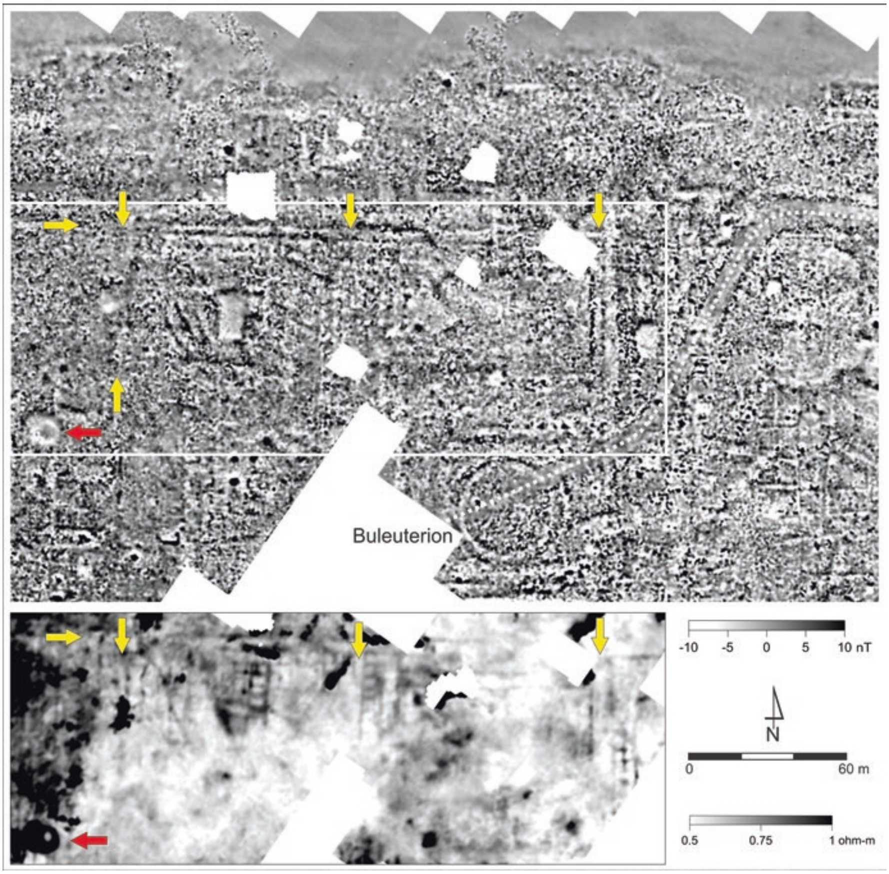

Fig. 5 Pelusium/Tell el-Farama. Above: results of the magnetometer survey of the north-eastern part of the town. The white box marks extent of the resistivity survey. Yellow arrows point to the streets. The red arrow indicates a structure built of stone (well?). Dashed line marks the modern dirt road

3.2 Palatial Centres

In the case of prospection covering large areas, analysing town plans can lead to the discovery of expected buildings the location of which had not been known, such as a royal seat of power. Avaris again is a good example, the city being the capital of Egypt during the 15th Dynasty (1650–1550 BC). A royal palace, measuring roughly 1 ha in size, was identified. It had two rows of building sections, each of different size and containing units of different size, arranged around courtyards (Fig. 6). The plan bears no resemblance to Egyptian palaces with their consecutive room arrangements and seems to owe its origins to the Near Eastern concept, indicating its link with the foreign Hyksos dynasty (Bietak et al., 2007). Excavations confirmed the

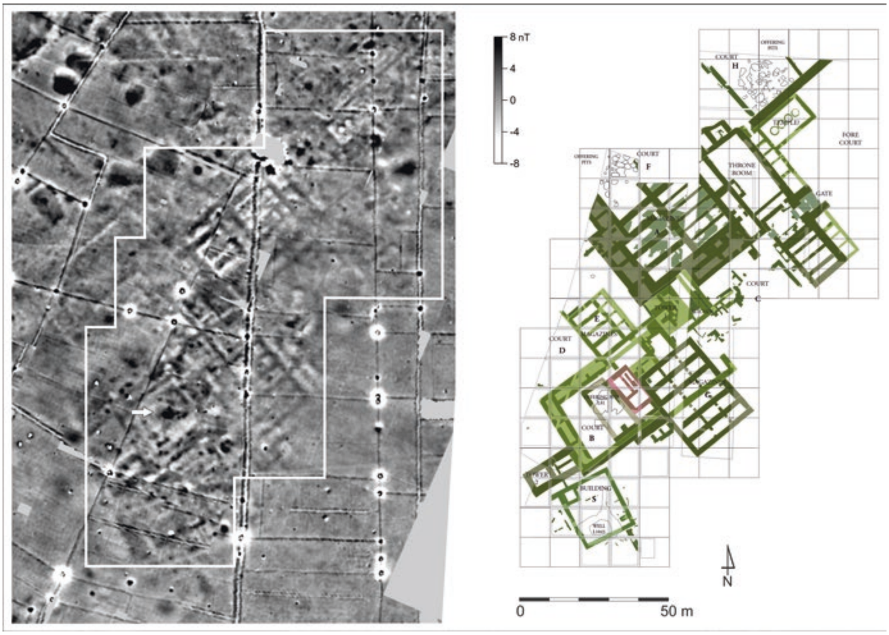

Fig. 6 Avaris/Tell el-Dab^ca. Left: results of the magnetometer survey of the Hyksos period palatial complex. White line marks the extent of the excavation grid. The white arrow marks an anomaly corresponding to a ceremonial pit filled with pottery. Right: plan of the palace after excavation. (Courtesy of Manfred Bietak, ÖAW)

Hyksos attribution of this building, bringing to light both: seal impressions with the name of king Khayan from the 15th Dynasty; and 6000 pottery vessels from the period found in pits. The largest of these ceremonial pits corresponds to an oval anomaly (more than 5 m of diameter) with high magnetic values (Bietak, 2011; Bietak et al., 2013).

At the same site, magnetometer surveys were also useful in precising the plan of a Thutmosid palatial complex from the early New Kingdom (c. 1479–1400 BC). A preliminary tracing of the southern palace G showed to be twice as big as the northern palace F, discovered earlier. Another monumental building appeared to have stood southwest of palace G (Fig. 7). The palaces were built on platforms corresponding in plan to the buildings raised on them. The good results allowed different parts of the structure to be assigned provisional functions in analogy to the palace F (courtyard, vestibule, sanctuary, throne hall). The extent of the building was also determined. (Bietak et al., 2001, pp. 74–85).

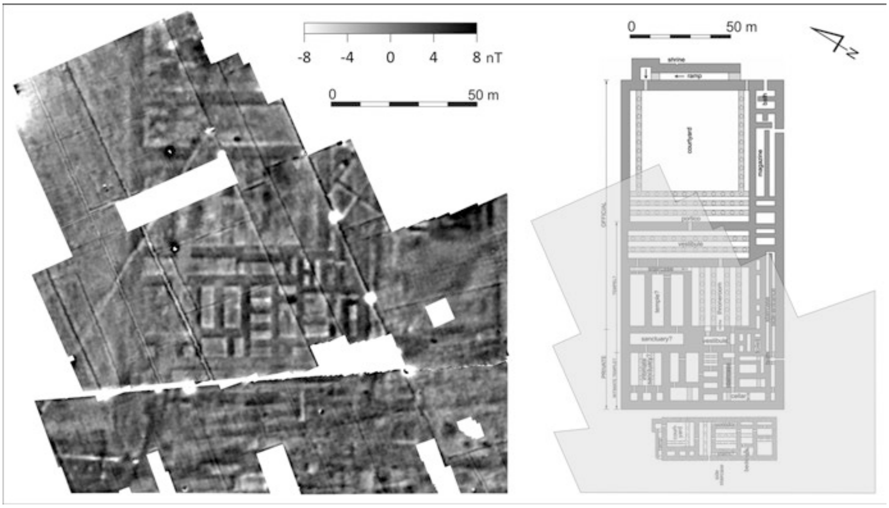

Fig. 7 Avaris/Tell el-Dab^{c}a. Left: results of the magnetometer survey of the Palace G (Thutmosid period). Right: plan of the Palace G, based on results of excavation and the magnetometer survey. (Courtesy of Manfred Bietak, ÖAW)

3.3 Cemeteries and Cult Places

Tombs in Upper and Middle Egypt were located on the desert fringes neighbouring with the Nile valley, making them easily traceable with magnetometry because of the high contrast between magnetically susceptible mud-brick walls and the less magnetic desert matrix (Herbich, 2019, pp. 221–232). In the Delta, however, where cemeteries were founded near settlements, in Nile alluvial soils, the case is different because they are rarely marked on the surface and hard to find on cultivable land. Hitherto most of the cemetery discoveries are made on tells, which are not under cultivation, or else when surveys cover large swathes of agricultural land (as was the case of the Tell el-Dab^{c}a site, Forstner-Müller, 2009).

Buto and Tell el-Farkha are good examples of burials discovered by geophysical prospection on tell sites. At Buto the cemetery occupied the area of an abandoned earlier settlement. Saite Period tombs were located at the northeastern edge of the tell, in the ruins of the Old Kingdom site. Anomalies of rectangular form, with reduced magnetic contrast than their surroundings, correspond to tomb structures (Fig. 8a). The specificity of this type of response was demonstrated once excavations revealed that there was a greater amount of sand in the layers filling the tomb structures (Hartung et al., 2009, pp. 91–94, Fig. 2) (Fig. 8b). Remains of residential structures from the Late Period are also clearly visible south and east of the cemetery. Clusters of dipole anomalies with values ranging −20/+20 nT (Fig. 8a) correspond to Roman-age burials, which were placed in the ruins of buildings a few centuries older in date. These burials were made in terracotta coffins, a material

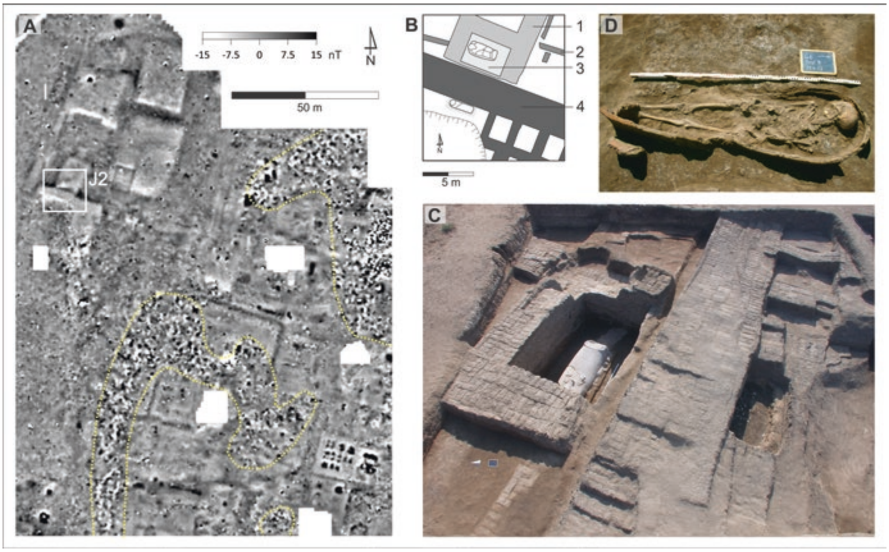

Fig. 8 Buto/Tell el-Fara'in. (**a**) results of the magnetometer survey of the north-eastern part of the site, with the location of trench J2. Dashed yellow line marks the extent of the Roman-period burials in terracotta coffins. (**b**) map of trench J2; 1—Third Intermediate Period walls; 2—Old Kingdom walls; 3—tomb J2/89 with limestone sarcophagus and sand filling; 4—probable Saite walls (after Hartung et al., 2009, fig. 2, p. 86). (**c**) Tomb J/89 seen from the west. D –Roman-period burial in a terracotta coffin. (**c** and **d**: courtesy of DAI, phot. Ulrich Hartung)

characterised by a high magnetic susceptibility and thermoremanent magnetisation (Hartung et al., 2003, pp. 253–254) (Fig. 8d).

At Tell el-Farkha, just as in Buto, excavations revealed the nature of the identified rectangular magnetic anomalies. These rectangles never exceeded 5 m in length and turned out to be Predynastic burials. Their study has contributed extensively to broadening current knowledge of burial practices in this period (Dębowska-Ludwin, 2012). The anomalies were caused by the different magnetic susceptibility of the backfill of the rectangular chambers compared to the values yielded by the mudbrick chamber walls and the surrounding matrix. The presence of large sets of pottery vessels inside the burial chambers also tended to change the magnetic value of the backfill of these rectangular features; the arrangement of the anomaly enabled a reconstruction of where the vessels were located in these tombs (Herbich, 2004).

The graves found at Tell el-Dab^ca were not verified by archaeological excavations and are dated based on the recorded shape of the structures, which can be compared to excavated burials and dated accordingly, as is often the case in the investigation of cemeteries in Upper Egypt (Forstner-Müller, 2009).

The effectiveness of magnetometry to explore cult centres was demonstrated by the survey of the Great Temple Enclosure from the Saite and Late periods at Tell el-Balamun. Excavations over a long period of time uncovered and identified the most important elements of the temple complex: sanctuary dedicated to Amon, temples built by Psamtik I and Nectanebo I; a fort with an annex on the north-east; a series of burials; and some structures from the Ptolemaic period (Fig. 9a). The enclosure walls of the temenos had been traced and dated (inner wall: 26 Dynasty—664-525 BC, outer wall: 30 Dynasty—380-342 BC) and surface remains clearly indicated the presence of production areas (Spencer, 1996). The objectives of a magnetometer survey at a site so extensively explored were supposed to be limited initially to explore a few areas in between the excavated structures but the results brought so much new and unexpected information that the entire enclosure was surveyed in effect. For example, the prospection uncovered the only larger

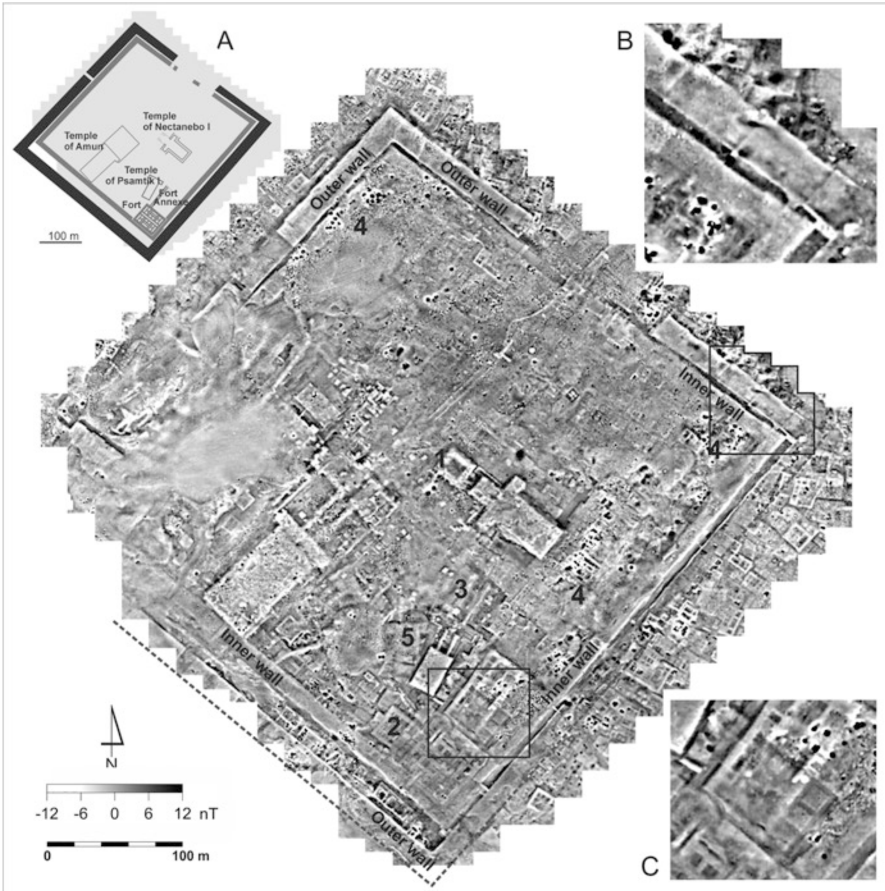

Fig. 9 Tell el-Balamun. Results of the magnetometer survey of the Great Temple Enclosure. The boxes mark extent of maps B and C. The explanation of numbers is included in the text. A: plan of the enclosure based on excavations conducted prior to the magnetometer survey (after Spencer, 1999, plate 1). The extent of the magnetometer survey is in light grey. The inner enclosure wall (26th Dynasty) is in grey, the outer enclosure wall (30th Dynasty) in black. B: detailed view of the results of the magnetometer survey of the outer wall. Dynamic −6/+12 nT. C: detailed view of the results of the magnetometer survey of the buling erected above Fort Annexe. Dynamics −6/+12 nT

stone building preserved in the complex, namely, a bark-station in front of the temple of Nectanebo (Fig. 9; 1). A previously unknown casemate-type building was mapped next to the so-called fort (Fig. 9; 2), and the approach to the temple of Psamtik turned out to be more extensive than previously supposed judging by the anomalies in front of the pylon (Fig. 9; 3). Industrial areas with pottery kilns or similar manufacturing facilities were also located (Fig. 9; 4). An analysis of the magnetic map also revealed an older sanctuary adjacent to the temple of Psamtik (Fig. 9; 5). The remains of this earlier structure were so poorly preserved that its identification would not have been possible without the magnetic image. The recorded fragments of a 30th Dynasty enclosure wall (on the northern side of the temenos) allowed for an in-depth reconstruction of the wall structure, its size and shape made up of separate, projecting and recessed panels of brickwork (Fig. 9b). At some points, the survey showed evidence of buildings on multiple levels; for example, the magnetic map of the Fort Annex revealed that the southern part of the building is completely overbuilt by a later structure (Fig. 9c). The architecture observed southeast of the temenos indicates that the outer wall had a very shallow foundation that had eroded revealing older buildings beneath, dated probably to the Saite and Third Intermediate periods (Herbich & Spencer, 2009; Herbich, 2016).

3.4 Production Centres

Evidence of production activities is practically universal at all sites. It comes in the form of features that were used to produce objects requiring high temperatures and which took on magnetic properties through the process of thermoremanence (Gaffney & Gater, 2003, pp. 37–38). These features include all kind of hearths, pottery kilns, metallurgical furnaces and traces of food processing, like breweries, for example.

The effectiveness of magnetometer surveys to reveal pottery production centres is shown by the results achieved at Buto, a known centre of the industry in Ptolemaic-Roman times. A few dozen furnaces were discovered in the northern part of the site, occurring rarely alone but in clusters of from 2 to 10 production units (Fig. 10). The furnaces were recorded in places already suggested by large amounts of slag, ash and burned soil (e.g., furnaces in trenches P1 2002–2003), as well as in areas with no observable evidence of production on the surface, e.g., trenches P3 and P4) (Hartung et al., 2003; Ballet et al., 2019). Excavations established the date of the complex in the Roman period, identifying the pottery-making technique as one known from western Roman and eastern Mediterranean workshops, but not evidenced earlier in the Near East. Traces of architecture from the Late Period and Ptolemaic times, already abandoned when the industry began, were also mapped (Hartung et al., 2007, 2009).

Traces of metallurgical production were noted during the investigation of the site of Marea on the southern banks of Lake Mareotis. The workshops were located on a peninsula situated about 100 m from the city itself. The magnetometer results

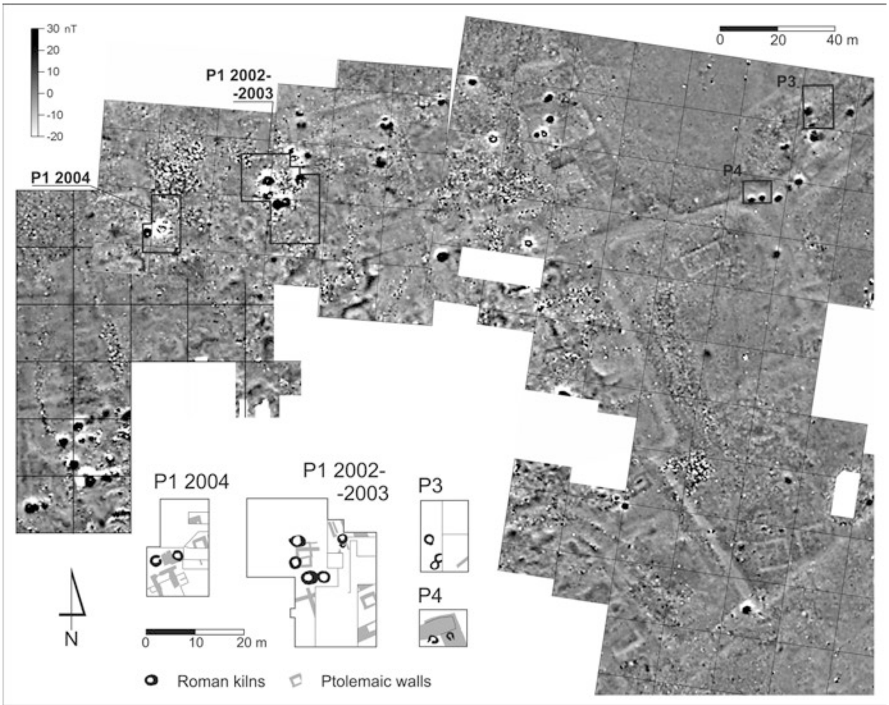

Fig. 10 Buto/Tell el-Fara'in. Results of the magnetometer survey of the Roman pottery production centre in the north-eastern part of the site. The boxes show the location of kilns and other architectural remains. (After Hartung et al., 2007, pp. 126–143)

revealed a large workshop quarter extending over much of the surveyed area (Fig. 11). The walls correspond to negative anomalies, indicating the use of stone of weak magnetic properties, limestone in this case. The outlines of some units were established by anomalies of high magnetic values (reaching −30/+100 nT), interpreted as remains of a metallurgical workshop. Excavations confirmed the interpretation, uncovering a workshop which processes iron and bronze (Pichot, 2010). The high values were caused by slag, small fragments of iron and iron oxides, and ash covering the entire surface of the room. The metallurgical centre is Ptolemaic-Roman, earlier than the city, which is dated to the fifth to seventh centuries AD. The magnetometer exploration of the city area, with stone-made structural remains, did not produce an equally distinct result (Derda et al., 2020). Soils in this area are characterised by a low magnetic susceptibility in the range of $0.2*10^{-3}$SI—$0.3*10^{-3}$ SI. The enhanced contract at the production area between the soil and walls of stone in terms of the magnetic susceptibility was due to waste, chiefly ash, metal fragments and slag, being present in the surface layers. Therefore, the soil and other deposits had a high magnetic susceptibility which strongly contrasted with the weak magnetic susceptibility of walls, something that was not the case in the city area.

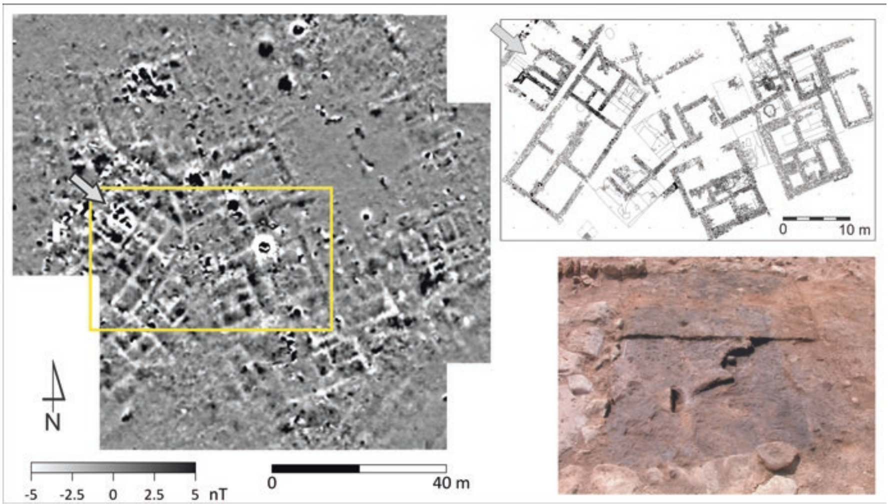

Fig. 11 Marea. Left: fragment of the results of a magnetometer survey of the industrial area on the peninsula. The yellow box marks extent of the excavated area; the arrow marks the anomalies of high magnetic values corresponding to a metal workshop (Space 10). Right, above: map of the excavated area (courtesy Valerie Pichot, CEA). The grey arrow marks Space 10. Right, below: Space 10 seen from the north-west (phot. Valerie Pichot)

Magnetometer prospection in Hierakonpolis led to the discovery of a series of breweries. Excavation of one of the clusters of anomalies interpreted as possible production centres uncovered clay vats for making beer as well as pottery kilns and evidence of food processing, all from the Predynastic period (Baba et al., 2017; Herbich, 2019, pp. 235–238). The centre was presumably a place of activities connected with the neighbouring cemetery, and it constitutes unique evidence of food processing directly connected with pottery production. Breweries like those from Hierakonpolis, discovered in the Predynastic layers at Tell el-Farkha, were not observed there because they were too deep below the surface (Ciałowicz, 2012).

3.5 Landscape Research

The introduction of handled tape recorders and field computers to geophysical research in the 1980s made it possible dense sampling of large areas, enabling measurements of areas outside sites, the objective being a reconstruction of the landscape around the ancient settlements. Tell el-Dab^{c}a and Qantir are both examples of magnetometer prospection of this kind. The total area covered by measurements exceeded 350 ha. The cities were situated on the now defunct Pelusiac branch of the Nile. Drillings carried out in this area in the 1990s traced the river course and established the extent of higher ground during the annual Nile flood, which as a matter of course invited permanent settlement and was therefore a potential area for

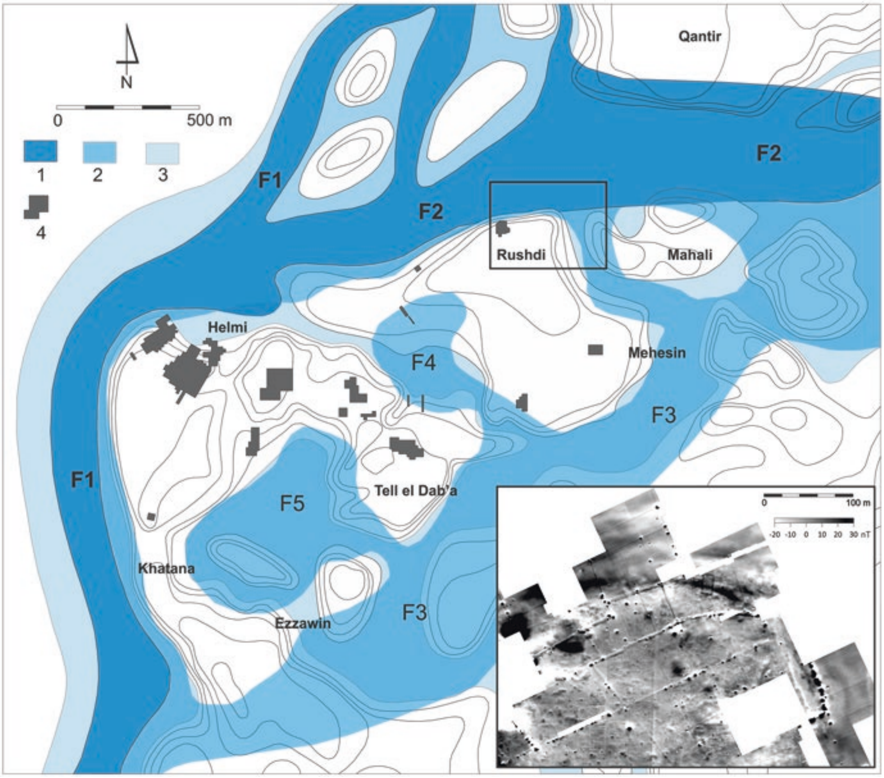

Fig. 12 Tell el-Dab^ca/southern Qantir. Reconstruction of the water channels of the Pelusiac branch of the Nile and the inundated area. The box marks the extent of the survey using a caesium magnetometer and the results below (by Christian Schweitzer). 1—main river channels F1 and F2; 2—inundated areas/F3 channel according to the survey results; 3—extent of inundated area according to Dorner (1999), not verified by the geophysical survey; 4—excavated areas. Contour lines after Dorner (1999)

archaeological exploration (Dorner, 1999) (Fig. 12). A hypsometric map of the area as it would have been 4000 years ago was verified with geophysical prospection applying both the magnetometry and electrical resistivity (in this case using vertical electrical soundings or VES) (Forstner-Müller, 2009; Herbich, 2024). Measurements of the total Earth's magnetic field with a caesium magnetometer gave good results in terms of tracing the course of the Nile in this area and the extent of the floodplain. The results revealed the location of the riverbank and the orientation of deposits in the riverbed, aligned with the flow of the main current (Fig. 12, box). Measurements with a fluxgate magnetometer were not as clear regarding the riverbank but turned out useful in reconstructing the waterfront and pinpointing mooring areas and places for loading and unloading goods. The VES performed in several places (every 10 m or 20 m, along lines of combined length equal to 8.6 km) helped to trace the interface between the riverbanks and floodplains thanks to a strong contrast between the low-resistivity deposits in the river bed and the higher-resistivity surface layers representing human occupation (Herbich & Forstner-Müller, 2013). A juxtaposition of the geophysical results with the geomorphological map changed the reconstruction produced as an effect of the drillings. The F3 branch was hardly a dead bay accessible only from F2 in the north but was connected with the F1 branch flowing around the southern part of the city (Herbich, 2024) (Fig. 12). Considering the bays on this branch, of which the northern one (F4) was a harbour, the mooring places on the left bank at Ezzawin and Mehesin, and the presence of a Hyksos palace in the southern bay (F5), one should view the F3 branch as a year-round passage rather than a temporary branch.

4 Concluding Remarks: What the Future Holds

The number of archaeological sites in Egypt tested by geophysical methods in the past 30 years is probably close to 150–180, much less than in most European countries, but if one looks at how many of these have been verified archaeologically, then Egypt clearly ranks among the highest on the list. Personal observation by the author suggests that broad-scale excavations have been conducted at almost all of the sites where he has carried out geophysical research, sometimes covering areas measured in hectares (e.g., Fig. 6). It clearly sets down the objectives for geophysical research in Egypt: it is considered as a tool to identify settlement or cemetery site layout and search for features to be excavated. The key function of archaeological geophysics in some European countries, which is to determine areas for heritage protection, is practically unknown as such in Egypt.

It does not seem that magnetometry will lose its primacy in the investigations of sites in Egypt to be the superior method of geophysical prospection. As discussed above, it is the result of a combination of feature/pedological/geological characteristics and logistic-related aspects. The share of projects where GPR will be applied will probably increase in the near future. The method has shown potential to establish the layout of settlement structures at desert sites, where so far most of the work was done exclusively with magnetometry. GPR has the further advantage of being capable of tracing changes in urban layout at different depths. Its application would be particularly effective on sites located on the fringes of oases and the seacoast where the silt used for brickmaking has a poor content of iron oxides. It could also be a method of choice for sites with an abundance of pottery in the surface layers, where magnetometry cannot be applied due to the high magnetic disturbance.

In term if instrumentation, mobile multi-probe systems used for magnetometry do not appear to have a future in Egypt. The size of individual plots of land in the Nile Valley (including the Delta) is very small and there is an extensive system of irrigation channels. Also, the ground surface at desert sites is usually too uneven due to extensive illicit digging in the past. In the author's experience, a system of this kind could be applied only to a handful of sites of this kind.

Another specificity of Egypt is that most of the geophysical prospection is carried out within the frame of projects run by archaeological centres located outside of Egypt. Egyptian geophysicists working on archaeological sites are for the most part from NIARG, an institution for which archaeological geophysics is definitely a sideline. Their publications seldom include examples of archaeologically verified results, while the interpretations presented are based usually on earlier determinations regarding given sites (e.g. Abdallatif et al., 2019). It is only in recent years that the presence of geophysicists in Egyptian archaeological projects has started to be noticeable, showing a change in the relation between the two specialties. This will probably be a growing trend because the number of strictly Egyptian archaeological projects is steadily on the rise.

There is also another factor in favour of archaeological geophysics in Egypt—ultimately, virtually every survey in the Nile Valley and Delta, at least with magnetometry, will reveal archaeological features owing to the specificity of sun-dried mud brick used as the principal building material. This is hardly the case in European archaeology. Therefore, the results of research in Egypt provide examples that I believe convincingly support the use of geophysical methods in archaeology, understood as a discipline that studies the entire cultural heritage, regardless of region.

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Part VIII
England

On a Commercial Scale – Archaeological Geophysics in England

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Abstract Geophysical prospection for archaeology was first trialled in England over 75 years ago and, as the profession has matured, a dedicated research community has developed in the country. For over 30 years, archaeological geophysics has played a major role in developer-funded archaeology. Whilst no official figures exist for active archaeo-geophysicists in England, it is likely that the number of practitioners is in the 100s, and is perhaps one of the largest communities worldwide. Standards and Guidance are available to support the profession, but it is a challenge for these to keep pace with advancements in technology and methodologies. The balance between improving cost effectiveness, mainly through increased speed of field data acquisition, whilst maintaining research to increase the level of information gained by such investigations remains an important question for both the commercial and academic archaeological sectors.

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1 Introduction

1.1 Preface

Archaeological geophysics has been practised in England for over 75 years, with possibly the first recorded survey undertaken in 1946 (Clark, 1996). For over 30 years it has played a major role in developer-funded archaeology, especially at the pre-determination stage of planning applications, as part of the Environmental Impact Assessment process, and in Scheduled Monument Consent applications.

Whilst not currently a statutory requirement, the continuing commitment to best practice within the UK archaeological sector would suggest that, in general, a geophysical survey should be considered a standard part of the overall strategy, where appropriate, for archaeological investigation. However, standard recommendations and requirements currently vary between the regions for a variety of reasons, including regional research frameworks and the perceived efficacy of geophysical survey over different geologies and soils.

This overview aims to introduce how geophysical survey was established in England within the archaeological sector, and its development, present use, and potential for future innovation. Please note that this overview necessarily has a commercial focus as the majority of geophysical survey undertaken in England is carried out within the commercial archaeological sector.

1.2 Limitations

This overview is far from exhaustive and only the most common terrestrial geophysical techniques are discussed. Since the end of the Archaeological Investigations Project (AIP), which collated data between 1990 and 2010 (Darvill et al., 2019), it has become increasingly difficult to estimate the amount of geophysical work being undertaken in England annually. Estimates of current activity could be drawn from the number of projects deposited on openly accessible archives. This would be likely to underrepresent the full extent of geophysical survey work in progress, due to the number of surveys undertaken at early stages of the design/feasibility process and prior to planning application.

Where possible, the text has been designed to be accessible to all those with an interest in archaeology, for further technical detail please consult the reference materials.

1.3 Requirements, Standards and Guidance

The current requirement for archaeological investigation during the planning process in England is laid out in National Planning Policy Framework 2012 (NPPF) as "developers to submit an appropriate desk-based assessment (DBA) and, where necessary, a field evaluation" (NPPF, 2021). There is no specific statutory requirement to undertake geophysical survey, although it may be specified as a requirement in a planning condition issued by a local planning authority (LPA) or government agency. Some authorities have navigated the issue of archaeological geophysical surveys being undertaken pre-application, and therefore potentially without their knowledge or advice, by publishing their own specific requirements, for example magnetic surveys in Norfolk should conform to sub metre traverse intervals and request cart-based survey unless "site conditions prevent the use" (Robertson et al., 2018). Buckinghamshire Council Archaeology Service (BCAS) have similarly published a generic brief for archaeological geophysical survey, which again suggests that cart-based magnetometer survey should be undertaken with traverses at less than a metre (BCAS, 2021). Such guidance may lead to a reduction in active management for Local Planning Authorities (LPAs); a benefit given that currently, all regulatory models in the UK are under resourced (Belford, 2021). Unfortunately, there is currently no central register for county- specific requirements.

The Chartered Institute for Archaeologists (CIfA) identifies the archaeological sector in England as a self-regulating industry. CIfA was originally conceived of in 1973, but only formally established in 1982 as the Institute of Field Archaeologists. In 1986, the Institute passed a resolution that the use of 'paid volunteers' was directly contrary to the 'highest standards of ethical and responsible behaviour' as set out in its Code of Conduct (Hinton, 2011; CIfA, 2014a), far in advance of the publication of PPG 16 in 1990 which brought another level of professionalism to commercial archaeology with the 'polluter pays' principle, followed by the implementation of the Valletta convention in 1995 (European Convention on the Protection of the Archaeological Heritage, 1992). By 1999 the Institute had set out a suite of grades of accredited membership to demonstrate professional competency and associated minimum salaries. In recognition of the broad range of disciplines within archaeology, CIfA was renamed as the Institute for Archaeologists in 2008, and attained a Royal Charter in 2014, demonstrating professionalism in line with other occupations (Hinton, 2011).

There is however no legislative requirement for an archaeologist or archaeological organisation to be a member of CIfA. CIfA's *Standard and Guidance for Archaeological Geophysical Survey* (2014a), whilst not a statutory requirement, is accepted by all individual members and Registered Organisations (ROs). The Standard is also a commonly stipulated requirement in a brief or contract. The Standard states that a geophysical survey will "determine as far as is reasonably possible, the nature of the detectable archaeological resource within a specified area using appropriate methods and practices" which allows for broad practice to reflect the versatility of archaeological prospection. This guidance is primarily designed for the planning process but covers all geophysical survey within archaeology. It includes geophysical survey in terrestrial, marine and inter-tidal environments but retains a predominately terrestrial focus. The level of detail within the CIfA guidelines is appropriate for project management but does not include technical specifications. It was originally written with a U.K. focus, but as CIfA is now an international institution this will be addressed in the current review of the guidance.

Most geophysical procedural methodologies in England originate with the comprehensive Geophysical Survey in Archaeological Field Evaluation. First published by English Heritage in 1995 and comprehensively revised in 2008 (English Heritage, 1995, David et al., 2008), it was transferred over to Historic England in 2015 when the Arm's Length Government Body was separated from the now-charitable English Heritage Trust. The European Archaeological Council (EAC) guidance is considered to supersede the Historic England guidance (although see discussion of the use of the EAC guidelines below), and as such is signposted from the Historic England website stating "The EAC guidance incorporates much of the advice from our 2008 document" (Historic England, 2022). Subsequently archived in 2018, Historic England's website currently states that there is "no firm plan to produce updated guidance", but this update remains a task which Historic England's Geophysics Team intend to complete. Methodology may have significantly developed in the 14 years since the original publication; however, much of the guidance is still considered best practice. Whilst this is a technical document for the most part, it covers the project lifecycle so may also support non-practitioners in planning, commissioning, and reviewing archaeo-geophysical products.

Historic England is England's arms-length government body, and the Geophysics Team continues to offer geophysical survey both for stand-alone projects and in collaboration with the other investigative departments, such as the Archaeological Excavation Team, to help better understand and protect the historic environment. They also support Historic England's Science Advisors with the more complex geophysical queries from LPAs etc. Archaeological prospection communities in England are connected through Historic England's Geophysics Team, who actively support and are supported by the International Society for Archaeological Prospection (ISAP), The special interest group for geophysics within CIfA (the GeoSIG), the journal Archaeological Prospection and the Near Surface Geophysics Group (NSGG) within the Geological Society of London.

The EAC Guidelines for the Use of Geophysics in Archaeology: Questions to Ask and Points to Consider, EAC Guidelines 2 (Schmidt et al., 2015) is the overarching guidance throughout Europe. The document largely brings together Revealing the Buried Past (Gaffney & Gater, 2003) and Historic England's (now archived) guidance (David et al., 2008). A concern with the European guidance is that it is designed to be used alongside national professional standards and legal requirements (Schmidt et al., 2015), therefore country-specific information has been actively removed when transferring the base texts. However, there are currently no active national government guidelines for England. Whilst cart-based systems are addressed in both the English Heritage and EAC guidance, these may benefit from being revisited to continue to steer the sector through challenges that have been encountered as the technique has evolved, such as demonstrating resolution compliance through track plot provision, maximum interpolation and the inclusion of crosslines.

Within the EAC guidelines section "Competence of Survey Personnel" it recommends that a geophysical project manager should have "formal geophysical training" and "extended experience in all aspects of geophysical investigation". This is designed to fit with Historic England's Management of Research Projects in the Historic Environment: The MoRPHE Project Managers' Guide (MoRPHE), which complements the Prince2 project management method (Lee, 2006). MoRPHE guidelines recommend a project manager enlists a variety of "Experts" or "Expert Team Leaders" within specific project stages which, in addition to geophysical survey, may include desk-based assessment, evaluation, excavation, geoarchaeological investigation, post-excavation analysis etc. within a multidisciplinary project.

1.4 Employment

Commercial Archaeology directly contributes £218 m to the UK's economy (2019, Rocks-Macqueen & Lewis). The most recent profile of the profession in the UK does not separate England from the rest of the U.K., nor does it differentiate between intrusive and non-intrusive field staff so there are no definitive figures for the number of archaeological geophysicists in England. To understand the size of commercial archaeology in the U.K., it is estimated that there are 6300 (Full Time Equivalent) archaeologists working in the sector, meaning the sector employs more people than 291 other professions in the U.K. (Aitchison et al., 2021). Despite these figures, the profession is on the official skill shortage list (Home Office, 2022).

CIfA ROs, when filtered for in-house geophysical survey provision and with offices in England, returned 24 results. Of these, two ROs offer marine services and a further three ROs do not include geophysical survey as an in-house service on their website. Of the remaining 19 ROs that offer geophysical survey, some do not appear to have a dedicated geophysics department (or in some cases, dedicated archaeological geophysicists) whilst four of these ROs' primary focus is geophysical provision (CIfA, 2021). However, there are some additional unregistered organisations that also provide geophysical survey services to the archaeological sector.

From data retrieved from the British Archaeological Jobs Resource (BAJR), 116 adverts have been placed for roles in England within archaeological geophysics over the past 5 years by 14 different organisations (Connolly, 2022). The level of knowledge and experience varied from Trainee through to Department lead, with annual salaries ranging from £16.5–42k over this period. This data does not provide exact figures for the number of roles that have been available, as some adverts are for unspecified multiple vacancies, nor is it possible to understand staff turnover within the discipline.

Anecdotally, staff turnover is thought to be reasonably high within the archaeo-geophysical sector in England. Opportunities for progression can be variable, not only linked to unit ethos and policies, but also to financial turnover and business need. Some surveyors may be continuously collecting magnetometer data, which is the main source of income for most units. However, ensuring that surveyors have an understanding of (at a minimum) of all the processes entailed in creating a reliable and high-quality geophysical product is vital in ensuring improved data collection as well as increasing job satisfaction. This is in addition to the difficulties faced in England relating to salary expectations for qualified and experienced archaeological geophysicists. The potentially detrimental effect which working away can have on an individual's personal life and mental health is an issue throughout the wider commercial archaeological sector (de Liaño, 2015). Some units have begun to understand these challenges and guarantee a working rotation to ensure regular office/home-based project work.

1.5 Networks

CIfA's Geophysics Special Interest Group (GeoSIG) is open to CIfA members and Affiliates who have an interest in the sector, with a committee of volunteers who represent the interest of archaeological geophysicists within CIfA. GeoSIG aims to promote the value of geophysics to the archaeological sector and acts as a reference point for other CIfA members (and the organisation) for specialised knowledge and information. It was formed in 2007 to give a voice within the structures of CIfA to U.K. practitioners of archaeological prospection. Early tasks for the group included the specialist matrix for CIfA competencies, as it was very difficult to qualify as an archaeological geophysicist under the previous competencies which were weighted in favour of excavation. The inaugural meeting was held at the University of Birmingham and was well attended with representatives from both commercial and academic backgrounds.

The Geological Society of London hosts the Near Surface Geophysics Group (NSGG) which is a special interest group for disciplines such as Engineering and Mineral Exploration but most pertinently to this review, Archaeology. The group holds a biennial meeting at Burlington House, the home of the Society, in the alternate year to the (also biennial) International Conference for Archaeological Prospection (ICAP). The first in the series was convened by Jenny Allsop of the BGS at Keyworth in 1992, inspired by her experience undertaking geophysical surveys with the Melton Mowbray Archaeological Society. This origin keenly demonstrates the strong links archaeological geophysics has to community archaeology. In the year in which ICAP is convened, the NSGG holds a Field Exhibition at their test site at the University of Leicester. The close collaboration within the community is reflected by the International Society for Archaeological Prospection (ISAP) holding its Annual General Meeting (AGM) at the NSGG meeting. The NSGG often facilitates further cross-discipline collaboration by holding joint meetings where geophysics for both forensic and archaeological sectors is explored.

The International Conference on Archaeological Prospection (ICAP) held its first conference in Bradford, England in 1995, and since then it has also been hosted in Japan, Germany, Austria, Poland, Italy, Slovakia, Turkey, Ireland and France (International Society for Archaeological Prospection, 2022). Similar international conferences have originated in England. The Maxbleep Symposium was first hosted by the Oxford Research Laboratory for Archaeology in 1964. By 1968, this had developed into the Symposium on Archaeometry and Archaeological Prospection following European interest and by 1975 had become the International Symposium on Archaeometry and Archaeological Prospection (Clark, 1996). The International Society for Archaeological Prospection (ISAP) was formally established in 2003, to complement the Archaeological Prospection journal and host the ICAP conference committee. Whilst this is an international group, ISAP was formulated by Armin Schmidt when at the University of Bradford, who with his then colleague, Chris Gaffney, has continued to influence the direction of ISAP.

1.6 Education

In 1973, Arnold Aspinall first offered the foundational course "Master of Arts in Scientific Methods of Archaeology" at the University of Bradford, with the first undergraduate degree course in Archaeological Sciences established the following year. These courses led to the formation of the School of Archaeological Sciences, within the Department of Physics, under the leadership of Aspinall (Schmidt, 2001; Clark, 1996). This was a huge development for the sector, and Bradford remains a centre of innovation for archaeological sciences today. Many of the UK's active archaeological geophysicists have passed through the University of Bradford, which offered the only dedicated Master of Science in Archaeological Prospection course in England. Whilst this course is no longer active, Bradford continues to help educate the next generation of archaeological geophysicists through their current master's level course Landscape Archaeology and Digital Heritage (University of Bradford, 2022).

With the EAC guidelines suggesting formal geophysical training, there is wider sectoral concern that there are no dedicated Archaeological Prospection courses currently available in England. Many universities teach geophysical survey within modules, but a review of currently available undergraduate archaeology courses suggests only a handful of them offer stand-alone modules devoted to understanding both the theory and practice of archaeological geophysics, for example, Bournemouth University offers Applied Geophysics to their undergraduate students and many other universities have archaeological geophysicists on their staff. There are undergraduate and masters courses which teach near-surface geophysics such as at Keele and Liverpool, with the University of Leicester offering an "Archaeological Geophysics Field Course" as an option within their Environmental Science BSc (NSGG 2019; University of Leicester, 2022).

A threat to the profession as a whole is the current vulnerability of academic archaeological departments. Whilst England claims the top three world university rankings for Archaeology undergraduate courses (Quacquarelli Symonds, 2022), “Archaeology in the UK faces a crisis in both professional and academic practice” (Belford, 2021). A number of university archaeology departments in England are threatened with closure, or in the process of being dissolved. This process is reducing the potential number of graduates entering the profession whilst it remains on the official skill shortage list (Home Office, 2022). The industry is campaigning against these decisions, with the Dig for Archaeology campaign and regular lobbying by CIfA (Dig for Archaeology, 2022; CIfA, 2021).

1.7 Community

Whilst the majority of geophysical survey in England is undertaken for commercial purposes, there is a hugely active community (or volunteer) archaeology sector in the UK which often maximises the benefit of geophysical survey on their projects. These projects are important as they investigate the archaeological record where there is no threat or where there is no funding for research. These archaeological geophysicists can be self-taught or receive training and / or support from professional archaeological geophysicists. Whilst the community network is extensive, BAJR maintains a directory of active societies (BAJR, 2022). The following examples demonstrate how community groups might be structured.

Leicestershire Fieldworkers is a network of archaeological community groups, who were able to supply a grant to the Hallaton Field Work Group, one of their member groups, to purchase geophysical processing software (www.leicsfieldworkers.org). With a lead for geophysical surveys on their committee and with geophysical instruments available from within the network, recent training provided by SENSYS and a number of committed and skilled volunteers, they regularly undertake geophysical surveys throughout Leicestershire.

The Local Community Archaeological Training and Equipment (LoCATE) Project is a partnership between Bournemouth University and the New Forest National Park Authority (Welham et al., 2018). The project aims to support local archaeology community groups to increase the skills and techniques available to them by providing instruction and equipment to undertake investigations. The project supported a geophysical survey to locate kilns at Sloden Inclosure, New Forest, undertaken in 2019 utilised the partnership through volunteers led by a university student. The survey followed intrusive investigations in the 1860s, 1915–1927, 1960s and 1989–1990 with magnetometer survey being undertaken in 1993 (Brown et al., 2019).

2 Development

2.1 Origins

The first archaeological geophysical survey in England (and until 2000 thought to be the first worldwide (Bevan, 2001)) is widely accepted as the earth resistance survey undertaken in 1946 at Dorchester-on-Thames, Oxfordshire (Atkinson, 1953). Evershed and Vignoles, at the invitation of Richard Atkinson, undertook the survey, with Atkinson then re-surveying the site himself (Clark, 1996). Atkinson, known for his work on Neolithic and Bronze Age sites (Darvill, 2003), had read about the method and realised the potential for geophysical survey within archaeological investigation (Clark, 1996). Following excavation in 1949, the Dorchester site was interpreted as a multi-phase Neolithic ring ditch and pit circle within a henge monument, the "Big Rings" (Whittle et al., 1992). Atkinson first published Field Archaeology in the same year, his practical, pocket-friendly and "shrewd" fieldwork manual (Hawkes, 1947) in which he wrote in a post-script of his intentions to experiment with archaeological geophysics (Clark, 1996). When the second edition was published, Atkinson included a chapter "The Detection of Buried Structures" (Atkinson, 1953), describing the method in such a way that it might be replicated by other archaeologists.

The instrument used by Atkinson, the Megger Earth Tester, generated the current by the manual rotation of a handle (Atkinson, 1953), but the method used in civil engineering for soil studies was considered too slow for archaeological prospection. Atkinson therefore improved the speed of survey by creating the "leapfrog" method and designed an accompanying switching system (Clark, 1996). The Megger continued to be used as the only geophysical instrument in archaeology until Martin and Clark developed a resistivity meter in 1956 specifically for archaeological purposes, a two electrode, transistorised Wheatstone bridge (Clark, 1996), which was first tested at the Roman town of *Cunetio*, Wiltshire, where it detected the foundations of the defensive town wall (Clark, 1957). The successful trial led to further development of the Martin-Clark Resistivity Meter to improve the effectiveness within archaeology (Clark, 1996). The impact of this invention earned the prototype its place in London's Science Museum (Bartlett, 1997).

The first use of a magnetometer in England followed a lecture at the Society of Antiquities by Canadian physicist John Belshé in 1957. Belshé presented his work dating pottery kilns by sampling their thermoremanent magnetisation. From this lecture, Graham Webster realised the potential for identifying buried kilns in the field, specifically in relation to his current project, The A1 Great North Road. Webster had evidence for the potential for such features along a 3 km stretch of road construction passing *Durobrivae*, a Roman town near Peterborough. Webster, in discussion with the University of Birmingham, and the Research Laboratory for Archaeology and the History of Art, Oxford, led Aitken and Hall to develop a prototype proton magnetometer. The survey covered 5 ha over 7 days, and successfully identified a kiln. It was here they discovered that negative, cut and filled features such as pits and ditches were also identifiable in the data (Clark, 1996). Interestingly, Aitken notes his initial "disappointment" at detecting rubbish-filled pits (Aitken, 1986), but Fowler recognised the benefits of identifying more subtly magnetised induced anomalies to understand the archaeological record, publishing in Archaeometry and refocusing the development of the discipline (Fowler, 1959; Gaffney, 2008).

The first full time archaeological geophysicist in England was Clark, one of the inventors of the Martin-Clark resistivity meter, employed in 1967 when the Ancient Monuments Laboratory (AML) was established as part of the Inspectorate of Ancient Monuments of the Ministry of Public Building and Works (Clark, 1996; Bartlett, 1997). In 1968, Clark took the opportunity to investigate the effectiveness of other emerging geophysical techniques over ditches relating to the Late Iron Age square barrows at Burton Fleming, East Yorkshire (Clark, 1996), later excavated in 1972 (Stead, 1991). A suite of geophysical survey was trialled for comparison, including AML's proton magnetometer and resistivity surveys, the former unsuccessful due to the unexpected presence of igneous material within the underlying geology (Clark, 1996). The new techniques invited to participate were the SCM soil conductivity meter (as a result of this investigation understood to be measuring the soil magnetic susceptibility instead), two versions of the pulsed induction meter (PIM) and an infra-red detector. None of these methods were successful in identifying the ditches, but here began the constantly evolving development of our understanding of the potential and limitations of different geophysical techniques (Clark, 1996).

2.2 50 Years of Archaeo-Geophysics in England

It is widely accepted that archaeological geophysics as recognised today had been developed by 1972, with Clark and Haddon-Reece publishing a paper in Prospezioni Archeologiche on their design for an automatic recording system based on fluxgate gradiometers which would set the standard for industry systems (Clark & Haddon-Reece, 1973; Clark, 1996). By this point, the first fluxgate gradiometer and the direct-reading earth resistance meter had been developed and were being utilised for archaeological prospection. Ground penetrating radar (GPR) and seismic techniques had begun to be experimented with in Japan and the U.S.A. but were yet to be applied to archaeology in England (Aspinall & Haigh, 1999).

Digital logging systems began to be fitted to existing equipment increasing the efficiency of survey. The early Bradphys resistance meter, the predecessor of the Geoscan RM4, was interfaced through an eight-channel analogue-to-digital converter to a portable computer (Kelly & Haigh, 1984), making it capable of storing 1000 readings (Clark, 1996). The Geoscan FM18 fluxgate gradiometer could store 3000 readings on its integral logger (Clark, 1996). By the time Aspinall and Haigh presented their review 'Twenty Five Years of Archaeological Prospection' in 1997 at the Computer Applications and Quantitative Methods in Archaeology (CAA) conference, the capabilities had progressed to the Geoscan RM15 storing 30,000 readings, whilst the FM36 magnetometer 16,000 due to developments in microelectronics and mass storage (Aspinall & Haigh, 1999).

Aspinall and Haigh saw three distinct phases of data processing and interpretation: visualisation, enhancement and reconstruction. In the 1970s archaeological geophysicists were simply attempting to give a visible form to their data, mostly through dot-density plots and contour diagrams (Aspinall & Haigh, 1999). By the end of the 1970s, it was widely assumed that archaeological prospection plateaued as many challenges had already been solved (Gaffney, 2008). In the 1980s, archaeological geophysicists began to improve the visual quality of the data thanks to the cost of computer processors decreasing, with spatial filtering (such as high-pass, low-pass, sharpening and smoothing) and interpolation becoming popular and 3D surfaces beginning to be produced (Aspinall & Haigh, 1999). The focus therefore moved onto advancing inverse data methods to better model potential archaeological features. Aspinall and Haigh also highlighted edge detection as a first step towards auto-interpretation (Aspinall & Haigh, 1999).

By the 1990s, the prevalent method was magnetometry, but all the techniques practised today were available. Whilst instruments were still handheld and expected to cover 1–2 ha per day, a previously unprecedented number of surveys were now being undertaken in England (Gaffney, 2008). The Archaeological Investigations Project undertaken by Bournemouth University for English Heritage recorded the distribution and scale of work from 1990 to 2010 with more than 2700 logged surveys (Darvill et al., 2019). The Geophysical Survey Database, originally created by English Heritage, recorded a further 3247 surveys in the subsequent decade (archaeologydataservice.ac.uk), suggesting an acceleration in the use of geophysics. This investigation is the most accurate understanding of the uptake of geophysical survey in England to date. Since about 2000, the scale of surveys has increased enormously because of long duration projects, new equipment and methods. This growth was intensified by Nationally Significant Infrastructure Projects (NSIPs) using large-scale geophysical survey as a mitigation tool to support energy, transport, and waste schemes.

It was during this period that the Institute of Field Archeologists (now CIfA) published Technical Paper No. 9 *The Use of Geophysical Techniques in Archaeological Evaluations* (Gaffney et al., 1991), which was the first guidance for the sector. The paper was aimed at archaeologists writing briefs or commissioning a geophysical survey and therefore presented geophysical techniques alongside their limitations and suitability for research questions and site conditions. This was superseded in 2002 by Technical Paper No. 6 by the authors, which addressed similar questions but with the benefit of over a decade of sector progression (Gaffney et al., 2002).

In 2001, the Evaluation of Archaeological Decision-Making Processes and Sampling Strategies (Hey & Lacey, 2001), which still today underpins best practice for sampling strategy for archaeological evaluation (trial trenching), was commissioned by Kent County Council. This study included an appendix on “the specific contribution of geophysical survey”, potentially limited by the bias towards magnetic datasets, sample size and data consistency (particularly spatial). From this study, it was considered that 70% of identified anomalies correlated with the subsequently excavated features, with 50% correlated to within 0.5 m. However, the "blank" areas, where there were no significant anomalies identified within the geophysical data were hugely variable (35–87%) (Linford and David, 2001). This reinforced the current convention that absence of evidence within geophysical data alone does not, necessarily, equate with evidence of absence.

3 Current Applications

3.1 Introduction

Archaeological geophysical surveys for commercial projects in England currently should conform to two sets of guidelines: the CIfA Standard and Guidance for Archaeological Geophysical Survey (2014a), and the EAC Guidelines for the Use of Geophysics in Archaeology: Questions to Ask and Points to Consider (2015).

The CIfA guidance defines good practice for the execution and reporting of geophysical surveys, in line with their other guidance and code of conduct. CIfA sets out standards for survey design, briefs, fieldwork, reporting, monitoring, and archiving but does not prescribe appropriate methodologies. The EAC guidelines offer more technical detail on considerations to be made when selecting geophysical techniques and methodologies. The EAC guidelines state that the purpose of a survey should be established at the outset so that appropriate geophysical techniques and survey methodologies can be chosen. They use the categorisation from Gaffney and Gater (2003) to help distinguish three broad levels of investigation:

Level 1—Prospection: to identify areas of archaeological potential and individual strong anomalies
Level 2—Delineation: to delimit and map archaeological sites and features
Level 3—Characterisation: to analyse in detail the shape of individual anomalies

Once the research aim, or purpose, of the survey is established, the most appropriate survey strategy can be determined. Various factors including the known archaeological background of the site, terrain, ground cover, soils, and underlying geology should be considered. The guidelines set out various techniques with suggested configurations and spatial resolutions to help tailor the investigation to the purpose and site conditions.

This section will look at the most widely used techniques within the commercial archaeological geophysical sector in England and how they have changed in use with client requirements and technological advancements. Whilst many surveys now are utilising multi-technique survey strategies, they are better integrated into wider archaeological investigations which may include components such as geoarchaeological investigation or excavation. Interdisciplinary projects are also becoming more common, where archaeological geophysicists may work with external specialists, such as unexploded ordnance geophysicists, to undertake fieldwork or even produce combined deliverables.

Comment on specific manufacturers and instruments is not provided within this review to avoid any potential conflict of interest.

3.2 Magnetometry

The most commonly employed geophysical survey technique in England is fluxgate gradiometry. This is due to the ability to cover large areas for relatively low cost and identify a wide range of archaeological features. Technological advancements over the past 20 years have seen gradiometer survey go from handheld single sensor systems with manual sensor balancing to multi-sensor towed arrays with automatic balancing. These advancements have seen a change in how gradiometer survey is employed in England.

With instruments such as the dual sensor systems (eg Bartington Grad 601-2), an individual acquiring data over individual grids systems may be expected to collect around 2 ha per day. Factors that may affect speed of acquisition include but are not limited to site conditions, sensors, length of working day and experience of the surveyor. These systems were beginning to become essential for large schemes such as HS2 by 2016, and have largely been replaced with cart systems by larger units and those with a geophysical business focus where, depending on site specific factors, such as the uninterrupted size of the field, length of working day and environmental conditions, a vehicle towed array may collect around 20 ha per day in favourable conditions.

The introduction of multi sensor arrays with their associated increase in speed and reduction in cost has seen a real change in how geophysics is deployed in the commercial sector in England. A decade ago, sites in the region of 25–50 ha would have been considered as relatively large, but now sites over 100 ha are commonplace and considerably more affordable. This has changed the perception of archaeological geophysical investigation as a small-scale evaluation solution to enabling a more landscape-scale view of the archaeology.

The cart-based systems are designed to utilise GNSS instruments to give accurate positioning for each data point and are often deployed with four or more sensors at a maximum of 1 m separation. The removal of the need to stakeout individual grids and the increase in deployed sensors both reduces a) cost as less staff are required b) time to cover the same or larger areas. The collection speed has been increased further with the introduction of vehicle towed systems, allowing expected coverage of over 15 ha per day. Contracts for archaeological geophysical survey are regularly won by the overall cost and the speed in which the data can be provided to the client, necessitating innovation.

While technological advances have significantly increased the speed of acquisition, there are factors within the collection of gradiometer data that have not been subject to improvement. The majority of datasets acquired for commercial use are still collected at 1 m traverse separations, as conventional for single and dual sensor systems where there are no requirements for higher resolution, for example as previously mentioned in Norfolk (Robertson et al., 2018). Of note, is the speed in which data can be provided to clients, with some commercial companies providing greyscales within 24 hours, or even providing access to real-time coverage.

There is continued debate over the most appropriate cross-line sensor separation for magnetic survey and whether a 0.5 m separation would offer advantages over the more standard 1 m separation, maximums suggested within available guidance for a Level 1 investigation. The CIfA Standard (2014a) states 'If the project has failed to determine the nature of the detectable archaeological resource within a specified area using appropriate methods and practices because of the way in which it was conducted, the Standard has not been met'. This requirement is most regularly compared to the EAC guidelines' description for a Level 2 survey "to delimit and map archaeological sites and features". As opposed to Level 1, where only "areas of archaeological potential and individual strong anomalies" are expected to be identified. The Standard is likely best reflected by Level 3—Characterisation which requires the investigation to "analyse in detail the shape of individual anomalies" thereby determining "the nature of the detectable archaeological resource". Hey and Lacey (2001) suggest using a sample interval smaller than the dimensions of the smallest feature that can be detected to avoid aliasing.

The EAC guidelines become open to interpretation at Level 2 as, whilst the guidance states a resolution of 0.5 m × 0.25 m or 0.25 m × 0.25 m, it also states that the lower resolution of 1 m × 0.25 m is appropriate for "some" Level 2 investigations. The ambiguity in the level of survey required for archaeological geophysical investigations reflects the disconnect between the guidelines and what is practised in commercial archaeological geophysics in England. The majority of surveys conducted are at a resolution of 1 m × 0.25 m, with perhaps the latter reading interval being smaller. There are only a few counties which specifically request a resolution of 0.5 m × 0.25 m and this is generally only in areas where pit features or a high density of archaeological remains are expected. Until this apparent disparity between the guidelines and practice is clarified, it is unlikely that survey resolution can be driven forward either through universal county archaeologists' requirements or clarification of the factors which define the sensor separation at Level 2.

When reviewing these Standards and Guidelines, it is essential to consider the purpose, or research aim, of a commercial geophysical survey. In general, commercial surveys are commissioned to inform planning decisions or to inform the scope and nature of any further archaeological work in the form of a mitigation or management strategy. This raises the valid question as to whether there is any value in increasing the data resolution for commercial surveys, particularly now that such large areas are being surveyed. Does the detection of smaller pit features and more detail to anomalies add any real value to a survey that is already capable of identifying the larger and stronger archaeological anomalies, when such detection will lead to intrusive interventions?

Conversely, does the real value of increased resolution lie in the potential to identify heavily ploughed down or ephemeral features that may be of archaeological importance and missed by lower resolution survey, and not detectable through intrusive intervention? Should we be developing more "stable" acquisition methods or investigating methods to increasing sensitivity? These questions may be better answered through future reviews of currently available guidance which will better reflect the current state of magnetometry and evolving commercial research questions and requirements.

3.3 Ground Penetrating Radar

GPR is often used either as a complementary survey technique to fluxgate gradiometry or in areas where gradiometry would be ineffective, such as in modern built environments. GPR survey represents a slower and more expensive option than fluxgate gradiometry and, as such commercially, is generally employed over smaller areas. However, as with gradiometry, advances in technology have allowed for vehicle towed multi-channel systems to significantly increase the area that can be surveyed in a day and present GPR as a realistic option on more sites, where the geology, soils and site conditions are suitable for this technique.

The advances in GPR technology follow a similar route to gradiometry within the commercial sector. There is an advancement from single channel GPR systems to multi-channel systems, and eventually to vehicle towing of the multi-channel systems. However, there is a key difference in how these advances have changed the use of this technique. Whilst the development of gradiometer survey has focussed primarily on increasing acquisition speed, GPR has managed to combine this with significant improvements to the resolution of the dataset. Whilst a reduction in cost is mostly realised on larger scale projects where vehicle towed systems can be deployed, the technological advances for GPR survey add significant value to the end product.

The major benefit of GPR survey is that it produces a three-dimensional dataset with responses that allow some degree of interpretation of the archaeological material and state of preservation. While there is a clear advantage to being able to tell the depth of features ahead, or indeed instead, of excavation, the benefits are important when considering the three EAC levels of investigation. The ability to give accurate measurements of features as well as comment on their composition means GPR survey with appropriate resolution is a characterisation survey (Level 3). This makes it a useful tool to target anomalies identified through prospection and delineation surveys. The targeted approach of smaller areas of GPR survey over larger datasets makes it viable on more sites within the commercial sector. However, the ability to identify different anomalies to magnetic survey mean large area GPR survey is a valuable option.

The features generally targeted by GPR survey are similar to those for which earth resistance survey is employed. Both techniques are capable of detecting stone and structural remains that may not be identifiable or as well defined through magnetometry. Over the last 10 years, there has been a combination of the discussed hardware advances in GPR technology, but also advances in the ease and speed of the data processing and visualisation. These advances have brought the cost of GPR survey much closer to that of earth resistance. Given the added value of a three-dimensional data set and characterisation survey offered by GPR, this has seen GPR increasingly replace earth resistance as the second most widely used technique in commercial archaeological survey since the mid-2010s. Whilst earth resistance remains a useful technique, its traditional role is being increasingly reduced as GPR becomes more cost effective and provides much more detailed datasets and interpretation. However, it is important to establish that the site conditions (including, but not limited to, soils and geologies) are appropriate for GPR survey.

The academic community has been actively promoting the use of GPR for research purposes for longer than it has been commonly used within the commercial sector. One of the most well-known examples of largescale GPR survey was undertaken at the Stonehenge and Avebury UNESCO World Heritage Site, in the south-west of England. The Stonehenge Hidden Landscapes Project was undertaken by an international consortium comprising of the Ludwig Boltzmann Institute ArchPro, University of Bradford, University of Birmingham, University of St Andrews, University of Nottingham (Ningbo, China), University of Lampeter and University of Ghent (ORBit). The geophysical surveys utilised seven primary survey methods, including magnetometer, earth resistance, electromagnetic induction (EMI) and GPR. The area covered was 10 km^2 of contiguous mapped area with nearly 170 ha of GPR data collected using both multi-channel arrays and single channel systems (Gaffney et al., 2018). This is the largest project of its kind to date, owing to the range of techniques as well as the site area. The project was widely reported in the media as previously unknown features of significance were identified. A circuit of pits was discovered, which were cored with the resultant artefacts radiocarbon dated to the late Neolithic (Gaffney et al., 2020).

3.4 Earth Resistance

Earth resistance survey was the first geophysical technique to be used for archaeological purposes in England and was once relatively widely used within commercial geophysics, but the efficiencies made in magnetometry and the advances in GPR technology have seen it become less popular.

EAC guidelines state that twin-probe or square / trapezoidal array electrode configurations are preferred for area survey. In England, the majority of earth resistance survey has traditionally been conducted using twin-probe arrays. Advancements in this technology have been relatively limited over recent years when compared to fluxgate gradiometers and GPR, perhaps in part due to the growth of these other techniques. Advances have been made to make data collection more efficient through the use of multiplexers but twin electrode arrays are limited by the practical size and the maximum width of the frame that can manipulated. Multiplexed arrays may improve survey speed and survey spatial resolution but also allow for multiple depths of the sub surface to be targeted, whilst not comparable to the detail provided by GPR these differing depths can greater enhance our understanding. The biggest change in technology has been the introduction of square array carts. These offer collection rates similar to or higher than a single channel GPR survey of comparable traverse separation. However, uptake of this technology has been limited within the commercial sector when compared to other countries, with continuing preference for the detailed three-dimensional data offered by GPR survey in most cases.

The area that earth resistance does maintain its advantage over GPR survey in the commercial sector is its cost. The equipment is cheaper, but more importantly it requires significantly less time to process and interpret the data. This combined with the advances in data collection speed have made earth resistance survey more commercially viable. However, as GPR technology advances with towed arrays it is likely the number of sites where earth resistance is considered the best option continues to reduce. Areas that are too undulating, are too small for a towed array or have adverse surface vegetation which prevent the use of GPR may still be investigated by earth resistance survey.

There is, however, one area of archaeological practice in which earth resistance survey is still widely used. The relatively low price of equipment and software (free of charge, open-source options are available) combined with the ease of use and maintenance make earth resistance survey popular with community groups. Whist this section focuses on commercial geophysical survey due to the significant level of coverage in England, community engagement should be a part of any commercial unit's work and such work adds to the archaeological record in places that commercial funding does not reach. Community groups tend to focus on relatively small survey areas comparative to commercial units but do not have the same time and budget constraints. Both research and commercial organisations working together with local groups add real value and understanding of an area's archaeology and heritage, helping communities to engage with and care for their local heritage assets.

3.5 Electrical Resistivity Tomography

Electrical resistivity tomography (ERT) is not a commonly used technique within archaeological practice in England but offers a good solution to several problems that are not easily solved by other techniques. Within English archaeological investigations, ERT survey is generally conducted as a series of individual lines at relatively wide spacings to produce two-dimensional data rather than employing a close spacing to create a three-dimensional dataset. This is due to it mostly being employed to locate or "chase" known features at depth, such as tunnels, or to provide deposit information associated with palaeoenvironments, and the comparatively high labour intensity of survey when compared to other techniques.

ERT is usually deployed alongside other techniques in order to provide more clarity or detail to the information that has already been gathered. For instance, in the case of a tunnel, it may be that a DBA or trial excavations have located its approximate location and ERT is then employed to provide a more accurate route and depths. For palaeoenvironments, ERT would usually be deployed alongside an array of boreholes or targeted over areas identified by previous survey (Bates & Bates, 2016). The aim would generally be to identify former high points in the landscape that may have formed islands and therefore more likely to contain archaeological material, or former water courses that could support human activity. By combining the ERT data with borehole data it is possible to construct a better-informed deposit model for a site than either technique could separately.

Due to the relatively slow nature of ERT survey it is not a cost-effective technique for a lot of sites. However, with its ability to provide data to depths deeper than most of the other techniques discussed here it can often be the only practical solution. When used as part of a carefully considered and designed survey, alongside other appropriate datasets, ERT can offer information that is not possible through other approaches.

3.6 Electromagnetic Induction

EMI survey provides two complementary datasets in the form of electrical conductivity and magnetic susceptibility. The multiple coil separations of some systems allows data to be collected over different depth volumes. The ability to provide data to depths of ~6 m or more with some instruments makes EMI an effective prospection tool, particularly when looking for large features at depths (e.g. palaeochannels). The nature of the large features being investigated allow for relatively low sampling density and rapid coverage over large areas. This can make EMI a useful technique for identifying paleolandscapes, particularly in waterlogged areas where ERT would not be effective.

EMI has been used to successfully provide detailed data plots of archaeological features, but when compared to gradiometer, earth resistance, or GPR data it generally does not provide the same level of clarity. EMI is probably an underutilised technique in England, with preference given to the other three techniques previously mentioned. However, there is certainly potential for EMI to provide complementary data to these techniques, allowing for an enhanced understanding of certain types of features and sites, as demonstrated by the Stonehenge Hidden Landscape Project (Gaffney et al., 2018).

3.7 LiDAR & Remote Sensing

Advances in other areas can also be utilised to enhance interpretation of geophysical data. The National LiDAR Programme undertaken by The Environment Agency aims to provide accurate elevation data at 1 m spatial resolution for the whole of England, with some areas available with spatial resolutions to 0.25 m. This offers an easily accessible resource for identification of archaeological features. Combining LiDAR data with geophysical survey data means it is possible to evaluate both extant and below-ground remains, enhancing the overall interpretation of a site and, in turn, providing a more complete baseline for effectively managing the archaeological risk through mitigation strategies and further investigations.

In addition to LiDAR, other sources of remote sensing data are becoming more commonly used due to the advancements in uncrewed aerial vehicle (UAV) survey and sensors. As UAVs have become capable of carrying larger payloads for longer flight times, it is now possible to offer a wider range of remote sensing services at a more commercially viable price. LiDAR, multispectral, hyperspectral, and photogrammetry data can now all be gathered efficiently using UAV survey, offering more options to be considered alongside geophysical survey at the initial evaluation stage. As well as this, the sensors are improving, allowing for higher quality data and better interpretation. Being able to select and combine appropriate survey techniques for specific sites is starting to greatly increase the information available and aiding management of archaeological risk.

3.8 Archiving

The contentious issue of archiving archaeological geophysical data in England is heavily debated. The standard was set by Schmidt in 2001 with his publication Geophysical Data in Archaeology: A Guide to Good Practice. The majority of invitations to tender will stipulate archiving to this standard along with an OASIS report, and the updated edition published in 2013 is referenced in the EAC guidelines (2015). However, a brief consultation of the Archaeological Data Service (ADS) website is enough to demonstrate that this practice is not universal. During 2021, 13 surveys were uploaded to The Geophysical Survey Database, despite practitioners widely reporting high volumes of available work.

The ADS is the only accredited digital repository for heritage data in England to ensure the long-term digital preservation of data. Whilst the ADS was established with funding (from the Arts and Humanities Research Council & the Joint Information Systems Committee) it is now predominately project funded, and underwritten by the University of York, where it is based. Each deposition has an associated cost, with the costing calculator calculating a quote of £192 for 1 ha of geophysical data and £522 for 50 ha in July 2022. Whilst some planning authorities in England and Wales now request an ADS quote to be submitted as part of a Project

Design, the absence of archiving costs can become the deciding factor. Cost is also a constraint for community groups however, the ADS offer the Open Access Archaeology Fund to support such investigations with the cost of publishing and archiving (www.archaeologydataservice.ac.uk).

OASIS is an online tool to share details of archaeological investigations with Historic Environment Records (HERs) (resources that relate to defined geographical areas, e.g. a county). Some organisations now include as standard their completed but unsubmitted OASIS form to demonstrate their compliance. The records are received then checked by the ADS and, where used by the local HER, checked by the appropriate authority, with the option to submit to other organisations such as Historic England. The records submitted are publicly and freely available through the ADS (www.oasis.ac.uk).

4 Future Focus

4.1 Future Guidance

As planning legislation in England is currently under review, there is no better time to update national guidance. The EAC guidelines are designed to work in tandem with country-specific guidance therefore the forthcoming Historic England update will be hugely beneficial to the sector. The overarching question currently is to what extent should it be procedurally prescriptive as opposed to allowing practitioners flexibility in methodology by simply specifying the outcome that must be achieved. There is also the difficulty in ensuring that any guidance is "future-proof", and to some extent the latter approach would allow for innovation. There is no question however that quality must be a consideration to any future advancements, in addition to improving survey speed and reducing cost. CIfA are currently updating their guidance for geophysical survey and ensuring that non-practitioners are included in the consultation to improve the support provided for users of geophysical products, as well as specialists.

Future reviews of available guidance would benefit from consultation throughout the range of potential stakeholders, from county archaeologists to geophysical units and the archaeological organisations that are end users of the data to help design mitigation strategies and excavations.

4.2 Data Acquisition

Within the commercial sector, future development will continue to be driven by reduction of cost or adding value to the data beyond what currently exists, such as with GPR survey replacing earth resistance for many sites. The easiest way to reduce cost for commercial survey is to reduce either the number of people required or the time that they are needed on-site. This has already been seen with the introduction of vehicle towed arrays which have become common place over the past 5 years.

A comparison of current cart-based fluxgate gradiometer systems with UAV based fluxgate systems show that while the UAV collected data is able to identify many of the same anomalies as cart-based survey, it does not show the same level of detail (Magnitude Surveys, 2021). The comparison does however show that UAV based survey is effective for at least identifying large and strong magnetic anomalies. This suggests that there is some use for Level 1—Prospection survey within areas that are hard to reach or considered too dangerous to physically survey, such as mountainous or intertidal areas. If the resolution can be improved, then UAV survey has the potential to offer many advantages over towed survey. UAV survey has the potential to offer greater collection speeds, be more environmentally friendly than vehicle towed systems, and remove the issue of ground conditions and crop damage. These questions are still very much in the process of being actively studied, researched and evaluated though and have achieved some promising results to date.

While the sensitivity of UAV collected data is currently an issue, a shorter-term goal of automating data collection could be to review the equipment that is currently being used. Until the sensitivity of UAV survey can reach an acceptable level for archaeological use, it is possible that land-based self-steering vehicles could provide a cost-effective enhancement to current towed systems or via improvements to sensor arrays.

4.3 Automation

Automation is likely to be seen increasingly in the processing and interpretation of datasets. Many processing software programs already offer automated or semi-automated options that apply standard processes to datasets. However, these still require overall quality control and adjustments by a geophysicist. With advancements in machine learning and artificial intelligence it is likely that identification of anomalies can, to some degree, be automated to complement user-led interpretation (Killoran, 2021; Kramer, 2022).

However, such developments could potentially lead to reporting becoming more of a compilation task than an archaeological interpretation of the data. It is most likely that artificial intelligence will be used as a tool to significantly increase the speed of digitisation and reporting, allowing for more focused interpretation and quality control to be provided by an experienced archaeological geophysicist.

4.4 Multi-Technique Platforms

One potential way of both reducing cost and increasing value is through the use of multiple techniques simultaneously. While many of the available techniques are not able to function in close proximity to each other, the potential of EMI and gradiometer sensors on a single cart has been proven. This offers a minimum of three datasets collected in the time of a standard gradiometer survey, with the gradiometer data alongside the conductivity and magnetic susceptibility from the EMI. The gradiometer and conductivity data offer complementary datasets similar to that of gradiometer and earth resistance data.

While the value added to the interpretation by including an additional dataset likely outweighs the increased costs from processing time, there is a reduction in safety for surveyors using manual carts. Adding further instruments and sensors to any array will increase the weight and therefore increases the risk of injuries associated with manual handling. It may be possible to mitigate some of this risk through the design of the cart or platform, but the best way is to remove it is through vehicle towed survey. However, not all sites are suitable for towed survey due to access, the risk to crops, surface obstacles or the size of the survey area. In these cases, the increased manual handling risk would need to be properly assessed to determine whether the survey is viable.

4.5 Deliverables

While much of this chapter has looked at developments with techniques and methodologies of survey, it is important to consider the end product of any survey, the report. As much as there has been value added to the data being fed into reports over the last 10–20 years, there has been little advancement in reporting, or how the data and interpretation is managed. Of these advancements however, graphical improvement over the past two decades to how the geophysical data is displayed and presented in reports should be noted. With better availability of more sophisticated CAD packages, graphics software such as Adobe Illustrator/CorelDraw etc and Desktop publishing software with a large range of price points to suit all resources, and even free alternatives which have allowed less well-resourced practitioners proportional improvement, such as community groups.

The increased use of GIS software in all aspects of archaeology also offers potential to add value to the end product of a geophysical survey with the production of an overarching geodatabase. Currently an interpretation drawing, produced in a variety of software, might be shared to aid evaluation at the DBA stage or to help place trenches for evaluation. However, it is unlikely that this drawing holds much information beyond polygons and interpretation categories. GIS software offers the ability to add more information to individual anomalies through the addition of an attribute table per interpretation category that contains several informative fields.

By adding interpretive attributes to anomalies within GIS, it is possible to add considerable value to an interpretation drawing as a standalone product, such as The Landscape Research Centre's work in the Vale of Pickering (www.thelrc.wordpress.com). This is not to say that a full written report would not be required, rather that by adding field values within the attributes for each interpretation category within a GIS it becomes more user friendly for both internal and external users. This can ultimately help to create a more cohesive project where individual elements and data sources can be easily cross-referenced, saving time and creating a more rounded overall product. There is precedent for this way of working; NSIPs, such as HS2, often work with an overarching schema for geodatabases. This helps to ensure a consistent approach to interpretation and display of data throughout the lifecycle of a project with multidisciplinary teams. This may also improve archiving, as the resulting added metadata and more standalone product would be much more "archive-friendly" for preserving geophysical survey derived information for the longer term.

While the advancements in survey technologies allow for more detailed datasets, there is perhaps little that can be done to improve the written interpretation without changing the standards and guidelines of what is considered acceptable interpretation. Increasing automation and processing speeds should allow more time to be focussed on archaeological interpretation of the data, allowing for reports that offer considered insights. Once an anomaly has been identified, archaeological interpretation firstly ascertains whether an anomaly is anthropogenic and/or archaeological, and suggests the feature the anomaly may represent e.g. ditch, gully, pit. Where possible, further information (referring back to the background research available e.g. DBA) as to the period and potential function of the feature e.g. Romano-British ladder enclosure, Bronze Age Banjo enclosure, medieval house platform may then be included, but this relies on the knowledge and experience of the archaeological geophysicist and the known historic environment context.

The quality and extent of archaeological interpretation is highly variable currently. Some units include only whether they consider an anomaly to have the potential to be archaeological, others will identify the potential feature but not all continue through to full archaeological interpretation of the feature within the historical setting. These disparities would benefit from clarification as to the extent of interpretation required for the intervention, whether that be through the research question, project brief or through guidance. However, within a competitive commercial setting, it is more likely that these time savings will be used to provide more competitive costings. The drive for higher standards of reporting would need to come through the standards and guidelines with proper evaluation and enforcement by LPAs rather than individual units and practitioners.

5 Conclusion

England was an early adopter of archaeological geophysics, the experimentation undertaken and the organisation of the sector between the 1940s and 1970s allowed for a recognised and resilient industry to develop. Archaeo-geophysical practices were established from the early 1970s, with the value to the wider archaeological sector becoming understood. There are of course many improvements we continue to make to our processes, but one of the distinguishing features of the use in archaeological geophysics in England is the framework of standards and guidance available, alongside the sheer volume of geophysical data collected by the commercial sector. Indeed, this is demonstrated by how the EAC guidelines adopted the majority of *Geophysical Survey in Archaeological Field Evaluation* (2008) for wider use throughout Europe.

Innovation within archaeological geophysics needs an environment in which it is encouraged, and experimentation is not only permissible but encouraged to sustain development. It is the responsibility of the geophysical sector to ensure that non-practitioners, whether professional or community based, are engaged and educated in the value and limitations of all forms of geophysical survey. We also need mechanisms to share good practice in an open and transparent manner. As demonstrated, England's archaeological geophysical community is hard to detach not only from the U.K., but from the European community. It is through the global collaboration of archaeological geophysicists that we have developed our profession as significantly and rapidly over the past 75 years. The discipline continues to combine efforts to advance archaeological geophysical practice to better understand and protect our heritage.

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Part IX
France

Variety in Archaeo-Geophysics: The French Example

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Abstract As a result of a long history in both archaeology and geophysics, France exhibits a wide panel of practices in archaeo-geophysics, going from archaeologists using geophysics as a supplementary tool for understanding their sites to applied geophysicists using archaeological sites as better constrained features and potential ground feedback. This chapter tries to scan this variety in the practices which overlap

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with a variety of contexts. After a brief overview of the backgrounds which control the practices in France, we show several examples that illustrate this diversity. Firstly, we will show a set of surveys of rural areas coming from both public and private institutions. Secondly, we will present how archaeological sites in urban areas are assessed with the geophysical techniques. Thirdly, we will address what can be done in what we define as the “specific” context. In each context, we will highlight how geophysical techniques could improve itselves with the help of archaeological sites took as the place for an intensive interdisciplinary research. We conclude that archaeology can be a way to make geosciences progress by bringing together geology, soil science, geotechnics, geochemistry, and geophysics.

1 Introduction

Since the first geophysical prospecting carried out by C. Schlumberger in 1912 in Normandy, French geophysicists have acquired a wealth of experience in this field and its various applications, including archaeology (Hesse, 2000). This history combined with the variety of geoclimatic conditions in the country (oceanic or continental climatic conditions and from plain to mountain environments) have resulted in many different practices in various kinds of context. Our focus will be on the practices during the 2000–2020 period. Going from general purposes to examples, we will illustrate the diversity in the French archaeo-geophysics experience. We chose to sort the examples in three sets which have been obtained through some classification processes answering the following questions:

- What is the main objective of the archaeological study?
- Does a combination of geophysical methods in addition to other techniques allow to reach the objective?
- In which context do the studies take place?

Among the answers to each of these questions, the last one appears to us as the simplest path to outline this chapter. The distinction between rural and urban contexts is fundamental regarding the choice of geophysical methods. We added a third category which corresponds to “exotic” places and that we named the “specific” contexts. In each part we describe some specificity of each context and illustrate it with several cases, scanning some other axes of interest like innovations in geophysical methods, archaeological feedback and some state-of-the-art examples. These three parts are an attempt to overview the recent state of archaeo-geophysics in France, but firstly we will introduce the background in which it takes place.

2 French Archaeo-Geophysics Background

2.1 Short Reminder About the History of the Discipline

In term of archaeological practices, France can be distinguished amongst European countries by a very specific set of official rules. Archaeological and cultural heritage studies are indeed strictly regulated. In particular, there are two kinds of archaeology. The first, research archaeology ("archéologie programmée"), refers to all studies which take place on non-threatened sites. The second, development-led (rescue and/or preventive) archaeology ("archéologie préventive"), consists in gathering as much archaeological information and material as possible before the destruction of the site (mainly due to urban and land planning). In that latter, two phases are distinguished, the evaluation (only done by state institutions) and the excavation (open to competition). The last one occurs only if the first one appears to be sufficiently fruitful. Geophysical prospecting could intervene in both phases.

The early beginnings of archaeo-geophysics in France (during the 1960s and the 1970s) mostly concerned the research archaeology (Brézillon & Hesse, 1962; Burnez & Hesse, 1967; Tabbagh, 1971; Martinaud & Colmont, 1971). Even if the Afan (Association pour les fouilles archéologiques nationales, French association for archaeological excavation), predecessor of the Inrap (Institut national de recherches en archéologie préventive, the state organisation currently in charge of preventive archaeology), was created in 1978, the question of archaeo-geophysics in the context of rescue archaeology was not really posed until the 1990s (Dabas et al., 1994; Dabas, 1999b; Ducomet & Druelle, 1996; Marmet, 2000).

This fact did not impede the technical development effort achieved during the preceding decades. It permitted to enhance the abilities of geophysical methods to quickly study wide areas using wide mesh prospecting (Dabas, 1999a; Marmet, 2000) or towed devices (Hesse et al., 1986; Dabas et al., 1994). Those advancements made application of the geophysical survey in the preventive context more affordable.

The first decade of the twenty-first century saw a transitional period in which all the actors (institutional and private) were trying to find their place. Many misunderstandings occurred, where archaeo-geophysics was considered as a real threat by some archaeologists and authorities in the preventive context (Demoule, 2014). Around the year 2010, the situation appeared to normalise. This is well illustrated by the prospecting over a large scale planned facility, a channel linking the Seine River to the Northern part of France, the Canal Seine-Nord-Europe, CSNE (Hulin et al., 2014). The approach adopted on this huge project, in addition to a PhD work (Simon, 2012) in the Alsace region, both demonstrated the limits of geophysics but at the same time these works revealed the high consistency of the use of archaeo-geophysics during the excavation phase (Hulin & Simon, 2012; Hulin et al., 2018). These works permitted to ease the tenses about geophysics and, nowadays, archaeo-geophysics appears as a tool at the disposal of the archaeologist in both preventive and research archaeology (Hulin & Simon, 2019).

2.2 Historical Highlight: Geophysical Studies Over Large Projects

If we define a large project by as one covering more than 10 ha prospected during one campaign, the first prospecting attempts were carried out, in France, on the A77 motorway project, in 1995 by the Terra Nova company. This manual survey showed that preservation of archaeological sites could rely on geophysical information and not only on direct observations in test trenches: as a consequence, a modification of the motorway route was chosen in order to avoid an important archaeological site that was only partially excavated afterwards. For the first time also, a project was managed by a GIS (Grass and Idrisi) and prediction maps of the risk of erosion/filling of potential sites using soil maps were produced (Chazaly & Dabas, 1997; Dabas, 1999b). Another consequence was the introduction of magnetic susceptibility measurements as a proxy for detection of archaeological sites for other motorways projects in France (A89, A20 and A66) even if it was shown that soil processes were also interfering with the magnetic enhancement measured over archaeological structures (Marmet, 2000).

In 2001, the Géocarta company (a spin-off from the CNRS) began the design of motorised mapping systems for precision agriculture, and specifically electrical mapping (ARP for detail, see Sect. 3.2). Then, similar motorised systems were designed for archaeology using array of magnetic sensors (AMP in 2006) and multi-coil EM sensors (EMP). The first archaeological appraisal for large development projects began in 2006. Over the next ten years, more than ten large-scale projects were undertaken, most of which correspond to development projects (ZAC) or linear infrastructures.

In 2011, the RTE project (Electricity Transmission Network) aimed at burying a high voltage electrical cable along a 22 km route. Beside a large impact for local farmers, geotechnical and soil hazards are considered to be high (presence of voids and artefacts from First World War—trenches and UXO). Archaeology was not really considered, and, due to the small dimensions of the trench (1 m wide), no archaeological appraisal was prescribed. Nevertheless, it was decided to survey a much wider swath of 100 m for detection of archaeological sites. Beside the standard ARP and AMP methods, multi-coil electromagnetic induction (EMI) mapping (using a DualEM421 system) was carried out in order to reach larger investigation depths (6 m). Resistivity maps made it possible to detect many artefacts linked to this battle zone (trenches, bomb impacts, access roads) and many pyrotechnic elements were found. None of these elements gave rise to an archaeological excavation given the very low impact of the burial trench. The final route was defined inside the 100-meter zone, considering all the information from the geophysics. In addition, it should be emphasised that the acceptance of the project by farmers was favoured by the production of soil maps derived from resistivity to improve yields.

2.3 Environmental Background

In Europe, France is one of the countries with more than three biogeographical units over a significant part of its territory (EEA biogeographical region map 2017). These units are defined to reflect the climatic and floristic homogeneity. Pedological maps (Gis Sol, Les sols dominants de France métropolitaine, 2011; Gis Sol, 2011) are another way to illustrate the variety of contexts which can be found in France. The combination of all these facts makes the design of archaeological prospecting complex. Thus, some regional/local expertise is required to correctly define the type of geophysical method to be implemented. In addition, changes in the land-use management defines which kind of area would be investigated by archaeologists especially in preventive context.

In the last decade, according to the French central agency for sustainable development (Commissariat Général au Développement Durable, 2015), the Corine land-cover index on land use exhibits changes inside and outside its major groups. This index is categorised in five major groups: artificialised surfaces, agricultural areas, forested and semi natural areas, wetlands, and waters bodies. If we gather the last three ones under the same label, it appears that these categories partially correspond to the ones that make sense for the geophysical methods implementation i.e. rural, urban and specific (this last category corresponding to surveys pushing the methods we use at their limits see Sect. 5 for more detail). We will use these as the main scheme for the following parts. The Commissariat Général au Développement Durable report (2015) mentions two key points: firstly, there is an increase of nearly 13% of the artificialised surface (350 kha) between 2000 and 2012. Secondly, one third of the artificialised surfaces which exhibit a change of land use between 2006 and 2012 were already artificialised in 2006. If archaeogeophysical surveys follow these trends, thus the ratio of surveys in preventive archaeology should be around 2/3 for rural context and 1/3 for urban context.

2.4 Trends in Archaeo-Geophysics Between 2000 and 2020

For this purpose, we built a database gathering as many surveys by as many teams as possible. More than 1100 surveys other the past 25 years were collected. Table 1 sum up the various entities which have contributed.

For this study, we limited ourselves to metropolitan France surveys and to ground measurements. We chose the year 2000 as a starting point, for two main reasons:

– The selective availability for the use of the GPS signal came to its end, allowing the survey of wide areas with a more accurate positioning and faster data acquisitions.
– The digital technology became extremely cheap, increasing greatly the size of the recordings.

Table 1 Number of surveys in the database by contributors

Data provider	Terra Nova Geocarta	Inrap	Universities[a]	Other teams[b]
Period covered	1995–2020	2002–2020	2005–2020	2009–2020
Number of surveys	466	265	290	155

[a]Including Université de la Rochelle, Université de Strasbourg, Sorbonne Université (formerly UPMC)
[b]Including companies such as AGC, PZP, SOT…

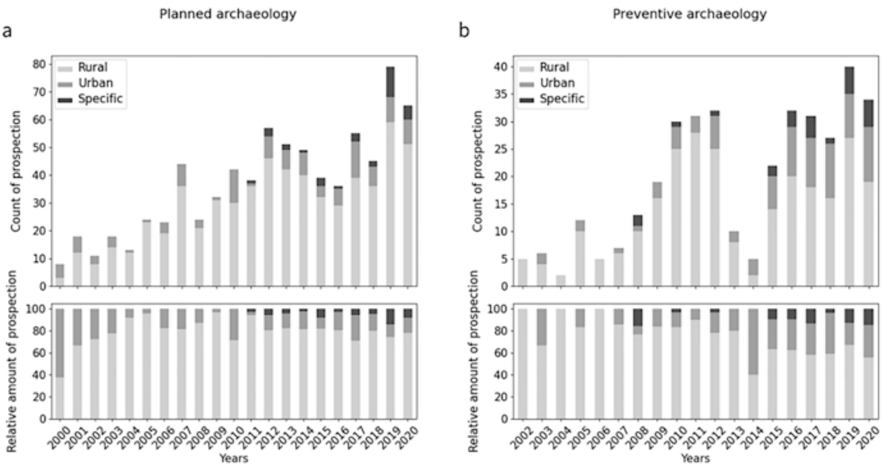

Fig. 1 Number of surveys in each context over the period from 2000 to 2020 (**a**) in research context, (**b**) in preventive context

Both above-mentioned elements allowed a great enhancement in the quality of the geophysical dataset obtained independently of the scale of the study. In addition, the 2001 law for preventive archaeology was adopted and Inrap was created. This French specific scheme had huge implication on archaeological policy.

Considering the diversity of actors, we decided to focus on the following elements:

- year of the survey
- surface covered
- geophysical method used
- context of the study (rural, urban, specific)
- type of archaeological context (preventive or research)

The first graph (Fig. 1) shows the evolution of the number of surveys by context since 2000. Most of them were done in rural context, though it is noticeable that the urban context is present from the beginning of the period too. Specific area surveys appear mostly in the late 2000s with no explanation (maybe due to the limited number of surveys between 2000 and 2005).

First the rural context is almost four fifths of the planned activity (Fig. 1a). In preventive archaeology (Fig. 1b), it appears that the number of surveys reached a plateau of about 30 surveys by year (with a marked decrease between 2012 and 2015 due to the combination of several factors (end of the CSNE project, end of the F.-X. Simon PhD, the “mesure 14” (Fichet de Clairfontaine, 2014), etc.) after an increase in the first year of the 2000s. In both preventive and planned archaeology, it also seems that the number of surveys in urban context is slightly increasing in proportion, mainly in preventive archaeology. It could be added that preventive surveys account for a third of the surveys done each year. Last point, the ratio urban over rural surveys in preventive archaeology seems to be around one third as expected according to the Corine landcover index.

Fig. 2a shows the number of surveys belonging to one of the three surface classes. Each category was defined according to the tertiles of the surface of our dataset (in the dataset, ‘small’ means an area under 3510 m^2 and include profiles, ‘intermediate’ means areas between 3510 m^2 and 20,000 m^2 and ‘large’ means areas above 20,000 m^2). This graph clearly shows that in the early 2000s the ‘intermediate’ areas were the most numerous in the surveys. After that, boosted by the instrumental improvements, the ‘large’ areas saw a fast increase and certainly, some surveys which would have been scattered in ‘small’ or ‘intermediate’ if manually handled were then done as one. After 2014, the ‘small’ surveys numbers increase slightly. It is very interesting to point out that in the last years, each kind of surface class was around one third of the total amount.

This overall trend can be explained by a combination of factors. In rural context, the ‘large’ areas are prominent while the ‘intermediate’ and the ‘small’ ones are more representative of the urban and specific contexts. As for the methods used (Fig. 2b), the classical methods (electrical resistivity and magnetometry) dominate. EMI proportion slightly decreases as the size of the area prospected increase. Ground penetrating radar (GPR) has a specific pattern being much less used in large

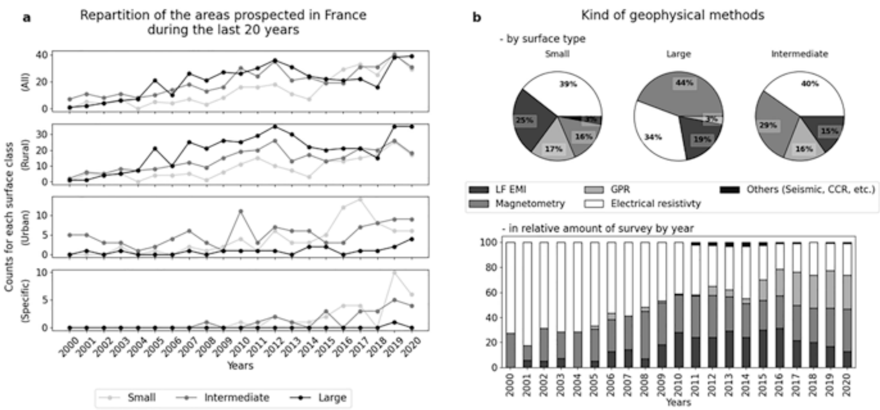

Fig. 2 Repartition of the surveys: (**a**) by type of surface and context; (**b**) by geophysical method and type of surface

areas. “Exotics” methods appear to be done over small areas which is consistent with their use for specific issues.

3 Geophysics in Rural Context

3.1 General Overview

The simplest conditions for the implementation of geophysical survey are best encountered in rural or open areas: these environments are easy to access and allow correct positioning using high precision GNSS systems. The use of towed systems for large areas and almost all geophysical methods can be implemented. In addition, these contexts are generally characterised by a lower level of ambient (mechanic and electromagnetic) noise and a limited number of metallic objects in the vicinity of geophysical sensors. For all these reasons, surveys in rural contexts still represent a significant part of the archaeo-geophysical ones undertaken in France, with 879 studies recorded between 2000 and 2020.

Despite all these advantages, some limitations should be noted. For example, the use of manure leads to soil properties modifications or entails modern metallic pieces (Dabas et al., 2021), plant sizes (vineyards, orchards), drainage and others artificial features which may impede the use of several methods (Simon et al., 2021). As soon as the soil is ploughed or harrowed, a very high degree of heterogeneity of the surface horizon can be observed, which can both prevent the use of the equipment and generate significant noise levels. France is a country with a highly intensive agricultural level and these issues are omnipresent for geophysical survey planning. Erosion issues due to agriculture should also be mentioned because it could seriously affect the archaeological remains preservation and the ability to detect them by geophysical means. As mentioned in the introduction, the variability of soil cover and climatic area on a national scale, have an impact both on the methods that could be used and the types of archaeological features we are looking for. A survey in south-eastern France on a Neolithic settlement will be different from the one of a settlement of the same period in North of France. Thus, it appears irrelevant to comment on the effectiveness of any method in France because there is no rule of the thumb about the method that could work in any given context. Therefore, and apart from specific contexts like mountain ranges and swampy areas, which will be discussed in Sect. 5, the use of several methods must be evaluated. Depending on the conditions, geophysics can be very ineffective, whatever the method. The use of towed systems makes it possible to cover large areas but also to acquire data sets with stable systems. By a combination of a GNSS system with accurate positioning, it is possible to reveal very small archaeological features when contrasts of geophysical properties are high enough. In France, these towed systems concern all geophysical methods (magnetometry, electrical resistivity, GPR and EMI) with notably the development of towed resistivity systems.

3.2 Methodology Highlight: Towed Electrical Resistivity Measurements Systems

In the middle of the 1960, a team led by Albert Hesse worked on the idea of a continuous electrical resistivity measurement for field surveying. The idea was to overcome the main limitation of the electrical resistivity measurements which requires to drive the array manually. Two major difficulties have to be overcome, the contact between the ground and the moving electrodes and a short duration measurement compatible with the motion of the array. The first efficient system was called RATEAU (Résistivimètre Auto-Tracté à Enregistrement AUtomatique, towed resistivity meter with automatic recording) and its specific electronics made the measurement of electrical resistivity possible while moving (Hesse et al., 1986; Dabas et al., 1989). Since this first version, the need to take measurements at several depths of investigation has led to a multi-electrode system, called Multi-depth Continuous Electrical Profiling (MuCEP, Dabas et al., 1994, Panissod et al., 1997). This system, first developed at the Geophysical Research Center of Garchy (later included in the UMR7619 Paris VI, Sisyphe/METIS) uses a specific geometry with electrodes arranged in a 'V' shaped array hence its first name of "duck flight" geometry.

The system consists of four axles, each made up with two spiked wheel electrodes. The first axle is the transmitter one. The other three axles are for measurements. According to modelling, it was shown that their distances to the injection dipole correspond more or less to the depth of investigation of each channel (Panissod et al., 1997).

In the early 2000s, the ARP system (Automatic Resistivity Profiling, Geocarta, Paris), derived from this previous development (Dabas, 2008), coupled absolute positioning information (RTK-type dGPS) with relative positioning (Doppler radar), liberating from any prior topography. This device therefore combines the advantages of continuous electrical profiling, a limited three points vertical electrical sounding (VES) and overall allows prospecting around 4 ha (up to 10 ha maximum) per day with an infra-metric spatial resolution. The distance between the profiles can be of the order of one meter at most. The measurements are sampled approximately every 10 cm along the profiles. The entire system is controlled in real time by a specific Geographic Information System (GIS).

We may point out that ploughing, or even stubble cultivation, pose the problem of moving machinery over this type of land and a change of soil density (introducing unwanted increases in resistivity). The combination of this techniques with magnetometry will be illustrated by the first example, the study of Fontaine-les-Bassets. The second example will be about the use of EMI electrical conductivity prospecting on the case of the autonomous port of Dunkerque. The third example is excavation feedback on the site of Longvic.

3.3 Combination of Magnetometer and Electrical Resistivity Survey: The Fontaine les Bassets Site

Identified in 1989 by aerial photography, the site of Fontaine les Bassets corresponds to a large Roman settlement which was not excavated at that time. In 2009, the archaeologist decided to jointly use three non-destructive prospecting methods: aerial, walkover, and geophysics in order to define the limits of this city and its internal structure. One of the objectives was to establish possible areas for archaeological excavations (Quévillon, 2012).

Like many other experiments carried out on similar sites (Le Vieil-Evreux: Dabas et al., 2005; Mandeure-Mathay: Thivet et al., 2009; Les Tours-Mirandes: Dieudonné-Glad, 2010), the electrical towed system ARP was chosen for its speed of acquisition and according to the types of structures sought. Electrical resistivity survey was carried out in three campaigns. As it is often the case, the first mission (6 ha in 2009) was carried out on the main aerial evidence showing a possible forum, streets, and a dense settlement. It allowed to validate the use of this method, all the built-up elements appearing as resistant anomalies with a strong contrast compared to the surrounding (ratio of about 1 in 7 for a background resistivity at 100 Ω.m). The missions of 2010 (14 ha) and 2012 (8 ha) made it possible to map the rest of the plots (Fig. 3a). All the anomalies appear in the first ARP channel (0 to 0.5 m) showing a superficial origin of the structures, which can also be corroborated by the fact that the cropmarks were clearly defined. Linear resistant anomalies could correspond to the ancient street network: four main axes oriented north-east/south-west as well as two north-west/south-east axes divide the urban space into irregular blocks. Within or bordering these blocks are some anomalies which can correspond to large buildings and others of more modest sizes. The density within each of the blocks is very different, showing a well-characterised central area around a quadrangular resistive anomaly which could be associated with a central square/religious complex. In addition, 200 m to the East, a semi-circular feature probably associated to a theatre is detected. The majority of anomalies were resistant, as is the usual case for features made of stone. Nevertheless, there were linear or punctual anomalies, in particular in the Southwest quarter of the plot, showing the existence of structures of a different nature, perhaps related to a small remains of ironwork material such as slag (identified during the walkover survey).

Finally, in 2014, a magnetometer survey (3 ha) was decided to provide additional information on the two main buildings (square and theatre) and the area between them (Fig. 3b). As is often the case with the anomalies associated with a magnetic gradient measurement, these are of shorter spatial wavelength than in electrical resistivity prospecting and therefore allow better definition of the structural limits. But a more in-depth study of the anomalies shows a larger number of electrical anomalies, in particular for the street network, which is not very visible in the results of the magnetometer survey.

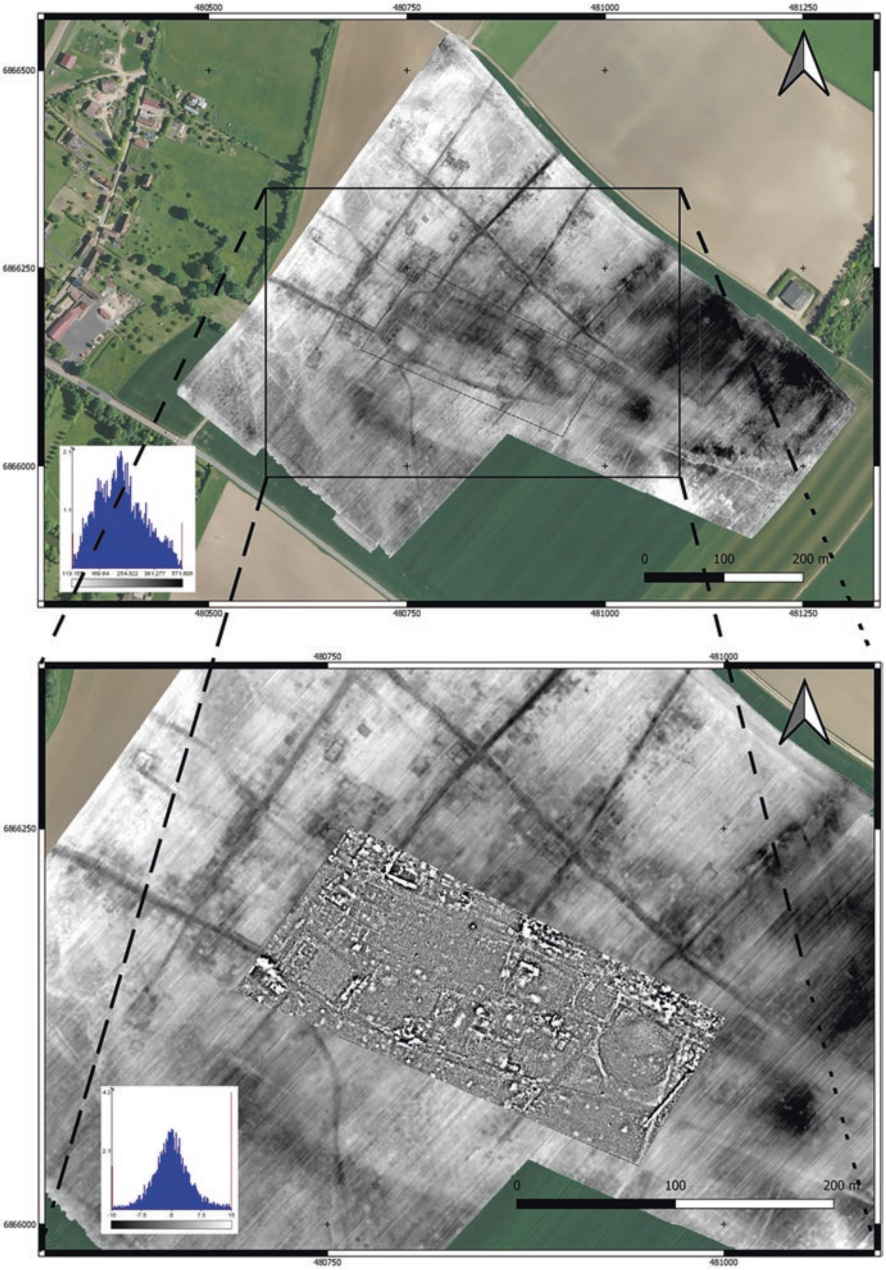

Fig. 3 Results of the prospection at Fontaine-les-Bassets. (**a**) 28 ha electrical resistivity ARP survey (113 to 571 Ω.m)—channel 1 (0 to 0.5 m) overlaid over orthophotograph (Bing Aerial Map), (**b**) 3 ha magnetometer survey (−15 to 15 nT/m) overlaying the ARP data

3.4 Geomorphological Study of the Dunkerque Autonomous Port

When the main objective is not to map the remains of a site but mostly reconstruct its landscape, the use of geophysical methods has been clearly proven to be efficient for decades (Castanet et al., 2015). Such a survey can be used as on its own and in the context of preventive archaeology. In that case, it allows to spatialise geomorphological features, which have been studied by the geomorphologist on a case-by-case basis and make it possible to go beyond the sampled vision of trench surveys.

This study, part of the extension of the autonomous port of Dunkerque, is a good illustration of this contribution. In this sector, an initial EMI survey was carried out in 2015 with an EM31 (Geonics Ltd) on a surface of 56 ha. It highlighted the interest of the EMI method for geomorphological applications on this coastal plain. This first campaign was followed by a survey carried out in the commune of Bourbourg as part of the same project. This second survey was carried out over two consecutive years in 2017 and 2018. During this time, approximately 180 ha were surveyed with profiles less than 10 m apart. The EM 31 was fixed on a trolley to facilitate its transport and was associated with a high precision GNSS positioning system. The results of the survey are shown in Fig. 4.

The strong contrasts between the filling of the clayey features and the sandy background enabled the visualisation of ancient channels, the detection of insulated conductivity anomalies and identification of the general shape of the palaeolandscape that is now filled in. Given the very loose sampling, these geophysical datasets did

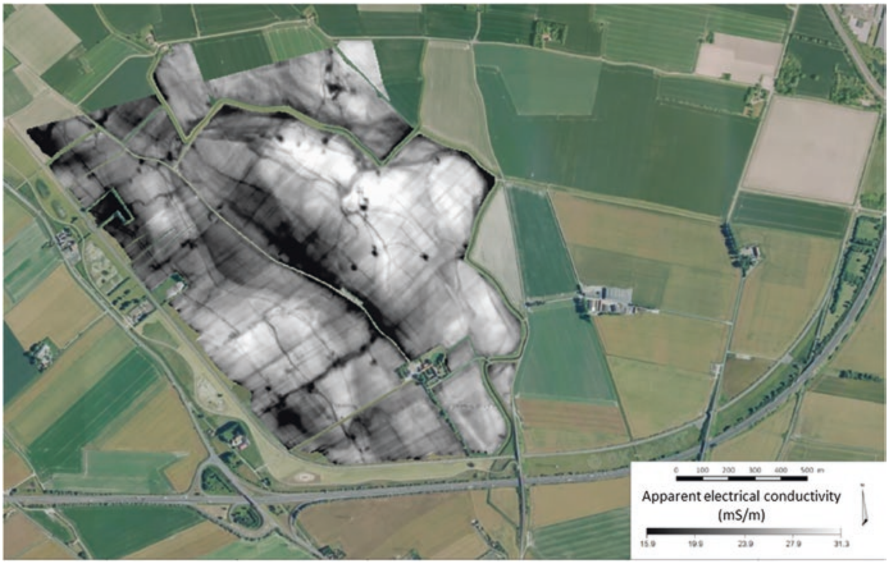

Fig. 4 Archaeological study of Bourbourg—Dunkerque autonomous port project, map of the apparent electrical conductivity (VCP mode)

not provide archaeologists with no precise evidence of human settlement. The very specific framework of this operation, as well as its annual scheduling, made it possible to plan the best time to intervene in the field.

Given the richness of the results, this type of survey was subsequently recommended by the local authorities to support the trial trenching and to provide the archaeologists with context setting maps of the remains. It also serves as a guide for geomorphological trenching, which allows the best possible targeting of the test pits and the documentation of the dynamics of sedimentary filling. The hindsight that is made possible by the multiplication of interventions in this sector has enabled the acquisition methods to evolve towards towed and multi-depth systems and to carry out cross-sections thanks to electromagnetic data inversions (Guillemoteau et al., 2019). Finally, in 2021, a total of 513 ha have been surveyed with EMI in this area to offer a global view of the palaeolandscape in correlation with archaeological features later found by trial trenching.

3.5 Excavation Feedback: The Longvic Magnetometer Survey

Excavation feedback is a great opportunity to confront geophysical data and interpretation. Due to the specific French legislative context concerning preventive archaeology, prospecting rural and open areas offer high potentiality of cross validating geophysical interpretation with archaeological feedbacks, especially during preventive excavation, even though it is currently under exploited. This cross-study of data sets enables to reflect on the undeniable difficulties encountered when geophysics is used as the only method of archaeological evaluation, but also to reconsider the interpretations. The example of the magnetometer survey on the archaeological site of Longvic illustrates this issue.

Following the discovery of a multi-phase site on a large area on the outskirts of Dijon during an archaeological field evaluation, a large-scale excavation was requested by the local authorities. Some sectors were tightly selected as a result of the trial trenching. However, other areas were designated as high potentiality but the extension and location of these evidences remained widely undefined. In order to constrain their location and to minimise unforeseen features during the excavations, a magnetometer survey was carried out over the whole set of areas to be excavated (i.e. approximately 7 ha).

Given the a priori knowledge on the nature of the soil, the land cover and the typology of the remains found in the previous step, an intervention plan was set up based on solid arguments. Magnetometry was first benchmarked over a representative test zone and, following the positive results, extended to the whole area. The map obtained made it possible to link the archaeological features observed in the various trenches to each other and to provide new clues on the potential presence of remains.

The Roman enclosure discovered during the archaeological evaluation was observed on the magnetometer survey map (Fig. 5a). Associated with this enclosure, numerous localised anomalies of medium to high amplitude could be observed and interpreted without ambiguity as archaeological pits. On the contrary, large blurry anomalies whose filling appeared to be heterogeneous were interpreted as natural features link to sedimentary features. The excavation did not validate the archaeological interpretation based on the geophysical maps. It was observed that the local anomalies corresponded to natural features (Fig. 5b), some shallow slumps in the substratum (an ancient alluvial terrace). The large and diffuse anomalies (Fig. 5c) arose from large anthropic developments with numerous storage pits that can be assessed on the geophysical data afterwards.

This feedback, allowed by the archaeological excavation, highlights all the ambiguity between archaeological features and geophysical anomalies despite optimal conditions of surveying. As the quality of the geophysical dataset on this type of site is good, cross and a posteriori analysis is possible. However, this case study invites us to always interpret geophysical data cautiously and to advocate, as soon as possible, a comparison with the excavation which allows to account for possible and unavoidable inconsistencies.

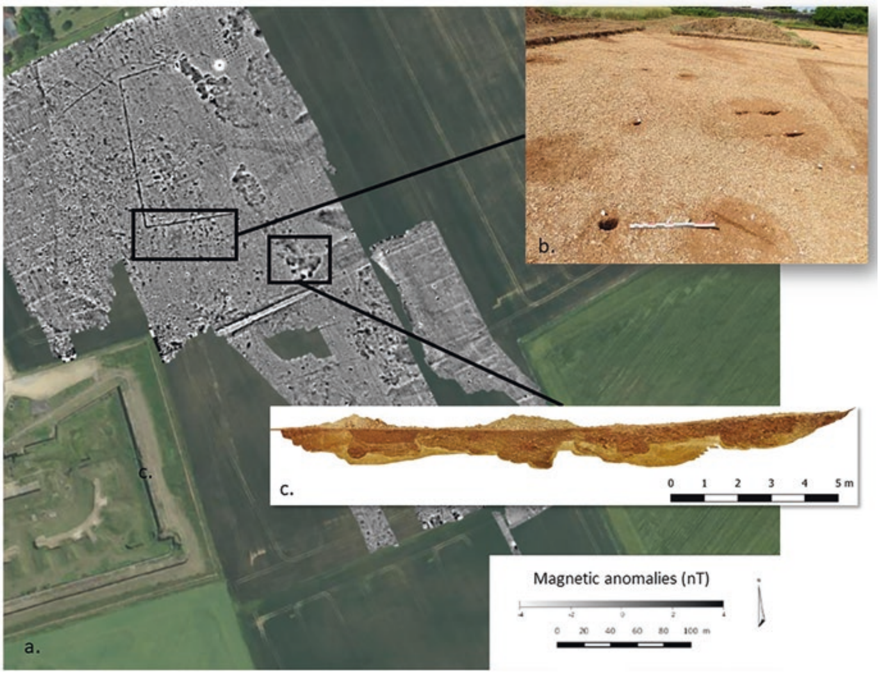

Fig. 5 Archaeological study of Longvic. (**a**) Magnetic anomalies map, (**b**) View of the shallow slumps in the gravel background (G. Videau, Inrap), (**c**) Stratigraphic section of the storage pits ensemble (G. Videau, Inrap)

4 Geophysics for Urban Archaeology

4.1 General Overview

Urban archaeology takes an increasingly important part in French archaeological research. The current trend in urban planning and the refocusing of development in town implies that preventive archaeological studies take place in city centre areas. Often associated with numerous constraints (accessibility, narrowness of the study areas, developed stratigraphy, backfill), urban archaeology more and more requires the support of alternative methods to strengthen their studies and among them geophysical methods play an important role. Indeed, our database includes 200 urban surveys.

For geophysics application, urban area presents a certain number of constraints. They are generally well known: presence of mechanical vibrations, electromagnetic noise, presence of infrastructures, urban furniture, pedestrians, cars obstructing the surface, presence of underground modern utilities, and most obviously, the presence of buildings and other superstructures which shatter the prospected area (e.g. Atanasova et al., 2014). These inconveniences combined to the heterogeneous state of the soil make it very challenging for the archaeogeophysicists.

Analysing the past of a city requires a wide approach based on iconographic, textual, geological and archaeological sources. Each of them could have their own timing and induce methodological biases. Geophysics, despite some constraints, has its own place in the evaluation workflow. The primary goals are mostly the determination of the density and the thickness of archaeological remains areas and/or the estimation of the stratigraphic sequence.

Results are often more complex to interpret in term of archaeological evidence than in rural areas and involves a collaborative work. In urban archaeology, more than elsewhere, the combination of all these approaches is necessary to develop reflection on a research area.

Depending on the project, several approaches on different scales can be carried out in an urban context, from the study at the city scale to recognize the ancient topography to more targeted studies at the scale of a plot allotment (Atanasova et al., 2014) or even a building (Bully et al., 2011). To deal with such issues, as in other countries, GPR is the most common method used in French urban archaeology. However, other techniques may be of interest such as the electrostatic method, also called capacitive coupled resistivity (CCR), highlighted below. This method is the counterpart of the DC electrical method and makes it possible to inject and measure current on hard ground by electrostatic poles. It is clearly complementary to the GPR method, especially for investigations over large areas or urban contexts (e.g. Dabas & Panissod, 1999). Other techniques, such as seismic methods have been used, on a more anecdotal basis, to image larger structures (e.g. in Thiesson et al., 2021 for defensive ditch).

4.2 Methodology Highlight: The Electrostatic Method with Capacitive Coupling (CCR)

The Capacitive Coupled Resistivity (CCR) or electrostatic method is certainly one particularity of current French research development. The electrical resistivity method is limited to areas where the probes or spiked wheels can be pinned in. Even if some examples of “wet” probes had been implemented successfully (Athanasiou et al., 2007), one idea to overcome this limitation is to use capacitive probes.

This development arose in the middle of the 1990s (Grard & Tabbagh, 1991; Tabbagh et al., 1993). As the geometry of the array could be similar to those used for electrical resistivity survey, it was considered at first as mean to extend the area which could be investigated using classical electrical resistivity mapping. The depth of investigation (about 10 m) is limited by the impedances of the pole (minimum operating frequency above 1 kHz) and the low induction number assumption (restricting both the maximum pole spacing and the maximum frequency). It makes this method very suitable for archaeological studies especially in the urban context (Dabas & Panissod, 1999). A significant number of studies has been achieved in monuments using this technique (e.g. Titus et al., 2001). Its combination with GPR techniques appears to be very informative as shown by the examples of Saint Germain Abbey (Sapin, 2000) or Saint-Étienne cathedral (Titus et al., 2001) both in Auxerre, the Gigny church vestibule (Bully et al., 2010) or more recently Notre-Dame de Paris (see Sect. 4.3 and Hulin et al., 2021a).

The CCR could also be adapted to evaluate the conditions of walls and identify stones (Souffaché et al., 2016) or to detect wall features hidden by surface dressing (Bully et al., 2010). One can imagine that this latter topic could be one leading development theme for this technique in future years in addition to GPR techniques (see Sect. 4.5 below).

Another development to consider is going beyond simple resistivity measurements. As the frequency can be varied and its effect is not negligible, it is necessary to take into account the polarisation phenomena to assess both the resistivity and the effective dielectric permittivity (Schamper et al., 2021; Tabbagh et al., 2021). Simultaneous measurements of several parameters could be of great interest especially in urban studies where the need for supplementary information is necessary to strengthen the interpretation.

The combination of CCR with GPR is illustrated by the first example in Notre-Dame de Paris Cathedral. As GPR is clearly the technique most adapted the urban context, the second example presents archaeological feedback on a small area in preventive archaeology. The third example shows the use of GPR indoor and belongs to the blurry limit between urban context and specific context.

4.3 Monuments Studies: The Notre-Dame de Paris Example

Geophysical survey inside buildings is an important field of application for French prospectors (Dabas et al., 2000). Requests are generally made when an excavation is difficult to carry out for obvious technical reasons. The archaeologist requires geophysics to gain insight into the study area. In France, these surveys mainly concern religious buildings, but also more atypical places such as cellars or crypts (Tabbagh et al., 2002; Bully et al., 2011). In this latter case, it is possible to get closer to the archaeological layers. “Underground” surveys represent a great opportunity for archaeologists to reach deep archaeological stratigraphic levels.

Implementation of geophysical prospection within inner areas is constrained. For instance, ground conditions such as metallic reinforcements in concrete or wooden floor with an air layer can make GPR measurement impossible.

An emblematic example is the recent study performed inside the Notre-Dame de Paris cathedral (Hulin et al., 2021a). Following the fire of 2019, the French Ministry of Culture requested the Inrap’s geophysics team to carry out a study of the cathedral’s floor. This survey was one among a wide panel of tools deployed to study the burnt cathedral. The objective of such a survey was twofold. Firstly, to take advantage of an empty cathedral to understand what was beneath the soil. Secondly, to anticipate possible restoration works affecting the near subsoil and the probable archaeological remains.

A dedicated methodology was implemented with three complementary interventions. First, a very high resolution GPR survey with a 3D-Radar step frequency multi-antenna (Fig. 6a). Then a GPR survey with a GSSI 350 MHz Hyperstacking antenna to investigate deeper anomalies. Finally, an electrostatic survey for measuring electrical resistivity and dielectric permittivity of the soil. For the electrostatic survey, the MP3 prototype (Fig. 6b; Flageul et al., 2013) from UMR METIS (Sorbonne Université, Paris) was used. The device has a V-shaped geometry and three different pole spacings (0.70/1.14/2 m).

This geophysical survey was carried out in a particular context requiring additional safety rules. First, a very high level of pollution from the hundreds of tons of incinerated lead from the roof and the spire had to be considered for the survey implementation and for the protection of persons and equipment. In addition, a large part of the cathedral (the nave and the transept) was totally restricted due to potential falls of building materials from the roof. These particular conditions required the geophysical devices to be adapted on a remote-controlled machine which performed the survey (Fig. 6a).

The combination of GPR and electrostatic surveys was successful and enhanced the knowledge of this emblematic monument. It has allowed us to recognise a poorly known service network and has also revealed totally unknown remains with notably a large wall in the northern side-aisle. GPR gives very detailed information about the near surface whereas electrostatic gives information about electrical resistivity distribution in the ground. In such a case, electrostatic can be considered as a GPR reliability map based on the information about soil conductivity.

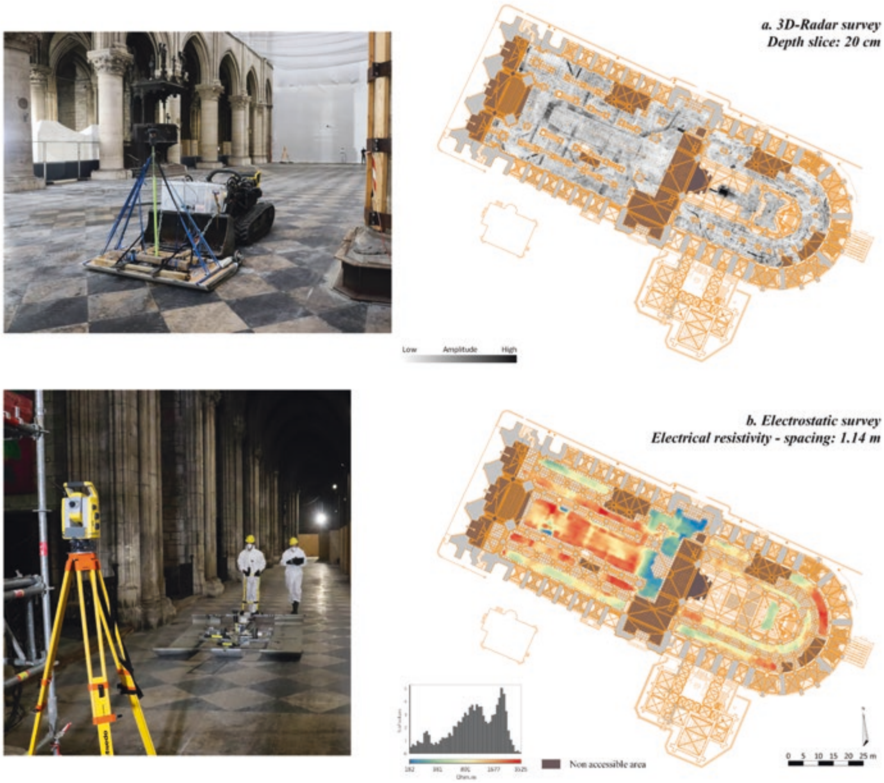

Fig. 6 The Notre-Dame de Paris Cathedral survey: (**a**). 3D-Radar towed with a remote-controlled machine and results; (**b**) the CCR survey device and results

4.4 Geophysical Studies Over Very Small Areas

In the context of urban archaeology, studies over limited areas constitute an important part of the surveys carried out these last years. The case study of the Notre-Dame car park project in Cherbourg is a good example of this kind of survey (Paez-Rezende & Hulin, 2021). The project covers a surface of approximately 5000 m^2 with significant urban infrastructures and furniture. The area was already excavated in the 1970s and many archaeological features were suspected on this area as a Roman castrum, a medieval castle, a church, and its cemetery. The prior knowledge indicates a potential stratigraphy of 4 m thick. As required by French laws, an archaeological evaluation based on trial trenching was done prior to the development of the car park. In addition to the trial trenching, a GPR survey was carried out as a preliminary.

The geological context, consisting of shale and sand, led to the choice of a GSSI 350 MHz Hyperstacking combined with a robotic total station for a real time positioning. The use of such device as an accurate replacement of GNSS constitute one of the main differences with open area studies for the positioning of geophysical data. GPR results are clearly reliable and give much information at different depths (Fig. 7a). Trial trenches were implemented according to the geophysical results to test archaeological features but also areas devoid of geophysical evidence (Fig. 7b, c).

In such a context, GPR data is clearly a valuable tool, as a complement to trenches and their limitations (size, underground utilities, traffic…). Walls corresponding to the medieval castle were clearly identified by GPR in perfect accordance with trial trenching results (Fig. 7b). More discreetly, the map of the medieval cemetery was expanded through punctual anomalies. These correspond to burials covered by slabs of schist (Fig. 7c). Burials without stones were not detected by GPR and are only identified by trial trenching. These latter correspond to the majority of the burials found on this site which shows the necessity of excavations to find this kind of artefacts. The back and forth between geophysical data and archaeological observations from trial trenching, based on the use of GIS tools allows to upgrade both approaches and provides a more exhaustive view of the archaeological context. For small to very small urban areas, this kind of approach is very efficient and need to be

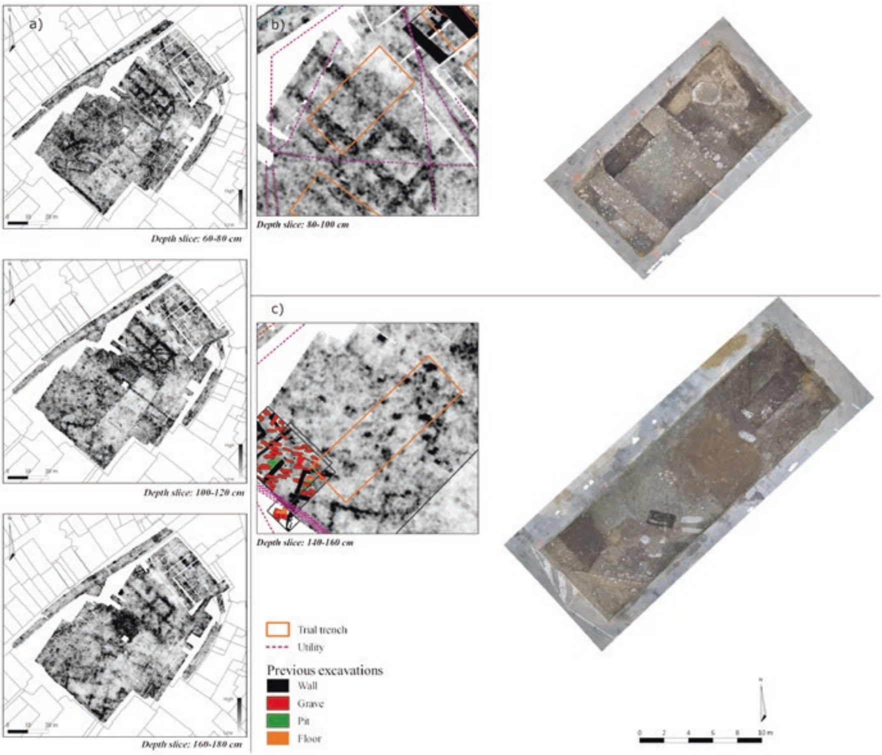

Fig. 7 Cherbourg-Notre-Dame car park: (**a**) GPR depth slices (**b**) GPR survey and orthophotograph of the excavation over the medieval castle (**c**) GPR survey and orthophotograph of the excavation over the cemetery

developed. However, it requires a close interaction between the archaeologist and the geophysicist and has to be wisely used, always combined with trial trenching.

4.5 Seeing in the Wall: The Commandery of Jalès Example

Among the approaches that are still underdeveloped in archaeological context, the auscultation of the walls of buildings is an important aspect that is mostly still in its infancy stage in France. The archaeology of buildings (grounds and walls) is also subject to the French preventive archaeology law. In fact, any change on the facade of an ancient building has to be preceded by an archaeological evaluation.

Many buildings walls have been covered with cement coating and are therefore no longer accessible to archaeologists. A destructive process of staking out the coating is then carried on an ad hoc basis to assess the archaeological potential on a few test areas. Very high frequency radar antennae (>1 GHz) can be used to answer much-localised questions by imaging a filled-in opening in the wall, a particular stone arrangement and so on. As for ground surveys, positioning the geophysical data by a robotic total station can greatly improve the quality of the survey (Benech et al., 2021; Hulin et al., 2021b).

The case of the commandery of Jalès is a significant illustration of the kind of information provide by a GPR survey for the archaeological study of buildings. The commandery was founded by the Templar order during the twelfth century and has been continuously occupied since then. The study of the outer face of the walls revealed different phases of construction, especially during the twelfth, fourteenth, and eighteenth centuries. The inner faces of the same walls are mostly plastered, and it was difficult to gather more information about the inner evolution of the building without geophysics. The survey of these walls was carried out with a pulseEKKO® Pro system (Sensors & Software) associated with a TR1000 antenna (centre frequency of 1 GHz) which allows an investigation depth of around 1 m (Fig. 8a). The walls were surveyed in both vertical and horizontal direction using a grid mesh of 5 cm.

The results obtained on different inner walls of the commandery appeared to be complementary with the building study: the GPR image brought significant information about the different phases of the walls, revealing reinforcements or reconstructions not visible from outside, as well as architectural elements of the earliest phases of the building like arches, sealed windows, or heterogeneities in the use of building materials (Fig. 8b).

This experimentation showed how useful can be such survey for the building studies, even if the walls are not plastered. Such an approach provides supplementary details on the different phases of construction and/or reconstruction of the walls to the traditional building architectural studies.

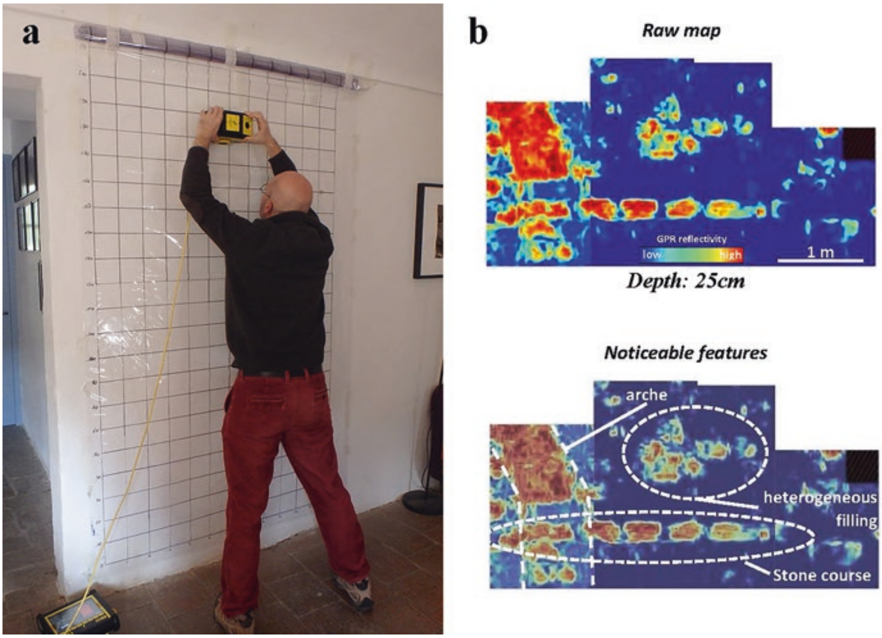

Fig. 8 Example of GPR wall diagnostic on the commandery of Jalès (Ardèche, France) a GPR setup using a pulse EKKO PRO TR1000 with a grid mesh of 0.05 m, b Result showing traces of an arch appearing 0.25 cm-deep inside the wall

5 "Tailor-Made" Prospections in Specific Contexts

5.1 General Overview

Beside of the rural and urban context, which represent most of the cases in archaeo-geophysics, a third category, accounting for 56 surveys in the database, is explained in this section. What we are calling 'specific' is any context (including environment and people involved) which bring us to consider a prospection pushing the limits of the methods we use.

In France, this kind of work is almost done by research teams because it requires some special designs which cannot be automated thus, they are not cost effective in time or/and in money. We gather under this cap studies taking place in challenging environments such as:

- indoor (in caves or building)
- in a humid context (coastal or wetland)
- in mountainous areas
- in forested areas.
- on stripped areas

Some of these contexts overlap with both previous ones, it is an illustration of the limitations of our classification. For example, the studies of stripped areas are undertaken in urban or rural context. Nonetheless, they need very strong interaction and high reactivity from both the archaeologist and the geophysicist which make it occurs rarely outside "specific" context.

Areas covered in this kind of studies are usually small (less than 1 ha). All geophysical methods could be used in this category on the condition that they can afford manual handling. The archaeological context of such studies goes from prehistoric sites with tenuous clues of human activities like these presented below to ancient mining facilities (e.g. Florsch et al., 2011, 2012, 2017). In these kinds of studies, the measurements of several parameters could be crucial.

The studies of salty wetlands, such as the numerous marshes along the French coast, which also present a strong archaeological potential are another good example. These environments can correspond to agricultural meadows, but also to more hostile environments such as wastelands sometimes covered with brackish water and often very vast and difficult to access.

It is necessary to define a protocol allowing to cover the whole area in spite of the difficulties related to the environment. This is most often done with a combination of several techniques. The most common set up is a wide mesh mapping used to detect areas of interest then more detailed studies on the spot chosen. Such an approach was used on the La Perroche marsh to study the physical environment of a prehistoric site (Laporte et al., 2009; Clavé-Papion et al., 2009). It has also been successfully followed for the research of ancient port installations, both on the Mediterranean (Mathé et al., 2016, 2018) and Atlantic coasts (Mathé et al., 2012, 2020).

It should be noticed that the EMI devices are a good candidate for these kinds of studies because they can measure two to more parameters simultaneously.

5.2 Methodology Highlight: (Electro)Magnetic Signal Measurements

EMI survey is mainly used to measure the electrical conductivity of soils often on large area as its acquisition time is fast and no contact between the soil and the device is required (e.g. in Sect. 2 Rural context). Nonetheless, this is only a small part of what can be assess with these methods.

Since the seminal works of Aitken, Colani, Tite and Mullins in the late 1960s (Colani & Aitken, 1966; Tite & Mullins, 1971), EMI devices are identified as sensitive to magnetic properties in addition to conductivity. In fact, Tabbagh (1974, 1986) demonstrated the conditions under which electrical conductivity and magnetic susceptibility responses can be separated.

Although devices with high quality phase detection are now available, the calibration of in-phase measurements is still challenging (Thiesson et al., 2014; De Smedt et al., 2013; Delefortrie et al., 2014, 2018) and the additional handling it requires can drastically slow down the survey. Nonetheless, after this step of calibration, the electromagnetic signal can be considered as robust and allows further processing. For example, it is possible to combine magnetic and EMI measurements to assess the remnant part of the magnetisation or to map the magnetic viscosity which allows some consideration about magnetic grain size distribution (Benech et al., 2002; Thiesson et al., 2007; Pétronille et al., 2010; Simon et al., 2012).

For approximately 20 years now, multi-spacing loop-loop systems have allowed geophysicists to work on the inversion process. 1D solution is now commonly used by the geophysical community, but this advanced processing is barely used for archaeological studies (Guérin et al., 1996; Brinon et al., 2012). These multi-spacing instruments also allow the 3D inversion of magnetic susceptibility in the frequency domain (Thiesson et al., 2017b; Guillemoteau et al., 2019). This last solution is particularly interesting for archaeological prospection as the magnetic contrast of the archaeological features is greater than electrical conductivity ones. This recent advance need now to be applied more often and associated with robust calibration procedure.

EMI prospecting, like CCR and Spectral Induced Polarisation methods, has the potential to go beyond simple measurement of electrical resistivity, and goes a step further by potentially assessing both magnetic properties (susceptibility and viscosity, Simon et al., 2015) and both electrical properties (conductivity and permittivity, Simon et al., 2019). The first step was achieved with multi-spacing, orientation or frequencies devices and has given some encouraging results (Benech et al., 2016; Thiesson et al., 2017a; Simon et al., 2019). Finally, the aim is to improve the EMI method beyond its frontiers combining measurements to propose apparent properties map which could be used for defining geophysical typology to be compared to archaeological or pedological ones (Thiesson et al., 2017b; Tabbagh et al., 2021).

The first example of this section is an illustration of the use of magnetic susceptibility measurements on a stripped surface. The second example concerns combination of geophysics and geotechnics to access the thickness of a sediment in a cave. The last example deals with coastal prospecting and its specific limitations.

5.3 Recognising and Characterising Anthropogenic Phenomena on a Stripped Surface

Geophysics can be implemented directly on a stripped surface during an excavation (e.g. David et al., 2003). This approach has been largely systematised for the first time in north of France, on the CSNE project (Hulin et al., 2012) followed by applications in Alsace (Simon, 2012; Simon et al., 2012). The objective here is different as it concerns the characterisation of soil levels and archaeological structures.

This characterisation is mainly based on magnetic parameters. It is indeed known that some human activities can modify the content and composition of iron oxides in soils and, consequently, their magnetic properties. These include heating, iron working and, to a lesser extent, organic matter (Le Borgne, 1955, 1960, 1965;

Aitken, 1958; Tite & Mullins, 1971; Marmet, 2000). Thus, the measurement of parameters such as magnetic susceptibility or magnetic viscosity can provide valuable clues to these different man-made phenomena. This magnetic characterisation is then added to the observations made by the archaeologist in the field, thus allowing a better understanding of all or parts of the site.

As the measurements are taken on a stripped surface, the removal of the topsoil gives two main advantages. On the one hand, it offers the possibility to get closer to the archaeological levels, hence obtaining a stronger geophysical signal. On the other hand, it makes it possible to get rid of an important source of magnetic noise generated by the heterogeneity of the shallower horizon (ploughed layer with out of place objects for example). The measurements carried out on a stripped surface are less noisy and have a higher dynamic for the signal of archaeological origin. Finer variations are more likely to be detected especially those which have left no visible traces on the ground. These are known as magnetic ghosts (Linford, 2004; Fröhlich et al., 2005; Hulin et al., 2012; Simon et al., 2012).

One of the most relevant applications is undoubtedly the detection of iron working areas like on the site of Sauchy-Lestrée which is particularly representative. After topsoil stripping, there was no indication of the presence of an iron working area. However, the magnetic susceptibility study revealed the presence of a well-shaped anomaly on the stripped surface directly on the soil considered as natural (Fig. 9a). Clear boundaries are present and can be interpreted as wall effects which are to be related to the archaeological plan.

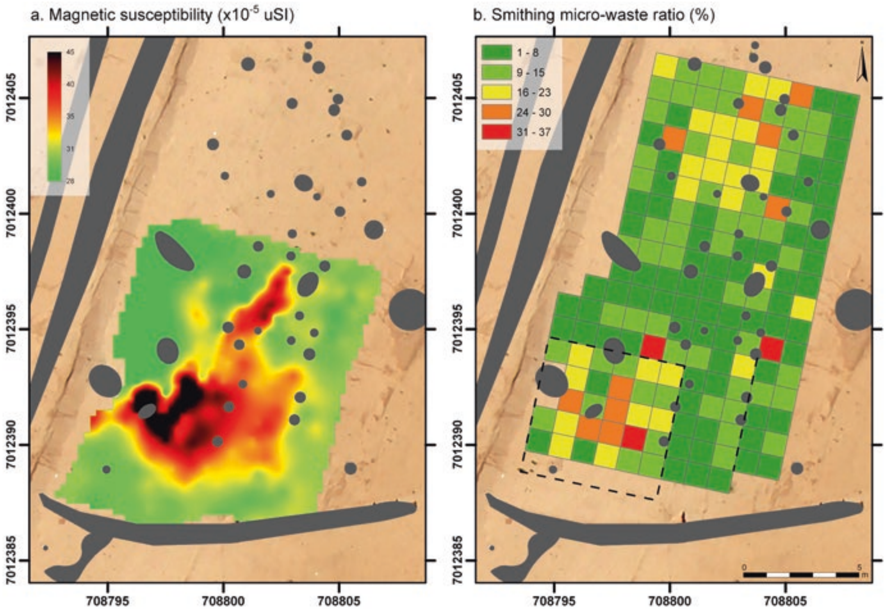

Fig. 9 Sauchy-Lestrée: Results of the survey over the stripped surface (**a**) magnetic susceptibility survey with MS2D (**b**) Smithing micro waste in proportion

Based on this detection, a grid was set up to take samples. Once processed, all the samples showed only a small proportion of magnetic elements per square, which can be explained by the high erosion level of the site. This corresponds to a "pollution" from the iron waste that has migrated to the depths due to bioturbation phenomena. Despite the erosion, there is a strong correlation between the micro-waste map and the geophysical map (Fig. 9b). In some places, the results diverge somewhat. Some relatively magnetic squares do not show high proportions of micro-waste. The heating hypothesis is therefore to be considered in this case. At the location where the high susceptibilities are correlated with high proportions of magnetic elements, microscopic observation has allowed the presence of typical hammerscales to be detected.

These observations give a first global picture of the organisation of the smithy which could be dated to the first half of the first century BC. Thus, the space where the metal was struck seems to be in the south-western part of the area, where one pit could have served as an anchoring point for the anvil. The mapping carried out after the treatment of the sediments also made it possible to observe an extension of the wall effects detected during the geophysical study and thus to provide a better knowledge of the forge building. The continuity of the latter can be observed towards the north-east where a second space with a concentration of magnetic elements—which was not detected during the geophysical prospection—seems to exist (Hulin et al., 2014).

This approach is now well implemented in preventive archaeology in the Inrap where it corresponds to 30% of studies carried out over during the last 5 years. The widespread use of this type of approach over the last 10 years has considerably renewed our knowledge of iron working areas, about large workshops and even more on smaller ones which have left particularly tenuous traces that are particularly difficult to observe visually.

5.4 Prospecting Prehistoric Environment Undercover

Caves and rock shelters are natural environments that people have used since prehistoric times, but also in more recent periods. Regarding the consequent number of open-air occupations, these sites are rare and are the object of reinforced conservation measures. This is particularly true in the presence of rock art. Therefore, the study of these sites by non-invasive methods is of great interest. However, caves are particularly difficult environments to explore. The small dimensions of most of these places linked to the proximity of the walls and the ceiling constitute a strong constraint that does not exist in open environments. It often results in difficulties of access and transport of equipment, but also in the impossibility of implementing the protocols of prospection routinely used in open areas.

Over the last decade, two teams led by French geophysicists have attempted to meet this challenge to study combustion paleo-structures. Among the rare archaeological structures testifying human presence in these caves, hearths are preferential targets, especially for specialists in magnetometer prospecting. However, the topography of the studied areas and the presence of archaeological remains on the ground forced the teams to adapt their protocol, mainly for the magnetometer surveys, as standing or walking on the ground with the sensors might not be possible or could damage archaeological evidence. One possible choice is to not use the "continuous" mode of the magnetometer but to prefer discrete measurements (Jrad et al., 2013). However, it is possible to fully exploit the sampling capability of current magnetometers. A specific protocol was developed to allow the sensors to be moved without walking on the archaeological soils while "continuously" recording the magnetic field and the position of the sensors in space. A system consisting of a motorised total station and a boom attached to a tripod was developed by F. Lévêque and used for the first time in the Fraux cave (Burens et al., 2014, 2019). This protocol was then implemented in several French caves and rock shelters such as Cussac, Chauvet, Castanet (unpublished studies) and Bruniquel (Jaubert et al., 2016). Another issue related to rock shelters and caves is the assessment of the volume of potentially anthropogenic sediment overlying the substrate. Estimating the volume and distribution of these deposits is an essential element for programming archaeological surveys. Relevant information can be provided by coupling dynamic penetrometer measurements with apparent electrical resistivity surveys (Martinaud et al., 1999).

The complementarity of these methods was exploited at "La Piscine Magdalenian" (Fig. 10). This deposit is located at the foot of a cliff made of Bajocian limestone

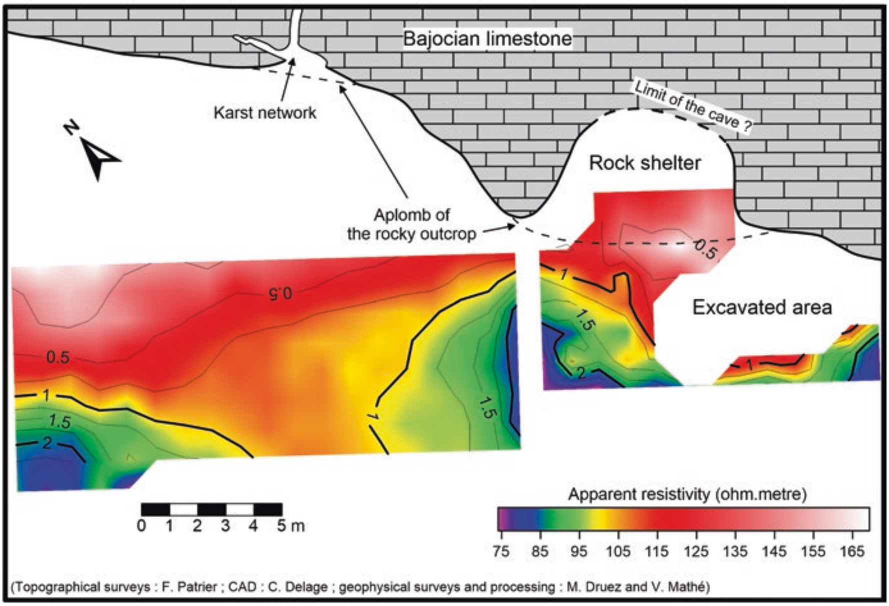

Fig. 10 La Piscine, Montmorillon, France, 2010–2011. Apparent electrical resistivity map (a = 1 m, 1 m² grid). Level lines equidistant of 0.25 m indicate the estimated thickness of the cover. (Data acquired in collaboration with C. Delage and M. Druez)

with several cavities. An area of 180 m^2 without major topographic anomalies was prospected in pole-pole configuration for three mobile electrode spacings (0.5, 1 and 1.5 m). Except for a few modern disturbances easily identified at the soil surface, low resistivity values are attributed to a deep substratum cover by silty-clay sediments, and conversely, high values correspond to a shallow substratum. The depth of the substrate was estimated using a VES inversion software. For this, we considered the near subsoil consisting of only two layers: the overburden, with a resistivity between 60 and 75 Ω.m, and the limestone substratum, with resistivity 230 Ω.m. The result is very robust as more than 95% of the 252 points considered shows an error of less than 7%. The largest errors, of the order of 15%, are at the location of previously identified modern disturbances. Dynamic penetrometer measurements performed at five locations confirmed the satisfying quality of the estimate of the cover thickness. The depth reached by the tip of the penetrometer is in all cases close to the estimation (less than 10% error) which seems to validate the approach. Near the cliff, the rocky surface appears very close to the surface. It forms a platform with a gentle slope towards the south, limited on either side by two depressions more than 2 m deep. Based on these results, the volume of sediment cover can be estimated between 170 and 200 m^3.

5.5 Coastal Prospection

Foreshore sites, located between the extreme limit of the highest and lowest seas, are particularly difficult to study. However, most of them are in danger due to climate change, erosion, and coastal development. Tides, storms and all the phenomena causing rapid displacement of large volumes of sediment on the coast, make this intertidal space very difficult to excavate. It is therefore necessary to have alternative or complementary methods to study the archaeological sites of the foreshore. Since the end of the 1990s, geophysical prospecting methods have been implemented, on an experimental basis, on the French West Atlantic coast (Laporte et al., 2009). Trials have been multiplied in recent years, in rocky, sandy, muddy, and mixed contexts (Mathé et al., 2021).

Due to the high salinity of the environment, electrical resistivity techniques deliver small signals and GPR has been excluded. Magnetometer and Slingram-EMI techniques were chosen (Mathé et al., 2018). As the possibilities of leaving markers on the ground and the intervention slots are limited due to the tide, GNSS positioning is often preferred to locate the measurements. On the other hand, it is more difficult, if not impossible, to avoid certain specificities of intertidal zones. Micro-topography is a common source of magnetic anomalies due to the non-constancy of the ground-sensor distance; it is also the source of disturbances in the electrical conductivity signal created by “puddles” of sea water. Another important limitation to the implementation of geophysics on the foreshore is the quasi-systematic presence of metallic waste in variable quantities. When all these noise sources are under control, the survey results are of great quality. One of the most significant recent results in such an environment was acquired in 2018 on Oleron Island. The magnetometer mapping revealed the presence of three curvilinear ditches of a Neolithic enclosure on the rocky foreshore (Fig. 11). The anomalies appear clearly near the dam, then gradually disappear towards the open sea where they have probably been completely eroded.

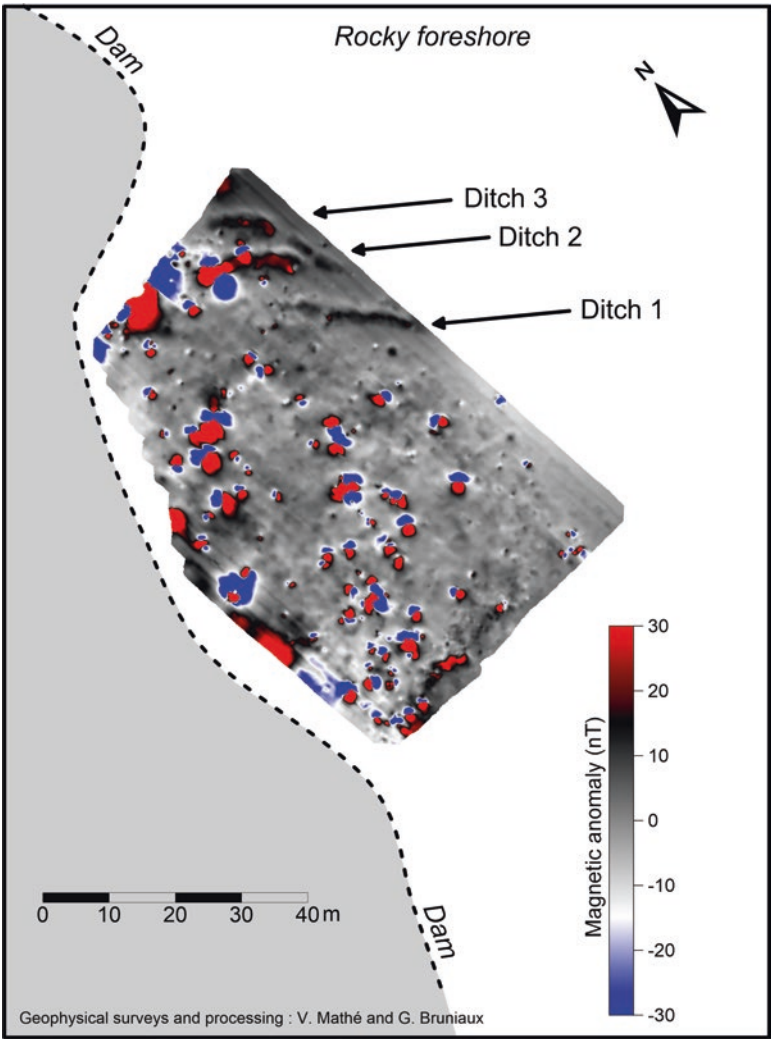

Fig. 11 Map of total magnetic field anomalies of Ors, Le-Château-d'Oléron, France. (Data acquired in collaboration in 2018–2019 with L. Soler and G. Bruniaux)

6 Conclusion

In this chapter, we have tried to make an overview of the French situation in the field of archaeo-geophysics. We have identified some trends in the type of surveys we are bound to. First, it seems that the rural context is still dominant in terms of numbers of operations done during the last two decades in France, even if other types of contexts seem to increase yearly. Second, the amount of surface prospected which were dominated by the 'intermediate' scale in the beginning of the 2000s are now quite balanced between the 'large' (above 20,000 m^2), 'intermediate' (between 3550 m^2 and 20,000 m^2) and 'small' (below 3550 m^2) categories. This reflects well the broadening of archaeological questions asked to the geophysicist. Preventive archaeology represents a third of the whole surveys and seems to be stable over the last years. Even if the Inrap's team contribution to the database is around one third of the studies, as their activity is balanced between both preventive and research archaeology, there is no clear explanations of that trend which arise from our data.

With the case studies, we tried to show the diversity of experience that could happen in archaeo-geophysics in France. Some examples used or cited here are the first attempts to widen the panel of techniques at the disposal of archaeologist (geomorphology, pedology, micromorphology, cone penetrometer tests etc.) but these attempts are far from being standard practices nowadays. It has to be noticed that Inrap and some other preventive archaeology companies (Éveha, ArkeMine) are developing their own group of specialists in geophysics. They have begun to be places where methodological innovations and combinations could rise under a unified framework.

The geochemistry is still under development. The XRF sensors are now available for the field, but the mapping is harder than in geophysical techniques (moreover the analysis is very time consuming after field work in the case of chemical extraction on samples). This is certainly a new way to be developed to interact with the archaeologist even if it requires an important referential work.

With the very specific policy about preventive archaeology, France has the possibility to offer great feedback to compare geophysical results and trial trenching/excavation results. It is really a singular opportunity, which provides us the possibility to greatly improve our interpretation experience and methodologies though it is still underdeveloped.

Finally, the interaction with all disciplines under the scope of the SAGA group are mainly driven by the archaeological questions. It means that the archaeology training programs should involve more and more courses on geosciences (and maybe the other way round). Another point is that some of us are not specialised on specific chrono-cultural targets, but mainly in hydrological, pedological or agronomical targets. That is another point of the applied geophysics in the French context, most of geophysical studies are not performed by archaeo-geophysicists but mostly by geophysicists working with archaeologists.

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Part X
Iraq & Kurdistan

Geophysical Prospecting on Soils in Mesopotamia: From Mega-Cities in the Marches of Southern Iraq to Assyrian Sites in the Mountains of Kurdistan

Jörg W. E. Fassbinder, Sandra Hahn, and Mandana Parsi

Abstract Enrichment of magnetic minerals in the topsoil and thus enhancement of magnetic susceptibility in archaeological layers and soils, the so-called "Le Borgne effect" is a quite common and a widespread property of the majority of soils worldwide. This effect is widely regarded as the main fundament and plays a crucial role for a successful magnetometer prospecting of most case studies for prospecting worldwide (Le Borgne, Ann Geophys 11:399–419, 1955; Mullins, J. Soil Sci 28: 223–246, 1977; Fassbinder et al., Nature 343(6254):161–163, 1990; Fassbinder & Stanjek, Archeol Polona 31:117–128, 1993; Jordanova, Soil magnetism. Applications in pedology, environmental science and agriculture. Academic Press, Amsterdam, 2016). Case studies both, in the wetland and marches of the Shat el Arab in Southern Iraq as well as on some sites of mountain areas of Kurdistan however, show that this effect plays a minor role in Mesopotamia (Fassbinder & Asandulesei, Peshdar Plain Proj Publ 1:112–119, 2016; Fassbinder et al., Magnetometer prospection of neo-Assyrian sites in the Peshdar Plain, Iraqi-Kurdistan. In: 12th international conference of archaeological prospection, vol 12. Archaeopress, pp 70–72, 2017a, Geophysikal research in the Bora Plain: magnetometer prospection at the Dinka Settlement Complex and Gawr Miran, 2016, vol 2. Peshdar Plain Project Publications, pp 18–32, 2017b, The 2017 magnetometer survey of the Dinka Settlement Complex, Iraqi Kurdistan, vol 3. Peshdar Plain Project Publications, pp 19–30, 2018, Geophysical prospection campaign 2019: magnetometry and Earth Resistance Tomography (ERT) at the archaeological site of Ur, Iraq. Unpublished report Directorate of Antiquities, Iraq, 2019a, Venice in the desert: Archaeological geophysics on the world's oldest metropolis Uruk-Warka, the city of King

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Gilgamesh (Iraq). In 13th international conference on archaeological prospection, vol 13, pp 197–200, 2019b, Petiti et al., Zeitschrift für Orientarchäologie Bd 15:120–162, 2023). Here we present a variety of further soil magnetic, rock magnetic and physical properties of archaeological sediments and features, explaining the success, failure, and pitfalls of these prospecting projects. While in the southern Iraq induced magnetisation and the variance in composition of mudstones dominates magnetic anomalies, the selected case study from Iraqi-Kurdistan is predominantly determined by the natural remanent magnetisation of rocks.

1 Introduction

Geophysical prospection at an archaeological site in Iraq was to our knowledge introduced for the first time by Italian and German researchers in the 1960s and 1970s (Ratti, 1971; Lanza et al., 1972; Becker, 1977; Hrouda, 1978). Due to the political situation of Iraq under the regime of Sadam Hussein (from 1978 to 2003) access to regions in the northern Iraq and in particular to Iraq-Kurdistan was nearly impossible and archaeological field research came to an abrupt end. Archaeological research resumed in these regions only after 2010. On the other hand, field research on a multitude of archaeological sites in southern parts of Iraq was still possible but nevertheless was very limited due to the political circumstances during and after the first Gulf War from 1980 to 1988. Although many archaeological excavations took place during the period from 1980 to 2000 but none of them included geophysical prospection in their research program. This is due also to the fact that in the 1980s "large area" magnetometer prospecting was still not as common as it is nowadays.

Helmut Becker and Jörg Fassbinder then undertook the first caesium magnetometer prospecting in Iraq in April 1989 on the Assyrian site Assur (Andrae, 1938; Becker, 1991; Fassbinder et al., 2024). It was Barthel Hrouda, (Director of the Institute of Near Eastern Archaeology LMU Munich, (in a cooperation with the Bavarian State Dept. of Monuments and Sites), was among first archaeologists working in the Near East who started his new excavation project in Assur by magnetometer prospecting of the site. Already soon after, Sadam Hussein invaded Kuwait and the second Gulf War began so that further geophysical prospecting could not follow up in Iraq.

It was then only in the year 2001 and 2002 when there was the chance to introduce archaeological geophysical methods by a magnetometer test measurement in Uruk-Warka (Becker & Fassbinder, 2001; Fassbinder et al., 2005; Ess et al., 2006). In a cooperation with the German Archaeological Institute (DAI) we were able to conduct a magnetometer survey of ca. 20 ha. Further work then again was interrupted by the American invasion of Iraq in 2003. Since 2016 however it became more safe and easier to access the southern part of the country for further prospecting (Fassbinder, 2020; Ess & Fassbinder, 2021). Meanwhile, archaeological geophysics were widely accepted as important toolkit by Near Eastern Archaeologist

Fig. 1 Map of Mesopotamia and Iraq. Archaeological sites in Iraq which where prospected by the Munich team is marked in red

and there are large ranges of sites, which where currently prospected magnetically by teams e.g. from France, Italy, Czeck Republic, England, Russia and many others (Nadali & Polcaro, 2015; Lambers et al., 2019; Campbell et al., 2018; Darras & Vallet, 2021; Jankowski-Diakonoff et al., 2021). From a multitude of archaeological sites that where prospected by our team in Iraq-Kurdistan, we present here the case study of Neo-Assyrian site Gird-I Bazar. From the southern Iraq, we show examples from our long-term project Uruk-Warka (Andrae, 1935), the Sumerian City of Ur (Woolley, 1934–1976) and Charax-Spasinou (Hansman, 1967) (Fig. 1). Further test-measurements done at Fara Shuruppak resembles magnetically the results from Uruk-Warka, will soon presented elsewhere (Hahn et al., 2022).

Magnetometry for archaeological prospecting using total-field caesium-magnetometers was developed and refined at the Bavarian State Department of Monuments and Sites in a close cooperation with the Geophysics Institute of the Ludwig-Maximilians-University Munich since the late 1970s. The caesium magnetometer probes, compared to commercial models, provide us by up to 100 times higher resolution (Breiner, 1965; Mathé et al., 2009; Fassbinder, 2015, 2017). These types of instruments, adapted to the specific requirements of archaeological prospecting, must be carried manually approximately 30 cm above the ground. Unlike vector magnetometers, such as fluxgate and SQUID magnetometers, any kind of magnetic metal near the caesium magnetometer will disturb and restrict its high sensitivity. Test measurements with a wheeled devised four-canal fluxgate magnetometer system failed (Parsi et al., 2019). Ground conditions at Uruk, Fara Suruppak and Charax and partly in Ur, are soft, muddy or dusty soils and sometimes combined with uneven terrain. Such conditions make utterly impossible to use a wheeled prospecting system. They will both stick in the soft mud or sand and damage the archaeological features.

2 Magnetometer Prospecting in the Mountains of Iraq-Kurdistan (Northern Iraq)

2.1 The Assyrian "Settlement" Gird-i-Bazar

The settlement complex Gird-i-Bazar in the Peshdar Plain was discovered occasionally in 2014 by the construction of a chicken farm. Already in 2013, a fragmented cuneiform tablet found by a farmer nearby at Qalat-I Dinka, turned out to be a legal document of Neo-Assyrian time from the year 725 BC. Karen Radner—following a suggestion from Jessica Giraud, who found Neo-Assyrian pottery during an extended surface survey at these areas—visited the site 2015 and decided to start a new research project, called the "Peshdar Plain Project" with the goal to investigate Neo-Assyrian monuments in the region. Already in the summer 2015 the Munich Prospecting team together with Andrei Asandulesei (University of Iasi) followed the invitation of Karen Radner to start a magnetometer prospection within the framework of this project. Meanwhile the site was prospected very widely and extensively by different geophysical prospecting methods (Fassbinder & Asandulesei 2016; Fassbinder et al. 2017a, b; 2018; Radner et al., 2016–2020).

2.1.1 Magnetometer Prospection

The magnetometer prospection completed in 2019 revealed a large settlement complex which covers an area of more than 500 × 700 m in size (Fig. 2). From the results of the survey, it seems clear that we are dealing with a single-phase site. In the centre, we detected traces of destruction by a mud-slice, but no further indication of a second archaeological phase became visible. The fundaments of houses, fireplaces and kilns show up by a very clear and high contrast to the adjacent soil. This is due to the highly magnetic gabbro and serpentine rock inclusions of the gravels (usually 10–20 cm in diameter) used as foundation material of the mudstone walls (Herr, 2017). Although there was a great variety of rocks from sediments such as limestone, dolostone and breccia, the occurrence of these few serpentines and gabbro's dominates the magnetic signal (see magnetic susceptibility values Table 1). In consequence, the magnetogram reveals a single-phase settlement and beside the destruction by an ancient mudslide, no further indication of second phase is detectable. However, first excavations inside the fence of the chicken farm from 2015 (Kreppner et al., 2016) proved already that the magnetogram at the area (eastern

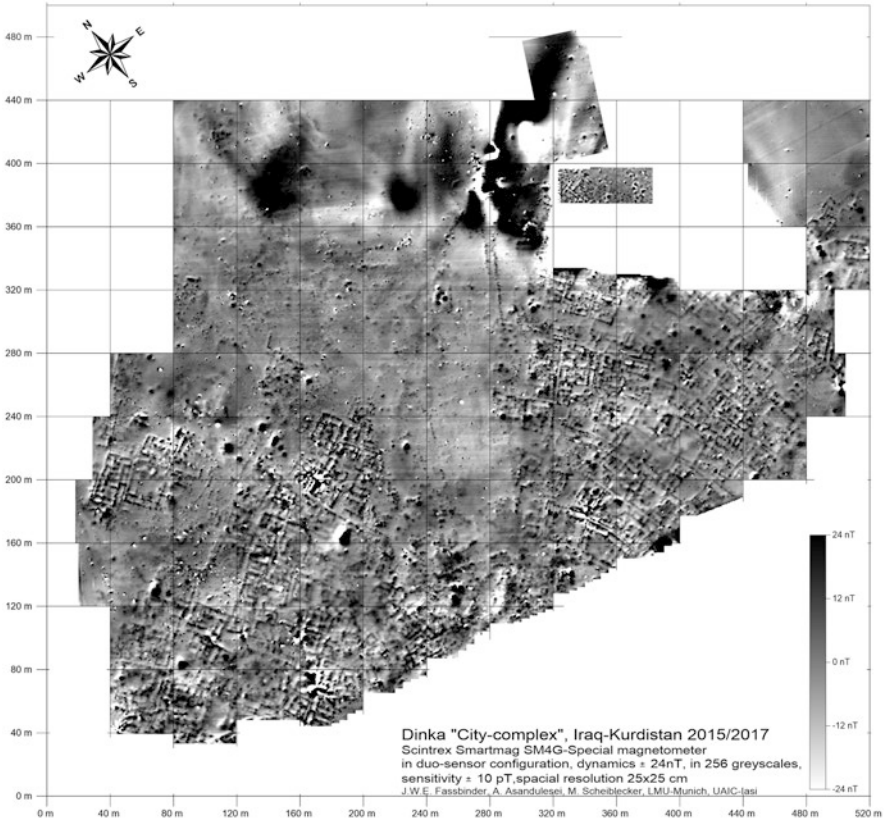


Fig. 2 Gird-I Bazar, Dinka lower town. Magnetogram of the settlement complex

trench) does not show any traces of the ground map (see Fig. 3a, b). Further “in situ” analysis of the fundaments in this specific part of the excavation by the kappa meter proved that here serpentine and gabbro rock where absent. Obviously, the builders of these houses used another quarry for gravels for their foundations.

The majority of archaeological features in Gird-i Bazar have rock foundations of houses that are composed by serpentine and gabbro’s and are thus very sharp and clearly identifiable in the magnetogram. However, the same layers and features can be also nearly invisible if their fundaments are solely composed of limestone and dolostones like in the right part of the magnetogram (Fig. 3). That means from the magnetometer survey we cannot exclude further features and buildings in the area since they could be invisible due to the less contrasting material. Moreover, test excavations and deep soundings at the area of Gird-i Bazar and electrical resistivity tomography (ERT) measurements undertaken in 2019 on the site reveal further deeper archaeologic layers beneath the Neo Assyrian settlement complex (Parsi & Fassbinder, 2020). No traces of these layers where detectable with the magnetometer survey. Surface surveys of pottery by Jessica Giraud (Giraud, 2016) however

Table 1 Kappa values of a selection of identified gravel rocks from Gird-i Basar and Qalat i Dinka. Note that the typical gravel rocks showed a great variety in the content of magnetic minerals (measured by kappa meter SM30, ZH-Instruments, CZ)

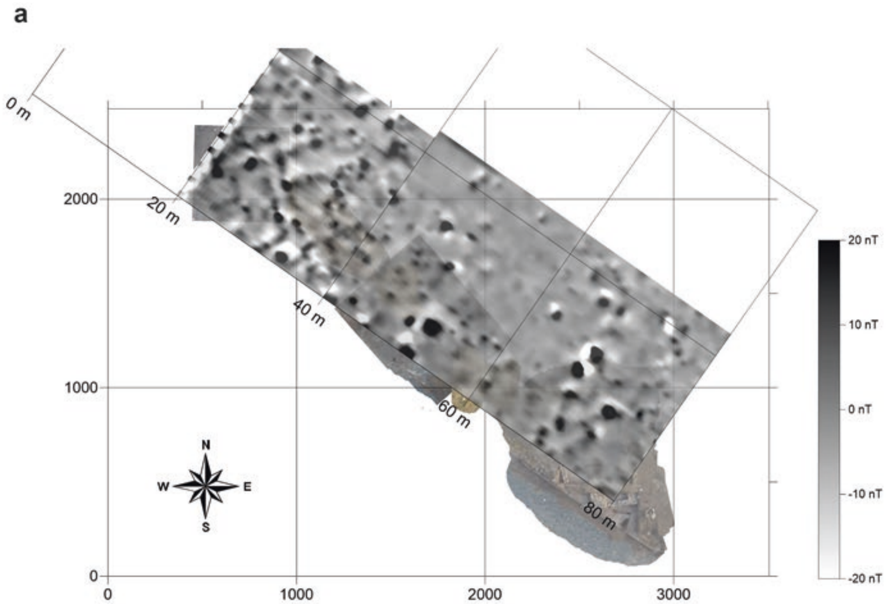
Serpentine…………………………..	76,400 [10^{-3} SI]
–	75.400 [10^{-3} SI]
–	54.400 [10^{-3} SI]
Gabbro ……………………………....	14.900 [10^{-3} SI]
–	14.300 [10^{-3} SI]
–	11.300 [10^{-3} SI]
Breccia……………………………….	02.880 [10^{-3} SI]
Limestone…………………………….	0.3180 [10^{-3} SI]
–	0.3100 [10^{-3} SI]
–	0.2870 [10^{-3} SI]
–	0.2500 [10^{-3} SI]
–	0.1370 [10^{-3} SI]
Dolostone ……………………………..	0.0857 [10^{-3} SI]
	0.0038 [10^{-3} SI]
Top soils ……………………………....	2.790 [10^{-3} SI]
	1.280 [10^{-3} SI]
	1.230 [10^{-3} SI]
	0.842 [10^{-3} SI]
Pottery	Ca. 8.00–11.00 [10^{-3} SI]

indicate the existence of features from older periods. From the magnetometer measurements, although they seemed to be perfect and clear, we cannot deduce that they reveal all the features, and it cannot be excluded that this single-phase settlement overlays and masks some older layers and features at the site. In the measured area of ca. 500 × 500 m, we found at least four lightning strikes identifiable by their typical star shaped and highly magnetic traces (Maki, 2005; Fassbinder, 2017).

3 Magnetometer Prospecting in the Marshland of Southern Iraq

3.1 Uruk-Warka

Uruk-Warka, already a megacity more than 5000 years ago, was first and foremost the centre for a multitude of technical innovations. This includes the construction of irrigation canals, the invention of plastic mortar, astronomy, writing, literacy and numeracy. It was also scene of action humankind's oldest surviving saga, the famous "Epic of Gilgamesh". First systematic excavations and archaeological research at Uruk-Warka took place already since 1912/13 (Andrae, 1935). By more than 40 campaigns, the German Archaeological Institute (DAI) have revealed the ruins of this metropolis. About 40,000 residents inhabited Uruk already by 3000 BCE, in an area of ca. 5.5 km^2. The diameter of the city is 2.6–3.1 km; the enclosing wall has a length of ca. 11 km. Meanwhile surface surveys, satellite image and air photo



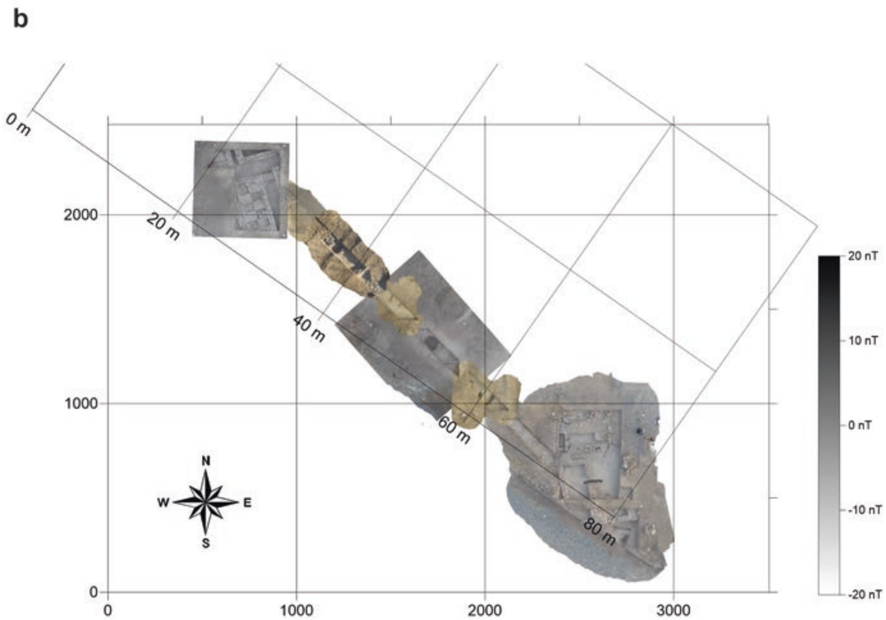


Fig. 3 Gird-I Bazar: Magnetogram top and excavation results bottom. The magnetogram is dominated by the occurrence of different gravels that were used. In the northern part magnetic gravels from gabbro and serpentine yield clear features—in the south-east the fundaments are composed of limestone and dolostone and thus remains invisible in the magnetogram image

analysis, geophysical prospection of six campaigns as well as excavations and cuneiform tablet texts have confirmed the presence of canals, houses, temples, and gardens even outside the city wall (Ess & Fassbinder, 2019, 2021).

It is self-evident that modern archaeological research into such an enormous site cannot be restricted anymore to excavation and archaeological surface survey. In 1999, it was first Margarete van Ess who came up with the idea to undertake a large-scale magnetometer prospecting of the site. First test were done already 2000 and 2001 following up until 2021 by meanwhile six campaigns of magnetometer surveys.

Magnetometer prospecting in Uruk was initiated 1999 by the archaeologist Margarete van Ess (director of the DAI in Baghdad) and carried out by the Munich prospecting team in 2001–2002. Further measurements resumed after the Iraq war from 2003 in 2016, and continued in 2018, 2019 and 2021. The first geophysical survey started in the southwestern part of the city, focused on an area north of the Sinkashid Palace and in the south and north in- and outside the city wall. Meanwhile we surveyed from north to south more than 100 ha (> 1 $km^{2)}$ which gives at least a sufficient insight into the organisation of the western part of the city (Fig. 4).

A large canal passes this area to from north to south and includes smaller canals and its branches, a harbour and settlement areas east of Sinkashid palace and settlement areas southwest and east of the palace. In the south, the survey area covers the southern city wall, bringing to light construction details of the monumental city-wall, nearby gardens, and fields as well as a water gate. In the south, outside the city, a large burial ground and a huge monumental building complex with related associated harbour was brought to light.

Meanwhile after several campaigns the magnetogram images provides us with a detailed insight into settlement areas, gardens, and fields close to the city wall, as well as a network of canals that obviously served as the main arteries of Uruk. This network of waterways and canals cross the city from north to south and makes the city quarters accessible, but also provide water for the irrigation of gardens inside the enclosed city. The main canal that is seen in the eastern part of the magnetogram for a length of meanwhile ca. 2400 m. It is 15–20 m wide and 3 m deep and, at several points, slightly smaller canals branch off to the west. Left and right of the canal we traced settlement areas, divided by the smaller canals that led to fields and gardens (Fig. 5). Canals of three or four different widths, the smallest belonging to the field irrigation systems, can be distinguished. The central part of the magnetically scanned area is characterised by two different main features. In the south, a large structure, running east west, seems to accompany the canals into the city centre. A similar shorter structure some metres to the west obviously blocks part of the main canal. None of these hydraulic constructions are visible neither from the air nor from the ground, which is very flat in this part of the city. However, they seem to control or guide the water flow and the canals. Here a selective excavation could determine the date and the nature of these structures. In the south, the city wall and a small canal crossing the city wall can be seen (Fig. 6). Here, the course of the city wall and, at regular intervals, its bastions known from previous excavations and documentation elsewhere in the city, are clearly visible. The high intensity of the signal over parts of the wall on its inner and outer faces

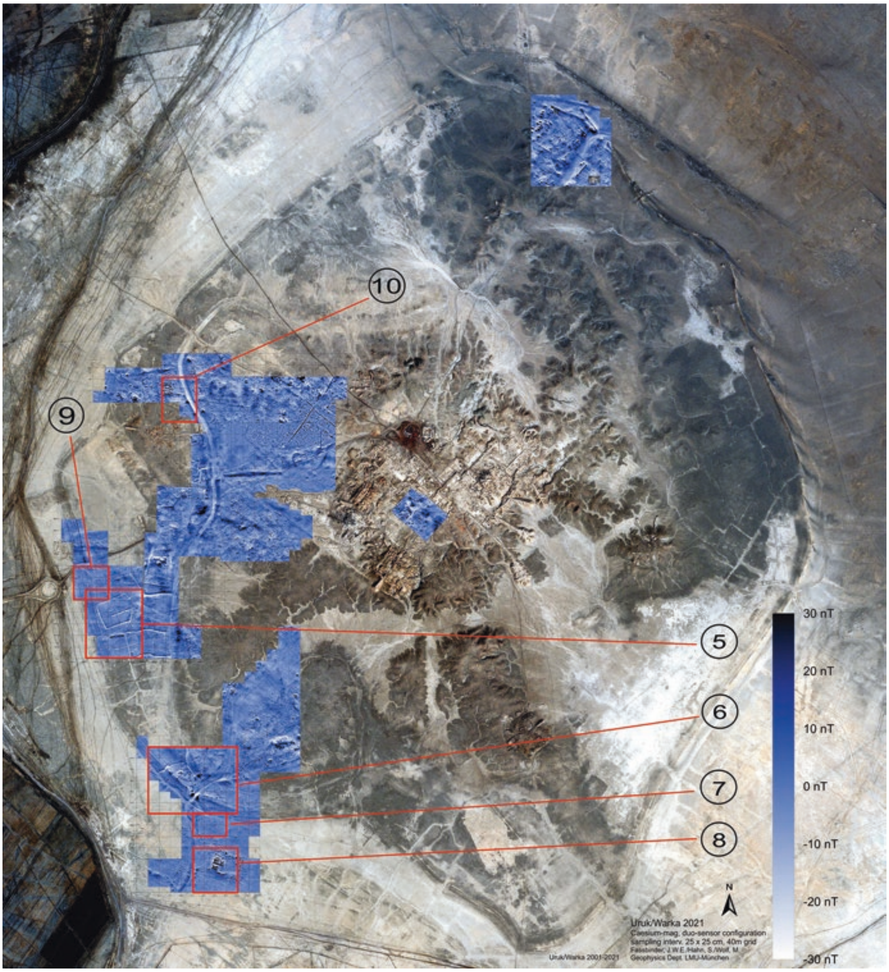


Fig. 4 Uruk Warka. Satellite image from 2005 fused by the magnetogram images from 2001 to 2021 (grid-size of magnetograms 40 × 40 m)

seems to indicate the presence of fired bricks, a detail that was not known before. Recent excavations brought to light that these bricks were composed with admixture of fragmented pottery (Fig. 9). It is also apparent that the fortification complex was constructed suing more separate walls than were previously known, and that the canal circling the city ran just outside it. The entire wall system was nearly 40 m wide. The wall itself, with its inner and outer shells of bricks, is ca. 9 m thick, an observation that corresponds to the excavation findings. Further details about Uruk's structure are provided by the magnetogram of the north and southwest gate, which are nearly 15 m wide and can be interpreted as a floodgate, where the inner city's main and central canals flowed in and out through the wall. On the outside, the gates were flanked by towers and walls that were strengthened with fired bricks (Fig. 6).

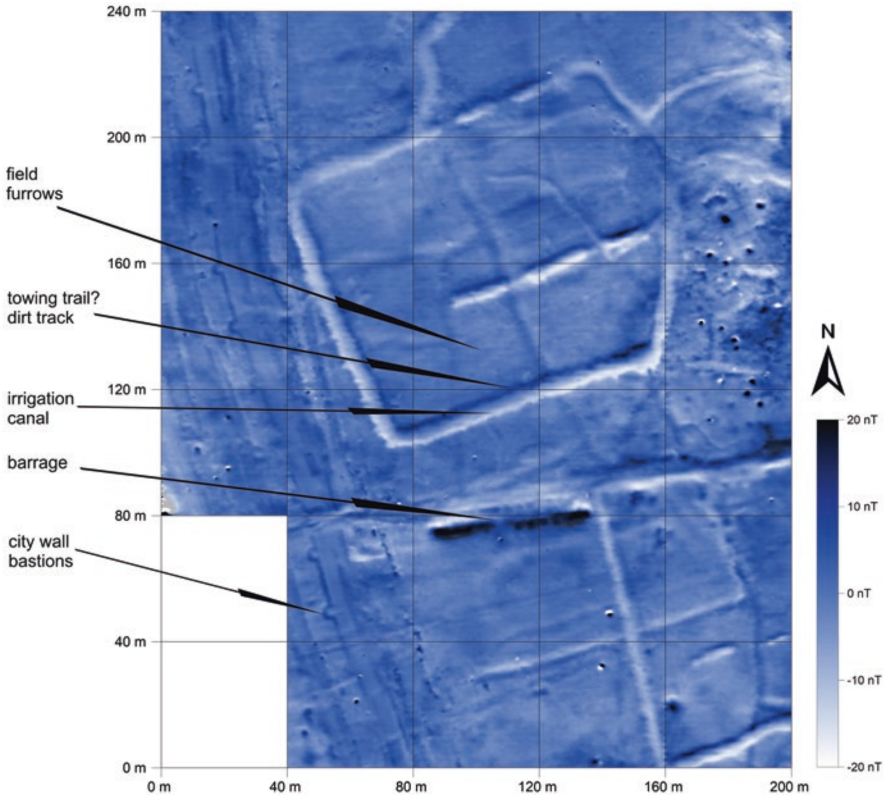


Fig. 5 Uruk-Warka. Magnetogram showing details of the city wall, bastions, gardens, ancient field furrows and irrigation systems

Downstream of the floodgate, a small side canal branches off to the southeast, expanding roughly midway in front of a large building of fired bricks into a small harbour-like structure (Fig. 8).

Archaeological features showed extremely high magnetic anomalies and were characterised by sharp magnetic contrasts to the adjacent sediments. Structures become magnetically visible due to different composition of mudstones and due to the thermo-remanence of burned features. Sarcophaguses and coffins on a burial ground in the south of the city (Fig. 7) show up both as positive and or negative anomalies due to different stage or temperature of burning (for more details, see Fassbinder et al., 2019b; Petiti et al., 2023). The waterways and canals show up by clear “negative” anomalies. This implies that heavy and magnetic minerals where already separated from the sediments before the water enters the city. Normally one would expect that like in ancient canals and palaeochannels magnetic minerals concentrates and forms positive magnetic anomalies due to the enrichment of heavy magnetic minerals by water separation (e.g. Babaev et al., 2019).

Although resistivity values were extremely low due to the high salt concentration (ca. 10%) of the sediments, the first tests with ERT in the spring season of 2019

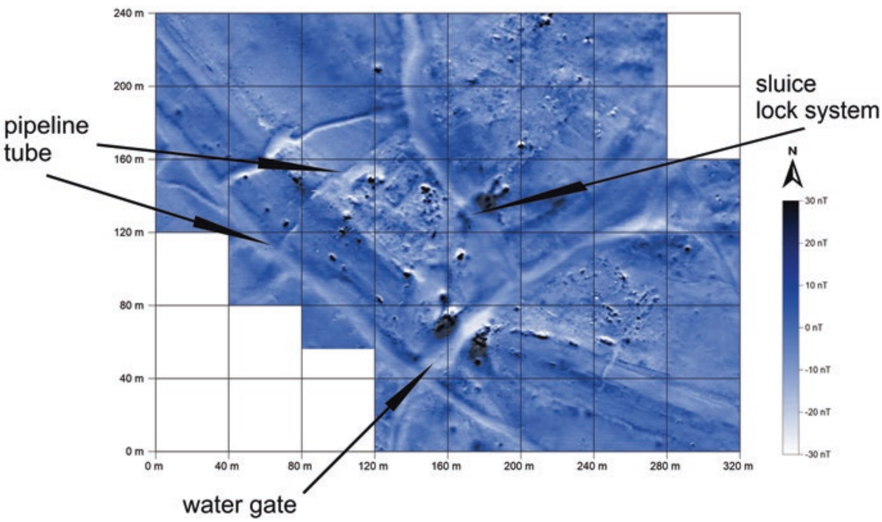


Fig. 6 Uruk-Warka. Magnetogram details of the southern water gate, the sluice system and pipeline beneath the wall

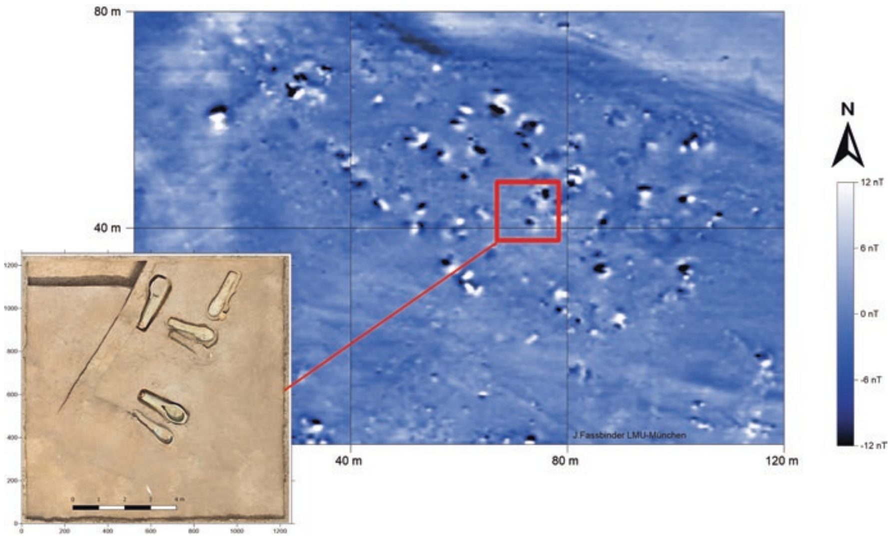


Fig. 7 Uruk-Warka. Magnetogram details of a cemetery with coffins of different magnetic compositions, generating both positive and negative anomalies

provided good results with respect to measuring the exact depth and extent of some archaeological features, such as the mudstone city wall and the shape and extent of the canals and harbours (Fig. 10).

Further work will involve a detailed analysis of the magnetograms, supplementary earth resistance or seismic surveys, satellite remote sensing, UAV surveys, topographical information. All these results, combined to the findings from targeted excavations, will allow a closer insights into the development, the structure and the functions of the city, even without large and costly excavation. The magnetometer survey hopefully will be continued and will offer a comprehensive picture of the structure of Uruk through time (Figs. 5, 6, 7, 8, 9 and 10).

10.3.2 Ur

Ur, the city of moon god and "Home of Abraham", was founded in the fourth millennium BC and is one of the most prominent cities in Mesopotamia beside Uruk-Warka and Babylon (Woolley, 1934–1976). There is the hypothesis that the occupation ends by a flood, formerly thought to be the one described in Genesis. The size and area of the inner city enclosed by a wall (ca. 1200 × 800 m) is much smaller than the city of Uruk. Nonetheless, in the next (Early Dynastic) period, Ur became the capital of southern Mesopotamia under the Sumerian kings of the first dynasty of Ur (twenty-fifth century BC). The last king, who left his traces at both Ur and Uruk, was the Achaemenian Cyrus the Great (sixth century B.C.), whose inscription on

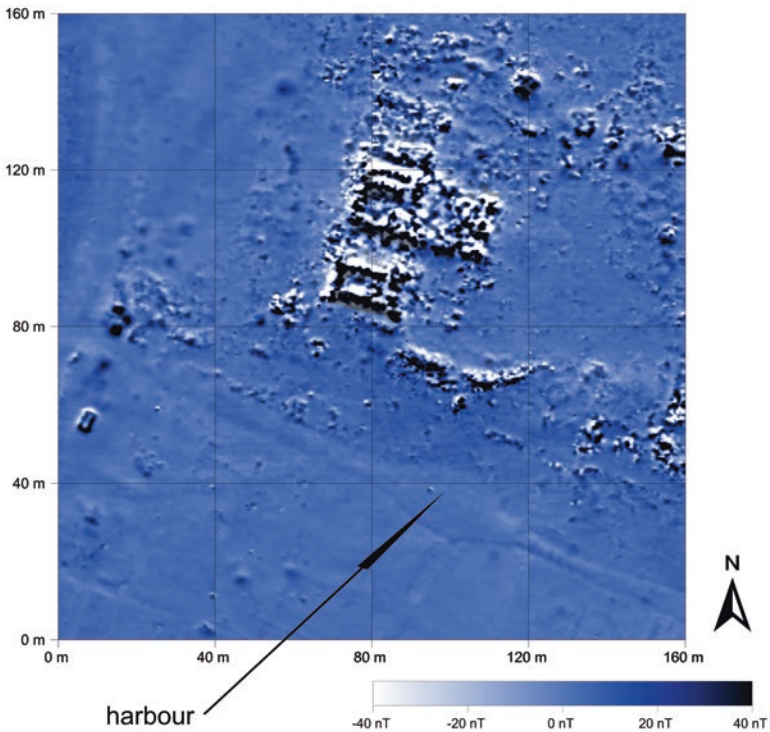


Fig. 8 Uruk-Warka. Magnetogram details of the southern palace and adjacent harbour

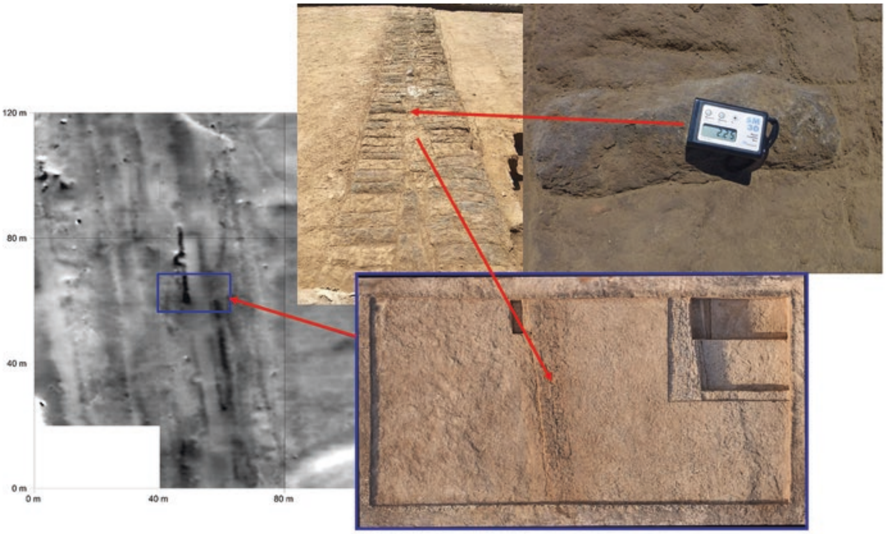


Fig. 9 Uruk-Warka. Magnetogram details from the monumental city wall. Parts of the U-shaped bastions and mudstone wall seemed to be from baked mudbricks. Excavations however revealed that these mudstones where composed by pottery shards and not by baked bricks

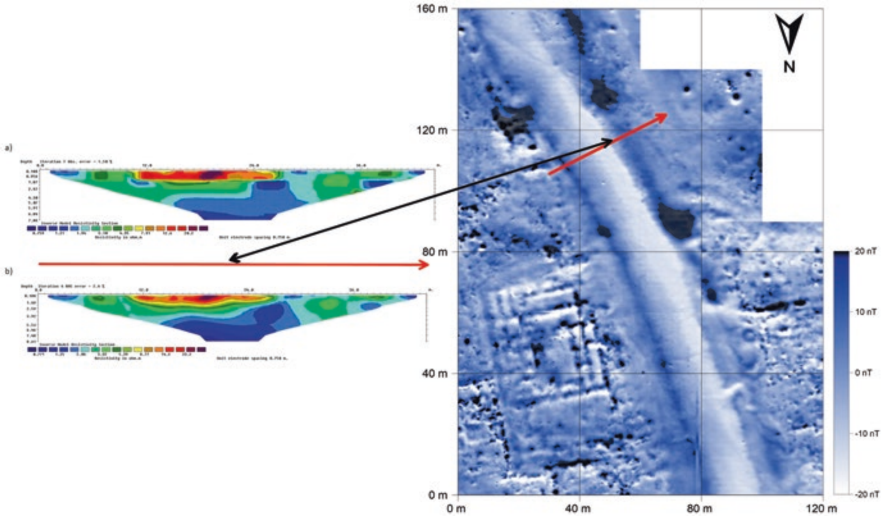


Fig. 10 Uruk-Warka. Magnetogram of the main canal of the city and associated data of ERT-profile. ERT results over the canal with dipole-dipole configuration and 0.75 m electrode spacing. (**a**) Left: The result of the robust inversion method, which shows the shape of the canal by its high resistivity values. (**b**) Right: The result of the Smoothness-constraint inversion method, which shows the sedimentation layers inside of the canal

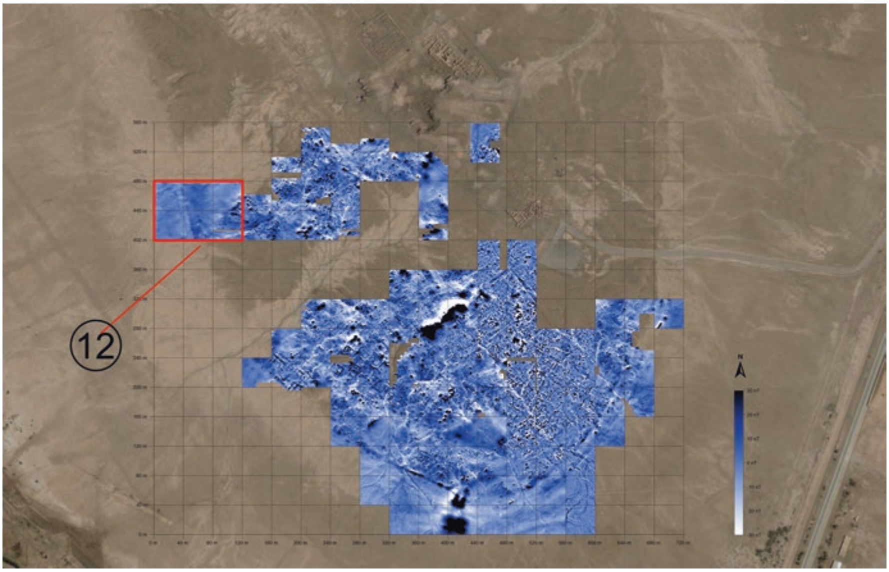


Fig. 11 Ur. Satellite image (Bing-maps) fused by the magnetogram image of 2019 (grid-size of magnetograms 40 × 40 m)

bricks was found in recent excavations. The cities survived until the reign of Artaxerxes II (third century B.C.). It was perhaps at this time that the Euphrates changed its course. Ur was finally abandoned with the breakdown of its irrigation system as the fields were reduced to desert. In contrast to Uruk, the remains and ruins of Ur are predominantly made from baked bricks and the infrastructure consist of a network of roads and footpaths instead of canals like in Uruk (Fig. 11).

The objectives of the geophysical exploration in Ur were to map the horizontal extent of the city wall, its vertical dimensions, and to acquire information related to the stratigraphic layering between the two main wall structures. Therefore, magnetometer and ERT surveys were combined at this site also.

Wide areas of the surface of Ur are simply not accessible or suitable for magnetometer prospecting. This is due to deep erosion canals and due to the old and extensive excavations from Woolley (1934–1976). In any case, the magnetometer surveys covered an extensive area. The results were dominated by high thermo-remanent magnetisation of baked brick. The debris of these bricks cover wide areas of the surface and thus sometimes hide or overlay the layout of archaeological features.

An ERT profile was laid out perpendicular to the direction of the wall, which had already been revealed by the magnetometer results. The results suggested that the wall is preserved to a height of ~1 m, which match Woolley's records. The width of the inner and outer wall was estimated to be ~4 and 2 m respectively (Parsi et al., 2019). The water content in the soil is a limiting factor that potentially can affect ERT interpretations. Soil moisture content was monitored with the repeated ERT measurements over the same profile for a whole day and the tomographic data was

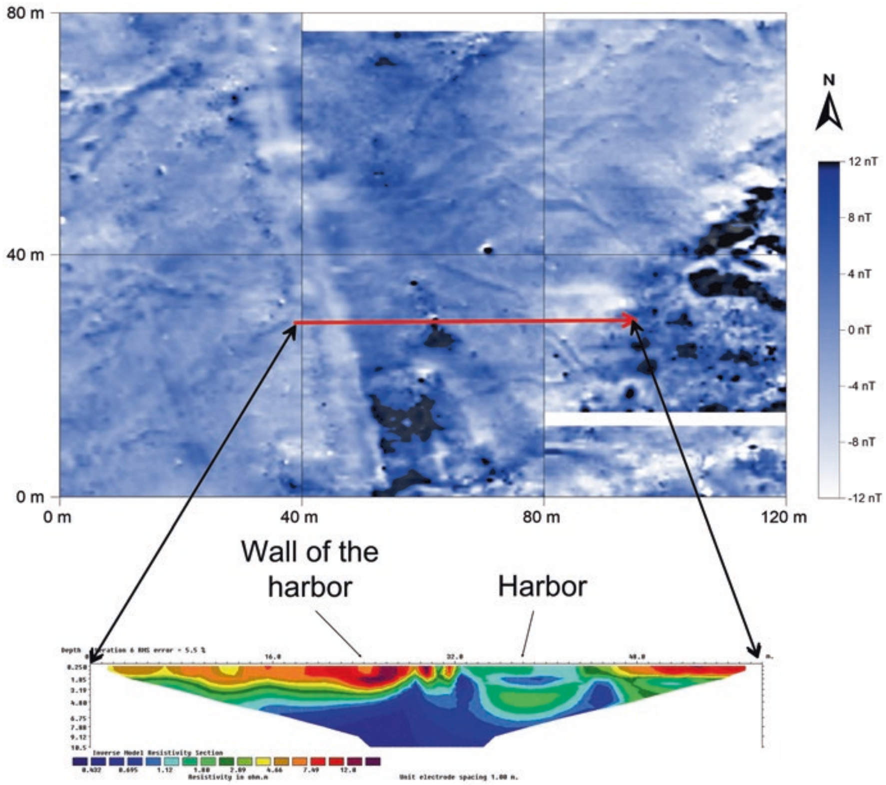


Fig. 12 Ur. ERT profile and related magnetogram over the harbour wall in Ur (electrode spacing 0.5 m, dipole-dipole configuration)

also supported with the collection of direct soil moisture, temperature, and conductivity measurements over the city wall with a Time Domain Reflectometry (TDR) instrument. The preliminary results showed a maximum moisture content change of about 10 vol% and plays only a minor role for the resulting data. Other ERT profiles with different electrode spacing targeted the location of the harbour to verify its existence, which was already suggested by the magnetometer results. The left side of the map in Fig. 12 shows the wall. The width of the harbour is around 15 m and its depth about 8 m. According to the result of the ERT, the wall could be made of baked bricks. This information also matches the evidence from the archaeological records. Overall, ERT measurements turned out to provide a suitable complementary prospection method to magnetometry. It delivered reliable information on the depths of archaeological features that are situated in clayey, salty and waterlogged soils. ERT also demonstrated potential to detect mudstone constructions in the adjacent clay and mud.

10.3.3 Charax

The ancient city of Charax Spasinou dates from the Seleucid to the Sasanian period (305 B.C. to 651 A.D.). It is situated in southern Iraq ca. 40 km north of Basra, between the rivers Tigris and Eulaios, at the modern location Jebel Khayaber. The city was founded by Alexander the Great and named Alexandria. After its destruction by a flood, it was re-founded in 166/165 BC by the Seleucid king Antiochos IV and re-named Antiochia. Later, a great flooding again destroyed the site. It was then rebuilt under Hyspaosines and named Charax Spasinou (ancient Greek for ‘palisade of (Hy)spa(o)sines’). Due to its favourable location Charax became a very important harbour in the Persian Gulf area and a major trading point between India and Babylonia, supplying goods further up to the Mediterranean (Campbell et al., 2018). Charax was first identified with Jebel Khayaber in 1965, when distinctive ramparts with an average height of 4 to 6 m were documented (Hansman, 1967).

In 2016, the University of Manchester, the University of Konstanz, and the Iraqi State Board for Antiquities & Heritage started a large prospection project to document and protect the ancient city of Charax Spasinou. The aim was to integrate satellite imagery analysis, walkover survey, and targeted excavations to reconstruct the city layout, its chronology, and document its state of preservation for site management purposes.

In the same year, the Munich prospecting team carried out a first survey to prove the suitability of magnetometry to detect buried structures embedded in the swampy and waterlogged soils of the Shat el Arab area in collaboration with Jane Moon and Robert Killick and the Iraqi State Board for Antiquities & Heritage, (Lambers et al., 2019). The former river course of the Karun has heavily eroded the southern part of the city, beyond the riverbed now visible in satellite images, but the results of the 2016 survey indicated that some parts of the city could still have survived. During the Iraq-Iran War in 1980–1988, the whole area of the ancient site was intensively used battleground and left traces of vast destruction in the field. The site is still contaminated and covered by a multitude of deep trenches from tanks, but also contaminated by metallic rubbish, destroyed weapons and military equipment.

To our surprise, this first magnetometer survey provided extraordinary results with respect to the high and clear contrast of the magnetogram image (Fig. 13). Although the site was highly contaminated by metal objects, the salty and wet environment seems that served to induce a fast corrosion of metallic iron to rusty weak magnetic iron oxide such as goethite ferrihydrite and lepidocrocite, thus not detectable anymore by magnetometers.

The results suggested that the streets of the city centre follow the typical Hippodamian grid system with a grid size of around 161 × 88 m (550 × 300 Attic Ionic feet) which is one of the largest we know from the ancient world (Campbell et al., 2018). Like in Uruk, streets and pathways were paved with pottery shards and thus showed up magnetically by a high and sharp positive anomaly. Two evaluation trenches revealed that the east-west streets at least appear to have been placed over a drainage sub-structure. This was composed of a ditch along at least one side of which three super-imposed rows of re-used storage jars drew the water from the

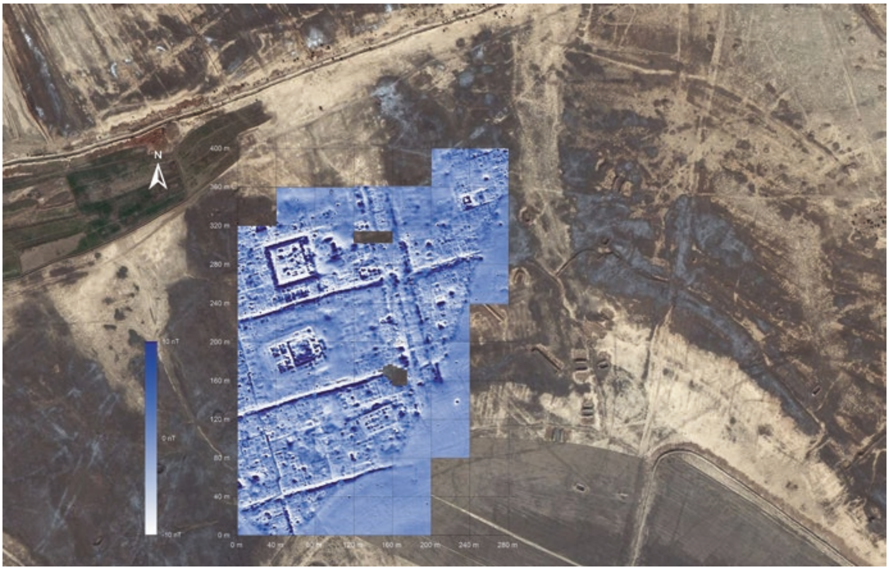


Fig. 13 Charax-Spasinou. Magnetogram fused by a satellite Image (Google-Earth) Scintrex SM 4G-Special Caesium magnetometer in a duo-sensor and total field configuration (grid-size of magnetograms 40 × 40 m)

surface (Campbell et al., 2018). The layout of these jars is marked in the magnetogram by a thermo-remanent magnetisation. Such a complex drainage system indicates a high level of investment in urban planning and the importance of resilience against repeated flooding. Unlike situations in Europe e.g. in the Netherlands but also at many sites in Bavaria, swampy or waterlogged soils do not necessarily imply dissolution of magnetic iron oxides magnetite, maghemite or titano-maghemites in the pottery shards as seen in this site.

While the magnetogram of most portions of the site shows a clear picture, some areas show traces of flooding, which eroded the main inner-city structures. In these areas, there are only few faint traces of earlier buildings.

4 Discussion and Conclusion

Unlike the situation in southern Germany and wide areas of Europe, pedogenic enrichment of magnetic minerals in the topsoil is of minor importance with respect to magnetic prospecting on archaeological sites in Iraq.

Remanent magnetisation of rocks and bedrock dominate the magnetic properties of the majority as well as of our selected case studies in Iraq Kurdistan—Muṣaṣir and Dinka in the Peshdar Plain. In the city of Ur the magnetic anomalies are dominated by thermo-remanent magnetisation of bricks kilns, fireplace and pottery kilns.

Induced magnetisation of magnetically contrasting mudstones, of mudbricks and canal sediments in the alluvial plain of the Euphrates River dominate archaeological features in the southern Iraq. Namely, at the archaeological sites from Uruk and Charax the magnetic contrast of mudstone and adjacent sediments depends on the composition of the mudstones. From excavations at Uruk and Charax we knew that mudstones are frequently tempered and composed by pottery sherds. Streets and pathway are paved by pottery shards and thus show up by positive magnetic anomalies.

Archaeological features in swampy and waterlogged salty soil are well visible in the magnetogram image—in contrast to the dissolution of magnetic minerals in the majority of European soils.

The intensity of magnetic anomalies of the archaeological features (total field measurements) has relatively high range of ±30–40 nT.

Magnetic traces of lightning strikes (Maki, 2005; Fassbinder, 2016) are frequent in the magnetograms from Iraqi Kurdistan while such traces but so far rarely reported from measurements in the southern Iraq.

A final observation from our long-term total magnetic field measurements is that the absolute value of the Earth's magnetic field in Uruk has increased by more than 200 nT from ca. 45. 950.0 nT in the year 2001 to 46,171.0 nT in the year 2021.

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Part XI
Ireland

Recent Soil Study Research in Irish Archaeological Prospection Strategies

James Bonsall

Abstract This paper addresses the current state of soil studies incorporated within archaeological prospection strategies in Ireland. Many publications fail to address the importance of soil science in their understanding of archaeological prospection data. The challenges presented by archaeological prospection, particularly in relation to the importance of soils and geology in a country dominated by carboniferous limestones, tills and peats, are reviewed. Six case studies demonstrate the integration of soil studies and their application to archaeological prospection. The challenges are not confined to soils and geology—an emergent knowledge gap is stifling the successful application of soil science for archaeology. The case studies presented in this paper emphasise the ease and benefits of incorporating soil science within a project, with preferences for soil recovery and analysis to aid (or refine) archaeological interpretations, and determine (in)appropriate methods of further research. More collaboration is required between geophysicists, excavators and soil scientists in order to plan, retrieve and analyse samples, as well as focused thought on how such data should be used to increase our knowledge of soil influence.

1 Introduction

Irish archaeology has more than 30 years of experienced geophysical survey practitioners working across the research, private and public sectors. Archaeological geophysics on the island of Ireland has a long history. The earliest surveys occurred at the early medieval Ráth na Ríogh on the Hill of Tara, Co. Meath, conducted by Professor Séan P. Ó Riordáin in 1952 using an unrecorded electrical resistivity survey, of which little is known (Byrne, 1995). Geophysical surveys thereafter were intermittent and infrequent, not becoming part of the Irish archaeological toolbox

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until the Celtic Tiger economic boom of the 1990s. Geophysical survey use prospered due to heritage-sensitive planning legislation that required scientific assessments of development-threatened archaeological sites, a situation that has more or less grown year on year. By 2010, archaeological geophysics was commonplace across the archaeological sector, substantially assisted by national road scheme infrastructure projects, private sector companies, academic institutions and the work of the Discovery Programme (a national research body).

This paper will review prospection strategies during that time in relation to soil analyses and their contribution to the discipline. The outcomes of a major research project on soil influence upon archaeological geophysics, completed in 2014, will be reviewed along with an examination of soil science in six case studies.

2 Reappraising Old Turf: 2001–2010

In 2010, the National Roads Authority (now known as Transport Infrastructure Ireland), commissioned a research fellowship to reappraise archaeo-geophysical surveys that occurred on their road schemes during the previous decade. The subsequent review of the 2001–2010 digital archives identified the impact pedological and geological variables had on magnetometry surveys (Bonsall, 2014; Bonsall et al., 2014a, b). The key challenges identified (Bonsall et al., 2014a) that are being faced by geophysical practitioners in Ireland include:

- Frequent carboniferous limestones (covering 49% of Ireland) and overlying boulder clay (tills), consistently returned poor results for 1 m × 0.25 m acquired magnetometry data due to low contrasts. This can be overcome to some degree via high-resolution data capture, with recommendations for the acquisition of magnetometry at 0.5 m line spacing.
- The physiochemical properties of peat and alluvium strongly influence the outcomes of geophysical assessments. With 16.5% of Ireland covered by peatland, it is an almost unavoidable challenge for practitioners working across a range of soils. Weston's (2004) research on conventional magnetic surveys over floodplains and alluvial soils in Yorkshire, U.K., is relevant for prospection strategies in Ireland: waterlogging impedes and/or prevents magnetic susceptibility enhancement. Less enhancement (or its absence) may occur in waterlogged environments. Heated soils (rather than burnt soils) in waterlogged environments suppress magnetic susceptibility, challenging the expected response (i.e. thermal alteration of a soil as a pathway to magnetic enhancement). Further case studies from California, U.S.A., and the U.K. (Singer & Fine, 1989; Armstrong, 2010) also found that magnetometry and magnetic susceptibility were of limited use on peatland, gleys, and waterlogged sediments—soil types that occur extensively across Ireland.

- The most common archaeological monument in Ireland, ringforts (early medieval circular enclosed farmsteads) failed to appear clearly in magnetometer data in 35% of cases due to local pedology. Ditches that were cut into heavy boulder clay and exposed to a wet climate, resulting in waterlogging and silting, were not identified by standard 1 m × 0.25 m resolution magnetometry. The wet climatic conditions promoted peat growth and the eventual depletion of iron-oxides (Doggart, 1983), resulting in low- or non-contrasting magnetometer anomalies for ditched enclosure monuments. An improved magnetic signal was found if a ringfort was cut by a drainage ditch, which reduced waterlogging and permitted iron-oxides within the ditch fill to contrast with the surrounding soils (Bonsall, 2014).

3 Breaking New Ground

Following review, improvements in acquisition and assessment strategies and guidance were recommended (Bonsall et al., 2014a, b; Bonsall, 2014), which Transport Infrastructure Ireland (TII) has since embedded within its procurement strategies to inform the design of appropriate geophysical specifications. These guidelines have also been used in specifications for infrastructure projects in Northern Ireland and Scotland, which share some of the same challenging soil conditions as Ireland. The poor performance of magnetometry on certain soils was noted and the increased use of electromagnetic induction (EMI) surveys to collect apparent electrical conductivity and/or apparent magnetic susceptibility data was advised. Since 2014 there has been an uptake in the use of EMI as a complement to magnetometry (Bonsall & Gaffney, 2016). Several years of intensive geophysical data collection have since occurred across Ireland, with improvements in data collection and a better understanding of techniques appropriate for varying geological conditions.

Despite improvements, few recent assessments have benefitted from an interrogation of soils themselves. Whilst it is standard practice to include a discussion of geology and soils encountered (and their expected or actual impact) in geophysical reports, these details are often absent from published case studies. Many recent high-profile publications for instance, omitted a discussion on the significance of soil properties upon the outcomes of a survey, many instead merely stating the geological conditions as an introduction to the receiving environment (e.g. Bhreathnach & Dowling, 2021; Cummins et al., 2018; Fenwick, 2017, 2021; O'Brien et al., 2014; O'Brien, 2017; O'Driscoll et al., 2020; O'Driscoll & Gleeson, 2021). A small number of welcome exceptions to this trend have been published however, five of which are critically reviewed here (Fig. 1). A sixth case study is presented from the island of Inishbarnóg, Co. Donegal, the findings of which suggest further pathways for integrating soil and prospection data. Together, these case studies provide a clear template for soil-focused prospection research with valid outcomes that are important for researchers in Ireland and beyond.

Fig. 1 Map of sites discussed

4 Topography

The first case study examines the use of topographical data. Soil influences upon prospection data include drainage, the organic horizon, topsoil and underlying geology. Any baseline study of soils should incorporate detailed topographic data. Curran's (2019) research integrated LiDAR data to prospect for archaeological sites in previously neglected areas of Ireland. Development-led projects are an important driver for archaeological assessments across the country, however these occurred infrequently in Curran's study areas of Counties Leitrim, Roscommon and Monaghan. The LiDAR analysis increased the number of previously recorded monuments by 21%. A key outcome of the research was the identification of ringfort monuments on the poorly draining soils that typify the study areas. The lack of drainage resulted in gleys that, as discussed above, historically hinder the detection of cut features in magnetometry. Geophysical surveys aided the research, but the outputs were chiefly generated from multiple LiDAR-derived visualisations within an integrated geographic information system (GIS) to study minute contrasts in topography.

5 Upland Peat

Knocknashee, Co. Sligo comprises two Neolithic tombs, a complex of Late Bronze Age house sites and enclosures on the summit of a small mountain in the northwest of Ireland (Brandherm et al., 2018, 2020). The entire 21.5 ha summit was assessed with a 5 m × 5 m volume specific (topsoil) magnetic susceptibility survey supplemented by selected magnetometry and earth resistance surveys over known house sites in 2016 (Fig. 2). The plateau contained at least 50 house sites (and possibly up to 64) identified from unmanned aerial vehicle (UAV) photographic and GPS surveys (Brandherm et al., 2018). Areas of low magnetic susceptibility coincided with areas of blanket peats and heather. Other areas had a higher magnetic susceptibility that coincided with archaeological sites and features, including the Neolithic passage tombs and adjacent Bronze Age house sites. The expectation was that occupation hearths would increase the magnetic susceptibility within house interiors. However, the majority of house sites occurred in areas of moderate magnetic susceptibility (1×10^{-6} SI), and two occurred in areas of very low or negative magnetic susceptibility (-2 to 0×10^{-6} SI).

Magnetometry of three house sites (acquired at 0.5 m × 0.25 m), covered only by short upland grass, found previously unknown structures and enclosing elements that were not mapped by the UAV photographic and GPS surveys (Brandherm et al., 2018). The magnetic contrasts encountered were extremely low. The dynamic range of the magnetometer dataset was −0.6 to +2 nT. These weakly contrasting data challenge geophysicists to interrogate results aggressively. This was a successful survey, with circular house sites slightly visible as contrasts of +0.2 to +0.9 nT and a single

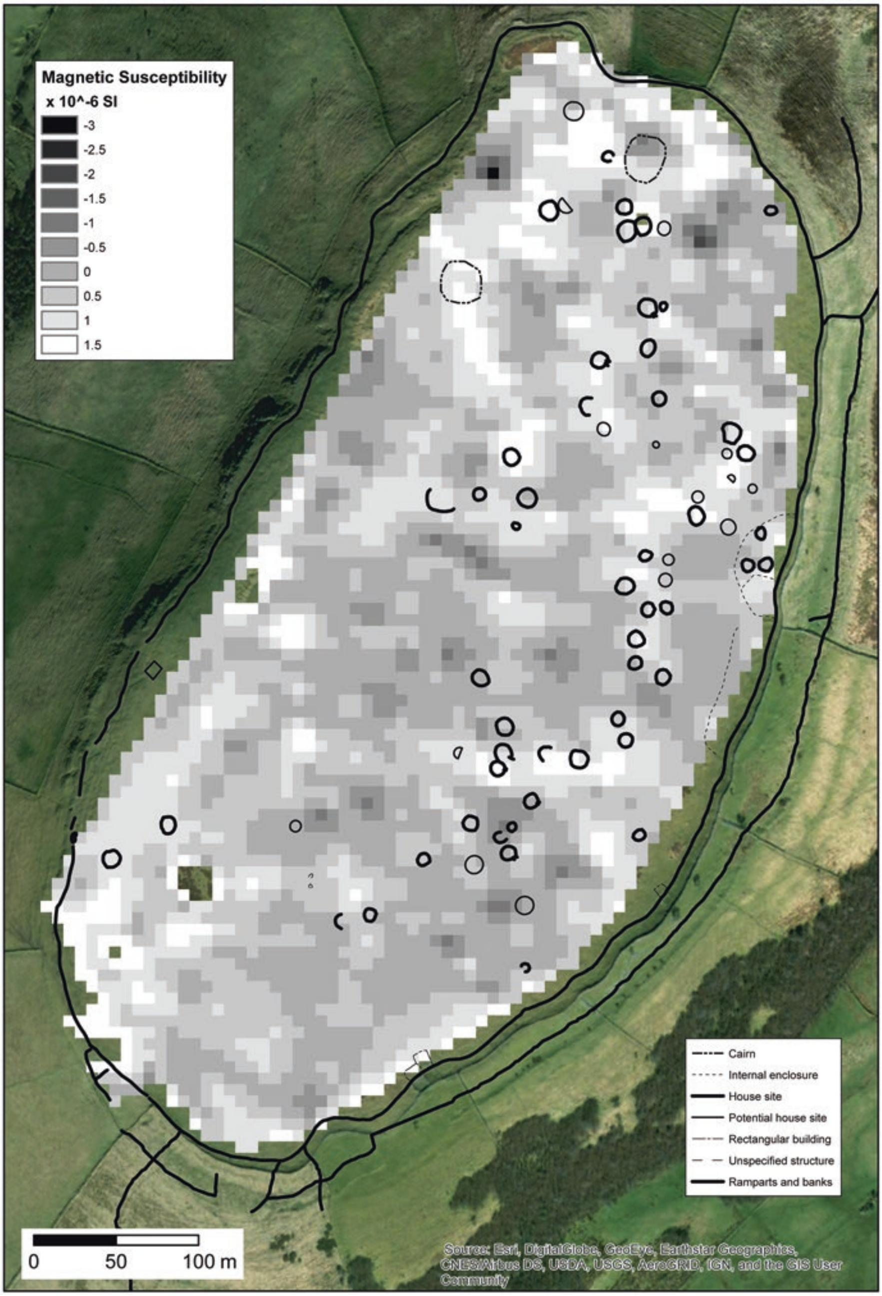

Fig. 2 GPS survey results overlain on magnetic susceptibility survey results at Knocknashee. (Reproduced from Brandherm et al., 2018)

pit identified. The impact of upland peats on geophysical data were discussed in the form of impeding magnetic susceptibility, both at Knocknashee and the wider area of Co. Sligo, where a combination of carboniferous limestone and overlying gleys are prevalent, often limiting the success of assessments that rely only on magnetic techniques.

Knocknashee included unpublished geochemical analysis (Bonsall, 2021). ICP-MS phosphate analysis of floor layers and wall footings were used to discriminate between buildings used for human habitation versus those used/occupied by animals. Moisture content, organic carbon, phosphate and mass specific magnetic susceptibility analyses suggested the deposition of organic material in a foundation layer of one house; waterlogged organic horizons formed after another house was abandoned; and limited peat growth suggested that some houses were more protected than others by extant wall footings. The geochemical data in turn allowed for a reappraisal of the earlier topsoil magnetic susceptibility and magnetometry data, particularly in relation to low-contrast or non-contrasting house elements. Weak contrasts can be managed when working with *a priori* data which targets specific sites that are expected to be present, such as the house sites at Knocknashee. However, for general prospection across large areas, the significance of weakly contrasting data representing archaeological features is typically overlooked.

6 Temporally Waterlogged Soils

Gimson et al. (2019) explored the impact of geochemical processes upon magnetometry data at Kilfinane motte, Co. Limerick. This medieval mound is surrounded by previously unrecorded archaeological features interpreted as banks, ditches, an outer bailey, external sub-enclosures, burgage plots, a large early medieval bivallate enclosure complex and pits, as well as a palaeochannel (Fig. 3). The clarity of the 0.5 m × 0.25 m data collected in 2017 is excellent but a notable change in polarity for the magnetometry data was observed. In Ireland, and most northern latitudes, the fill of cut features have a typically positive polarity; at Kilfinane they were mostly returned as negative anomalies. The magnetic susceptibility of some features was lower than the surrounding soils, resulting in a reverse polarity. This did not simply represent a strongly negative ditch-fill indicative of stony deposits (typically negative magnetism in this part of Ireland). Instead, the negative response was generated by the moisture retaining nature of the cut features, which was confirmed by EMI quadrature data (collected as apparent electrical resistivity). Two possibilities for this phenomenon are presented by the authors: (a) extensive waterlogging from a palaeochannel (which was also mapped by the survey as a negative magnetic anomaly), which caused the leaching of magnetic iron-oxides from the near surface and deposited them as iron-pan above deeper deposits, or (b) waterlogging combined with specific anaerobic conditions which impeded or destroyed the ability of iron-oxides to be magnetically susceptible. The effects of these two conditions, both of which are caused by the action of water, are known from other studies (see

Fig. 3 Results of the magnetometer survey at Kilfinane. (Reproduced from Gimson et al., 2019)

Weston, 2002; Kattenberg & Aalbersberg, 2004), but are rarely reported in such detail, and not in Ireland since the work of Doggart (1983). Gimson et al. (2019) found that similar conditions had been reported on a nearby infrastructure project, but those outcomes remain unpublished in a grey literature archive, accessible online. Another outcome of the polarity shift allows for a temporal classification of the archaeological features. Some cut features appeared as a 'normal' or 'expected' positive polarity, forcing the authors to conclude that the geochemical process could be used as a relative dating method. Gimson et al. (2019) argue that those anomalies returning an 'expected' positive anomaly, created during a drier climatic period, must therefore date to a different period than those with a negative polarity, effected by the extensive waterlogging. Of note is that the work was not commissioned by development-led projects or academic research, but by a small community group interested in their local monument, funded by the Heritage Council's Adopt a Monument Scheme. The results of a standard private sector 'monument survey' were unexpected and have led to research outputs that raised awareness of a rarely seen phenomena, benefitting the prospection community.

7 Phosphate Prospection

While phosphate analysis is sometimes used to investigate excavated soil samples (such as Knocknashee), it is rarely used in Ireland for prospection, with few papers published on the subject since the 1980s. Two recent studies have used phosphate prospection via a modified spot test, based on Ullrich's doctoral research that refined the Eidt (1973) method of determining inorganic active phosphorous. Despite the increased use of portable XRF in the field, it is interesting to see a variation of the Eidt method returning to archaeological prospection strategies following a critical assessment of its (often controversial) use and outcomes (Ullrich, 2010). The key modifications to the method are soil analysis in controlled laboratory conditions (eliminating temporal climate influences and unequal solubilisation of soil phosphate types), resulting in reproducible data, and a refined classification protocol that breaks phosphate values into quarters (creating a discrete and specific value rather than Eidt's broader classification system). For a full discussion of the modified Edit method, see Ullrich (2010, 2013) and Nevin (2021).

Ullrich's (2013) phosphate prospection surveys at promontory forts on Achillbeg and the Achill islands, Co. Mayo, looked at the division of space within the interior of Dun Killmore, pathways at Gubadoon, distinct patterning around structures at Dun Bunnafahy, and middens, banks and ditches at Dungurrough. Obtaining high-resolution 3 m × 3 m data from four promontory forts and controlled samples beyond the monuments, Ullrich challenged previous interpretations of the forts as small farmsteads due to the distribution of low background responses. The research lacked complementary geophysical/topographical data and other geoarchaeological analyses; phosphate responses were compared only to known features seen on the surface. Nonetheless, the investigation of use-of-space models will greatly aid future research as Ullrich assembled—for the first time in Ireland—baseline anomalies for a range of archaeological feature types.

Nevin's (2021) phosphate prospection survey contributed new and significant outcomes to research at the early medieval settlement complex of Raystown, Co. Meath. The survey was located over an enclosure that had been previously identified through magnetometry (GSB Prospection, 2002) and was contiguous to an excavated area of the core settlement (Seaver, 2016). Phosphate samples were recovered from the plough zone, on a 3 m × 3 m grid, mapped with an RTK GPS (Fig. 4). The 225 samples were processed using Ullrich's refined Eidt method (Ullrich, 2010). Increased phosphate responses occurred along most of the enclosure ditch as mapped by the magnetometry. The excavated portion of the Raystown settlement complex contained widespread metalled (stone cobbled) surfaces, and Nevin argues that a similar surface could be responsible for lowering phosphate levels within the enclosure. An unfortunate omission in this paper is an image of the magnetometry data, which would have led to important discussions of small, isolated phosphate peaks and their relevance to magnetic anomalies at the same location. However, new and significant insights were created by combining magnetometry interpretation drawings and phosphate data in a GIS. Discrete zones of increased phosphates that began at (and trailed away from) breaks in the enclosure ditch

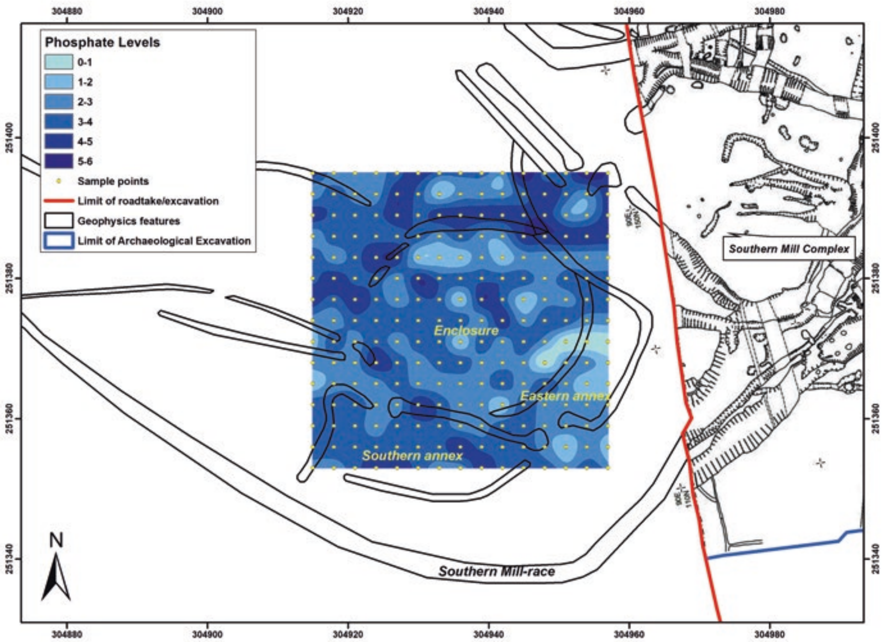

Fig. 4 Phosphate survey at Raystown. (Reproduced from Nevin, 2021)

revealed previously unknown pathways/droveways. The 2002 magnetometry survey benefitted from a 2011 phosphate survey, carried out some 6–8 years after a large-scale excavation in adjacent land. The Raystown phosphate research demonstrates clearly that new data can add to interpretations from legacy data archives.

8 Geophysics and Geoarchaeology at Inishbarnóg Island

A final case study comprises ongoing research at the island of Inishbarnóg, Co. Donegal (Bonsall, 2016; Bonsall, 2018). The investigation focuses on a magnetic susceptibility survey across the entire 4.9 ha island, which also benefitted from additional geoarchaeological analysis of soils recovered from eroding human burials at the east end of the island (see Fig. 5).

The only archaeological monuments or upstanding features on this uninhabited island are cultivation ridges, a midden and 22 early medieval burials (with disarticulated remains of a further 12 individuals) that were examined in 2003 and 2015 in response to erosion (Crumlish, 2006; Lynch, 2018). Inishbarnóg contains beach sands, cultivation ridges, peat, waterlogged soils, lithosols and rock outcrops from the underlying pelitic, semi-pelitic, psammitic schist geology. The deeper soils, containing areas of potential sub-surface remains, are compromised by substantial loose and fragile deposits that are disturbed by an unchecked population of rabbits. A volume specific magnetic susceptibility and detailed walkover survey occurred across the entire island in 2016. The survey assessed the suitability of detailed earth resistance and magnetometry use, based on the ease of pedestrian survey across/through the eroding rabbit warrens and the zones of archaeological potential suggested by magnetic susceptibility.

The survey data (Fig. 5a) were acquired at a 10 m × 10 m resolution using a Bartington MS2 Magnetic Susceptibility Meter and MS2D field loop, linked to a Trimble Pro-XRS Differential Global Positioning System that displayed predetermined sample locations. The weakly positive magnetic susceptibility responses may reflect soil alteration due to anthropogenic activity. Weak negative diamagnetic responses are most likely caused on the island by areas of waterlogging, surface water or organic matter. Topographically distinct nineteenth century cultivation ridges (known as 'lazy beds') produced a low magnetic susceptibility that may reflect an absence of iron-rich fertiliser. Relatively high responses occurred on the western and southern points of the island; these and some moderate-to-strong responses at the head of the bay around the intertidal zone may be indicative of hearths (ancient or modern) and middens (see for example Batt & Dockrill, 1998; Dalan, 2008; Napora et al., 2019).

Following the 2015 rescue excavation of exposed burials in the intertidal zone, soil samples became available for a geoarchaeological analysis of grave fills. The burials occurred within a 4 m × 4 m area, were shallow and exposed to erosional and depositional processes from storm tides. The bedrock was exposed at less than 30 cm from the surface during the excavation. Whilst no background samples were

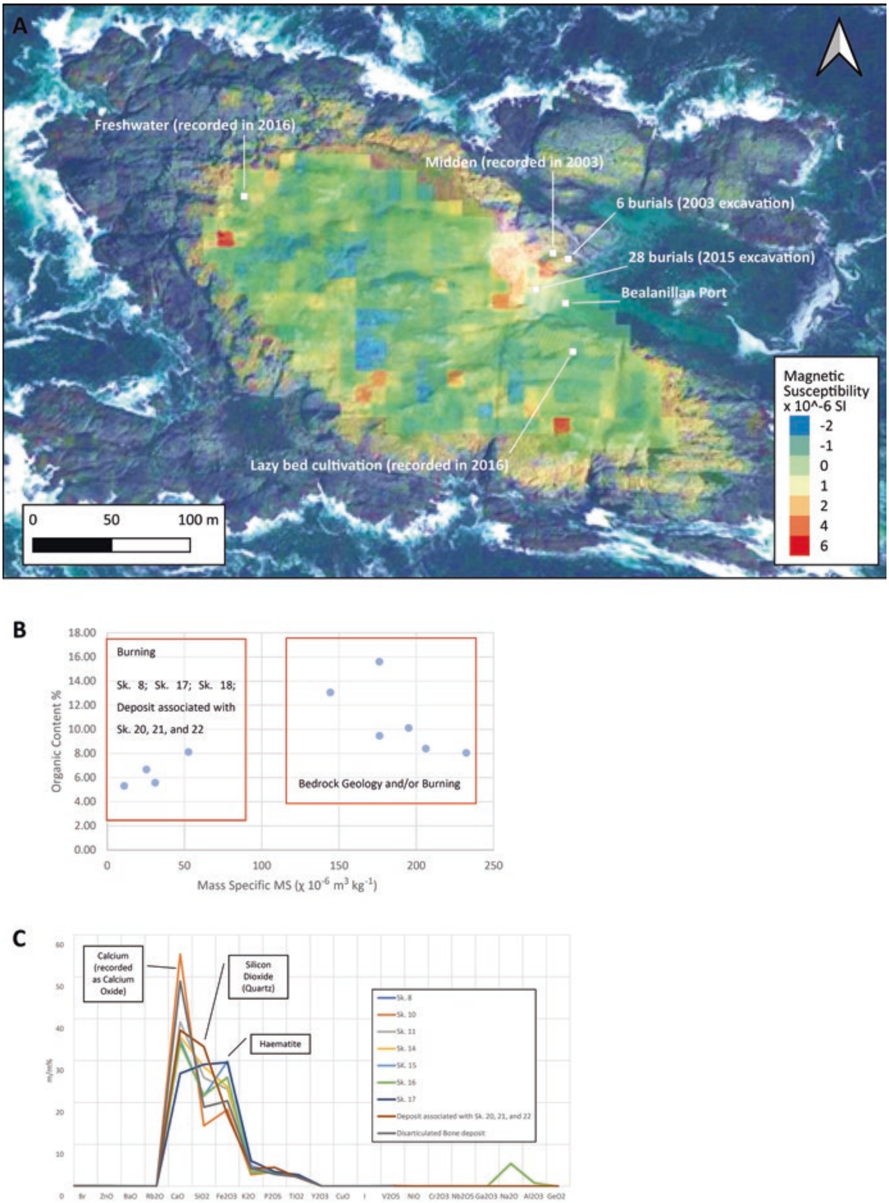

Fig. 5 Results from Inishbarnóg. (**a**) Magnetic susceptibility survey across the island overlying Digital Globe Satellite imagery (**b**) geoarchaeological analysis of soil samples from burials excavated in 2015 (Sk numbers quoted where relevant), (**c**) XRF results from soil samples associated with burials excavated in 2015 (Sk numbers quoted where relevant)

available for comparison, key differences were observed in soil chemistry, mass specific magnetic susceptibility, colour, organic content and moisture content for each inhumation soil sample. The diversity of inhumation samples has been attributed to a number of depositional and post-depositional factors (1) microvariations in chemical and physical properties of the locale that may occur naturally, (2) the decomposition of human remains which altered the measurable contrasts of the soil profile, (3) bioturbation from the rabbits, (4) the erosional/depositional tide that altered soil salinity (and potentially organic content), in turn influencing moisture content and (5) as identified by Lynch (2018), human disturbance of the cemetery to allow new burials.

The organic content and mass specific magnetic susceptibility (Fig. 5b) identified two groups of responses that reflected burning/low organic content and high magnetic susceptibility/high organic content. Mass specific magnetic susceptibility samples ranged between 11 and 232 × 10^{-6} m^3 kg^{-1} suggesting burnt soils and/or basic/ultrabasic rocks. The local schist geology is not a basic/ultrabasic rock, therefore the increase in magnetic susceptibility can be attributed to elements of burning within these deposits. This does not imply *in situ* burning, but could include burnt deposits within backfilled material.

An examination of minor elements and oxides were recorded by a laboratory Thermo Fisher Scientific QUANT'X X-Ray Fluorescence (XRF) Spectrometer. The XRF recorded small fluctuations and patterns for each burial deposit (Fig. 5c). Again, despite the small 4 m × 4 m size of the sampled area, a wide range of soil properties were exhibited, reinforcing the argument that each inhumation was an isolated event and that decomposition and erosion also contributed to differences in the geochemistry. The only similarities encountered are from two inhumations (Sk. 11 and Sk. 14) that have comparable minor elements present in the soil: these may have been deposited under similar soil conditions, at a similar time, or susceptible to similar post-depositional processes. These samples contrasted from the other burials considerably. There has been a substantial amount of exposure, erosion and deposition due to wave and wind action as well as some disturbance that allowed later burials. Some of the differences recorded by the soil analyses may reflect these variables in addition to decomposition.

The volume specific magnetic susceptibility survey of the island suggests that the cemetery is a component of archaeological activity focused around Bealanillan Port on the east side of the island. Some weak negative diamagnetic responses indicate that waterlogged soils or organic deposits are likely to be encountered across much of the island. The geoarchaeological analyses suggested that the benefits offered by a magnetometry survey will be compromised, to the point where the technique is expected to be inappropriate. The mass specific magnetic susceptibility and XRF data obtained from soil samples both warn of potential high contrasts due to the iron content of the backfilled graves. Earth resistance or EMI survey will therefore be essential when assessing the island. The walkover survey determined that further work will require a slow, deliberate and careful pace to enable hand-logging of data across parts of the island affected by extensive erosion and unstable, void-riddled rabbit warrens, precluding the use of articulated carts, rapid pedestrian survey and hand-towed GPR. There are however benefits offered by UAV-acquired photogrammetry, LiDAR and thermal imagery to avoid the challenges associated with terrestrial based-techniques at Inishbarnóg. The continuing evolution of UAV-acquired GPR and magnetometry is also promising for future assessments.

9 Conclusion

The case studies reviewed here have added to the corpus of soil studies and their application for archaeological prospection strategies, although there are thematic issues that need consideration. Knowledge gaps are clearly evident, with distinctions emerging between specialist geophysicists/soil scientists and non-specialist archaeologists who use geophysical methods. This is apparent in the use of geochemistry and EMI, and although no examples have been discussed here, also includes those techniques that require specialised knowledge, such as phosphates, ground penetrating radar, electrical resistivity imaging and induced polarisation. There are important benefits offered by these techniques, which are under-utilised in Ireland, and perhaps poorly understood by non-specialists. Archaeological interpretations were clearly increased by the added value of soil geochemical data in the work of Ullrich (2013), Nevin (2021), and the soils retrieved at Knocknashee and Inishbarnóg. Ullrich's collection of anomaly types for different archaeological features will particularly aid interpretations in the future. The knowledge gap created by the absence of Ronnie Doggart serves as a precautionary tale. Doggart (1983) published a variety of Irish magnetic susceptibility assessments that bridged the gap between archaeologists and soil scientists in the early 1980s; when he left the discipline, none were able or available to match his work and few if any surveys occurred. With few practitioners capable of carrying out the work, phosphate analysis may be similarly limited. Since adoption of archaeo-geophysical guidelines (Bonsall et al., 2014b) by Transport Infrastructure Ireland, the use of EMI increased to the extent that it has now become routine. The survey frequency of EMI devices increased from less than one per year in the late 1990s/early 2000s (13 between 1997 and 2011) to more than 12 per year in the 2010s (96 between 2012 and 2021). Despite this, EMI practitioners tend to be archaeo-geophysical specialists, contrasting with some magnetometry and earth resistance practitioners who are often non-specialist archaeologists with little training in geophysical techniques.

Curran (2019) and Nevin (2021) demonstrated the benefits offered by GIS to interrogate multiple datasets, particularly in relation to soil dynamics. This will only increase as Irish researchers now benefit from extensive soil data freely available online. The Geological Survey of Ireland (GSI) offers digital data for geology, quaternary, soils, groundwater, subsoil permeability and geotechnical borehole archives, all of which can be downloaded directly into a GIS. In addition to these datasets, the GSI (2024) has the Tellus database—the national mapping programme for geochemical and geophysical data across the island of Ireland, which collected airborne magnetic, radiometric and EMI apparent electrical resistivity data on 200 m transects at a nominal altitude of 60 m. These datasets, though airborne derived, assist broadscale planning for geophysical surveys when assessing the suitability or otherwise of magnetic techniques in areas of igneous or metamorphic geology. The geochemical data have been collected from stream sediments, topsoils and stream waters at locations that best reflect local land use/geology. The data are available as multi-element responses as well as topsoil pH, water pH, stream flow and non-purgeable organic carbon. Whist the scale is too broad for use at a single archaeological site, it does provide national baseline information that has previously been unavailable to the soil researcher, allowing for the first time a bespoke element of regional soil data.

All archaeologists should take an active interest in pedological and geological influences upon their data to increase the effectiveness offered by Irish prospection strategies. Sadly, this imperative tends to remain within the remit of specialist geophysicists only, despite the fact that soil influence is a key variable in the success (or otherwise) of an (in)appropriate geophysical survey technique. Too often published archaeological research in Ireland utilises geophysical data with only a cursory mention of geology, favouring instead a focus on data as a background map for site context or for excavation planning—'wall-chasing' is still very much alive.

The lack of integrated soil-geophysical prospection case studies can largely be attributed to the purpose of the survey and for whom it was commissioned. Private sector surveys adhere to best practice guidelines (e.g. Bonsall et al., 2014b; Schmidt et al., 2015) but rarely have time or budget to discuss research themes relevant to soil science—their contributions are most often confined to grey literature archives. Community-based geophysical projects, which have recently become a popular part of Irish archaeology, rarely engage in such matters which are largely beyond their remit, with Gimson et al. (2019) being a notable exception. It is then in the research arena that we should expect to see a careful consideration of the influence and impact of soils upon prospection data and sampling strategies. However, such analysis is largely lacking, and the reasons have been outlined above—there is an emerging knowledge gap between specialist soil-geophysical scientists and non-specialised archaeologists who use geophysical techniques. This gap must be bridged in order to advance the discipline and provide meaningful interpretations for archaeological research.

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Part XII
Mexico

Integrated Archaeological Prospection Studies in Mexico: A Review

Jorge Blancas, Luis Barba, and Agustín Ortiz

Abstract This chapter provides a retrospective of the work carried out by the Archaeological Prospection Laboratory, of the Institute of Anthropological Research, National Autonomous University of Mexico (IIA, UNAM). In 1983, geophysical surveys, combining different methods, were performed for the first time to study the San José Ixtapa archaeological site. Since, multi-technique geophysical surveys, integrating a wide range of complementary methods such as satellite remote sensing and soil analyses, have been performed at other sites in Mexico. To illustrate the development of the work carried out for this institution, the chapter syntheses the main achievement of some key case studies.

1 Introduction

The term Archaeological Prospection describes the employment of several techniques to discover buried sites or gather information on the location and extent of know ones. Barba (1984) has posited that to recover archaeological information in a minimally invasive manner, we must combine different methods in a sequence and apply each of them in an appropriate fashion to ensure both efficiency and success. This sequence aims to acquire the most complete range of information from an archaeological site by studying the context's chemical and physical properties and assisting archaeologists in deciding the most suitable excavation strategy while saving time and money (Barba, 1990).

Following the experiences of other laboratories, but specially the integrated proposal of the Lerici Foundation in Italy, the IIA-UNAM's Archaeological Prospection Laboratory was founded in 1983 to provide with new methods for archaeological research in Mexico. The initial methodological base has been further developed

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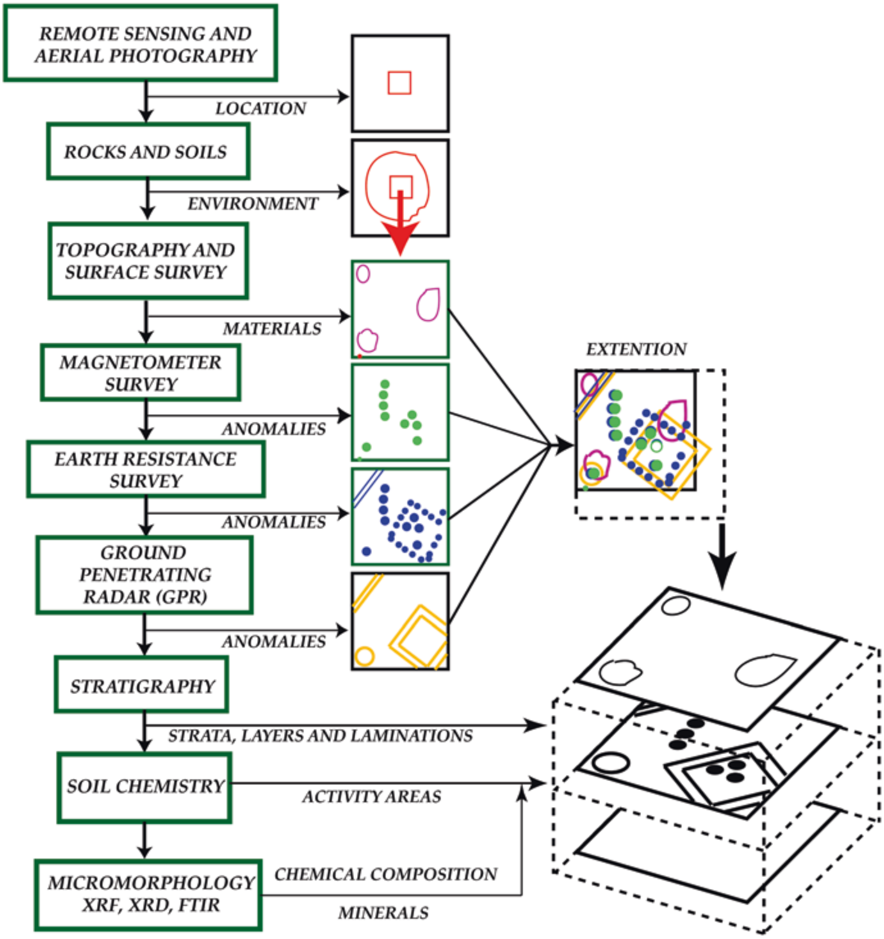

Fig. 1 Methodology applied by the IIA-UNAM's Archaeological Prospection Laboratory to study archaeological sites. (Barba, 1984, 1990; figure modified by Blancas, 2012)

including new technology such as satellite imaging digital analysis, ground penetrating radar survey and spectrometric analysis of soil samples (Fig. 1).

2 Case Studies

Table 1 summarises the methods used at the five case studies: San José Ixtapa, Oztoyahualco (Teotihuacán), Santa Cruz Atizapán, and Tlajinga (Teotihuacán). These sites have been selected to provide an idea of the technique's evolution over time, to emphasise the role of the lime as building material and chemical indicator, and the importance of encouraging the integration of methods.

Table 1 Summary of the techniques and data collection parameters used in the San José Ixtapa, Oztoyahualco, and Santa Cruz Atizapán sites, and the most important characteristics recorded with each technique

Site	Techniques used	Distinctive attributes	Survey parameters
San José Ixtapa	Magnetometer Survey (total magnetic field)	Low density readings. Detected hearths and large stones. Magnetic anomalies suggest the estimated location of firing places	Transverse spacing 4 m Line sampling 4 m Total area covered 14,400 m^2
	Earth resistance survey	Low density readings. Mainly detected compacted earthen floor areas	Wenner array a = 1 m Transverse spacing 4 m Line sampling 4 m Total area covered 3000 m^2
	Chemical analysis (Spot test)	Relationship between carbonates and soil clear spots	Sampling every 4 m
	Spatial distribution of archaeological materials	Define diagnostic materials concentration areas	Surface sampling every 16 m^2
Oztoyahualco	Magnetometer Survey (total magnetic field)	Concentrations of stone building materials and hearths on the mounds. Presence of lime kilns	Transverse spacing 4 m Line sampling 4 m Total area covered 5312 m^2
	Earth resistance survey	Presence of lime plastered walls and floors	Wenner array a = 0.5 m Transverse spacing 4 m Line sampling 4 m Total area covered 5312 m^2
	Chemical spot test	Relationship between carbonates and soil clear spots	Sampling every 4 m
	Spatial distribution of archaeological materials	Define diagnostic material concentration areas	Surface sampling every 4 m^2
	Aerial photography	Synoptic view of the clear soil spots produced by calcium carbonate concentration	Total area covered 7000 m^2

(continued)

Table 1 (continued)

Site	Techniques used	Distinctive attributes	Survey parameters
Santa Cruz Atizapán	Magnetometer Survey (magnetic field gradient)	Presence of volcanic stone building material	Transverse spacing 1 m Line sampling 4 m Total area covered 108,400 m^2
	Earth resistance survey	Detection of walls, floors, and trenches	Twin-probe spacings a = 0.5 m and 1 m Transverse spacing 1 m Line sampling 1 m Total area covered 3800 m^2
	Ground penetrating radar (GPR)	Detection of looted mounds, walls, floors, ditches, foundations	Transverse spacing 1 m Line sampling 100 scans/m Survey length 11.1 km
	Chemical analysis (Spot test)	Mapping of cultural activities enrichment	Sampling every 100 m Total area covered 0.6 km^2
	Aerial photography	Aerial photographic mosaic. Synoptic view of archaeological mounds	Total area covered 1.2 km^2
Tlajinga Teotihuacan	Magnetometer Survey (magnetic field gradient)	Presence of volcanic stone construction material, offerings and furnaces	Transverse spacing 1 m Line sampling 0.25 m Total area covered 69,800 m^2
	Earth resistance survey	Detection of walls, floors, and trenches	Twin probe array a = 0.5 m Transverse spacing 1 m Line sampling 1 m Total area covered 6600 m^2
	Ground penetrating radar (GPR)	Detection of mounds, walls, floors, ditches, foundations	Transverse spacing 1 m Line sampling 100 scans/m Survey length 5.42 km
	Remote sensing	Surface material of archaeological structures	Total area covered 9 km^2

2.1 San José Ixtapa

In 1983, the first study integrating geophysical methods and chemical analysis of soil samples at an archaeological site in Mexico was carried out at San José Ixtapa. This is a Postclassic (AD 900–1521) site in the Temascalcingo Valley, Mexico State. It was first located by aerial photography due to the presence of clear soil spots and later verified by finding ceramic sherds covered by a mud and grass mixture (Limón, 1978; Limón & Barba, 1981). The evidence recovered from surface suggested the use of cinnabar and quicklime to produce mercury in ceramic pots sealed with a mud mixture. The motivation of the study was to test the methodological proposal and provide more lines of evidence to support the apparent production activities at the site (Barba, 1984).

Firstly, the entire terrain was explored to observe surface materials distribution. Afterwards, the topographic mapping of the site was undertaken by putting three grids over the areas of maximum material concentration (A, B and C). On top of them, all the surface materials were registered. To interpret results, environmental data, magnetometer surveys, surface artefacts distribution and chemical analysis of topsoil samples were taken into consideration. Simple, quick, reliable, low-cost chemical tests (carbonate and phosphate tests and pH determination) were performed in the lab.

Magnetometer survey, particularly from Grid B, indicated the presence of structures, stone retaining walls, and heating areas. Near these heating zones, the distribution of surface material showed the concentration of clay-covered potsherds. The combined results suggested that at this site liquid mercury was produced by heating cinnabar using quicklime inside small ovens made of two conjoined vessels sealed with mud mixed with straw (Barba & Herrera, 1986). The results of the magnetometer survey suggested hotspots where potential ovens could be located. The concentrations of mud-covered pottery fragments around Structure 2 suggested that in that area the ovens' lids were broken (Ibid: 101).

The work at San Jose Ixtapa not only showed for the first time the benefits of studying archaeological sites with a minimally invasive methodology, but also the usefulness of integrating the ethnographic record to illustrate such production activities (Fig. 2). For example, until recent times, gambusinos (rural miners) of nearby communities produced mercury using this kind of ceramic pots (Barba & Herrera, 1986).

2.2 Oztoyahualco, Teotihuacán

In 1985, the Antigua Ciudad de Teotihuacán Project (PACT) appointed a minimally invasive survey to study the Oztoyahualco site. The site contains a Three Temples Courtyard and a residential area excavated in 1986–1988 (Manzanilla, 1993: 23; Barba, 1993: 47; Barba & Ortiz, 1993: 545). The objective was to identify possible

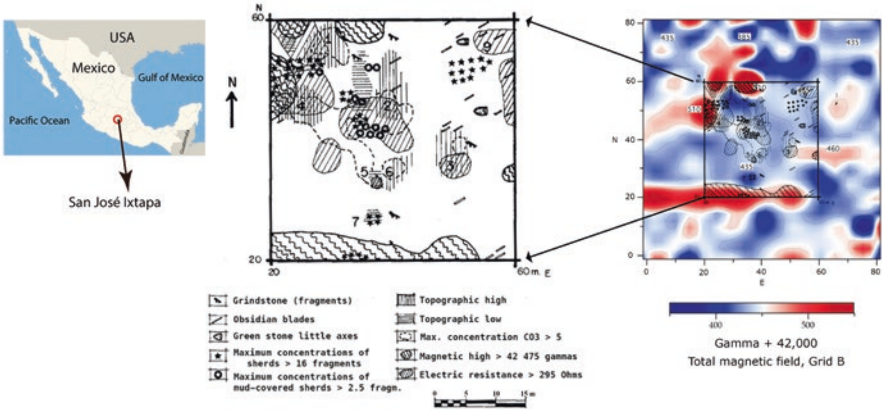

Fig. 2 Map of artefacts distribution and anomalies detected after the magnetometer survey in Grid B at San José Ixtapa. (Modified after Barba, 1984)

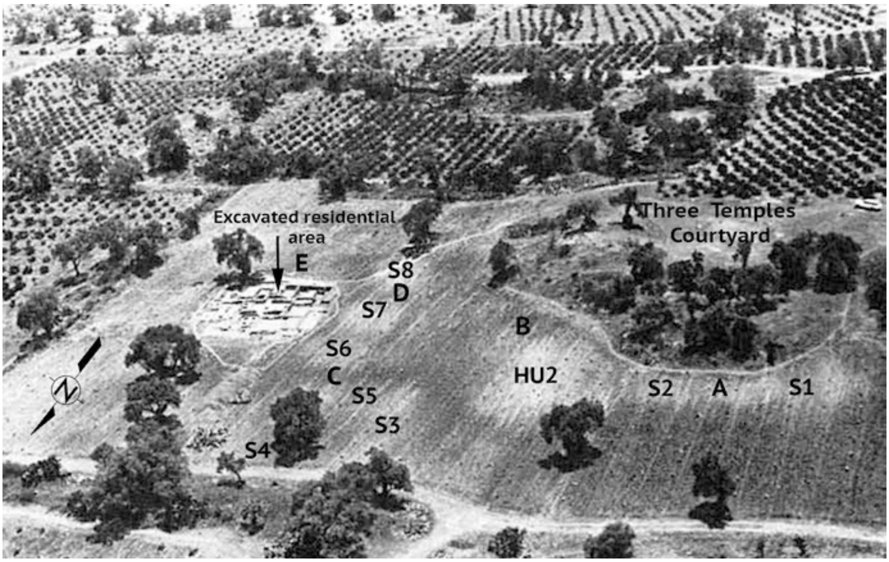

Fig. 3 Aerial photography of the studied area from a helicopter. Observe the clear soil spots produced by calcium carbonate concentration during the dry season. (Manzanilla, 1993)

archaeological features of interest as well as to explore the nature of clear soil marks identified in aerial photographs. The survey area (1 ha) was divided into the five sub-areas shown in Fig. 3.

A topographic survey (readings every 4 m) revealed a low mound at Area B and another at Area E. During a walkover survey, abundant building materials (e.g. volcanic scoria, stucco, and flagstones) were recorded at the centre-south of Areas A and B, west of Area C, and throughout the entire Area E. There were also clusters of small tezontle (volcanic escoriaceous stone) fragments impregnated in carbonates, especially in the north-eastern part of Module B, in central C Module, in the Centre-South sector of D, and the entire eastern band of E (Ibid: 50). The magnetometer surveys conducted at these areas detected magnetic anomalies of high intensity possibly related to subsurface hearths and burnt structures. The high resistance values of the earth resistance survey using a mobile array of electrodes (Wenner-Alpha configuration) also detected the presence of structural remains (Ibid: 57). The topographic data helped to define the total extent of visible mounds (suggesting subsurface structures), with good correspondence with the results of the earth resistance survey.

At the areas with clear soil marks, targeted manual augering was carried out to obtain information about the depth of these deposits. A maximum depth of 0.8 m was reached. Soil samples were collected every 10 cm for chemical analysis. Soil samples (of the top 30 cm) were also taken at modules C, D and E at 4-m intervals for chemical analysis (Barba et al., 1991). A direct correlation was seen between the carbonate concentration values and the location of the clear soil marks (Fig. 3).

Overall, the combined interpretation of all data suggested that north-eastern of the Three Temples Courtyard and north-western of excavated residential complex lay another residential unit (HU2) and other structures (S1–S8) (Fig. 3). The presence of high values of phosphate concentration in Module E indicated an accumulation of garbage and other organic waste close to the Oztoyahualco residential unit. The collapse of structures points to an accumulation of construction debris. Among these materials, the disintegration of lime plaster may have caused the high carbonate concentration values in the soil, hence the clear colour of the soil marks. Considering the distribution of the surface findings, the high concentration of carbonates, phosphates and the geophysical data, it was evident the potential presence of a rectangular structure in Module E and was suggested as a promising location to target with an excavation. This was later excavated, appearing a residential complex with several rooms, patios, corridors with several levels of floors and walls, as can be seen in Fig. 4 in the red outline and in the aerial photography.

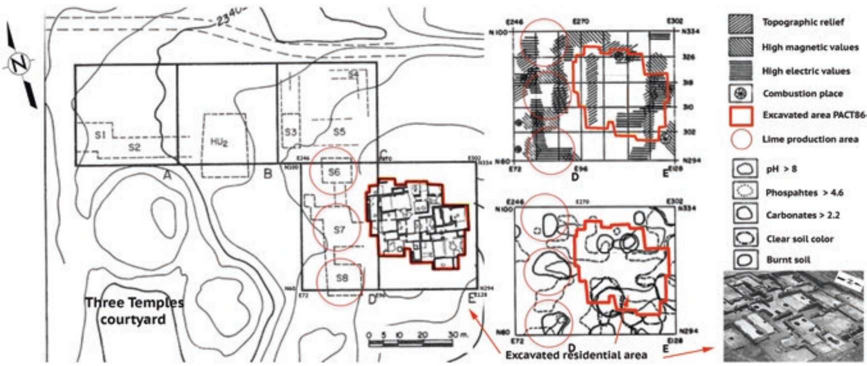

Fig. 4 Results of the different analyses carried out in Area *D* and *E*. The excavated area of the residential area of Oztoyahualco is outlined in red. (Figure modified from Barba & Ortiz, 1993)

2.3 Santa Cruz Atizapán

The Santa Cruz Atizapán site (AD 550–900) is located on the eastern bank of the Chignahuapan bog, in the Toluca valley, Mexico State, spanning approximately 1 km^2, encompassing 100 archaeological mounds. To build them, materials, such as sediments, wood, and volcanic stones were collected from surroundings. Many of these mounds were found near the shoreline of the bog, but the main structures were found on hillsides, ~10 m above the water surface (Fig. 5).

The surveys were conducted during several field seasons. The magnetometer survey revealed the presence of volcanic stones used to build the mounds, which had domestic and ceremonial functions (Blancas et al., 2017b). It also revealed a circular building of 10 m of diameter buried alongside a bell-shaped mound within the settlement's core and a straight stone paved road over 300 m long, and several small stone structures in a big artificial island (Fig. 6a) (Ibid: 44–139). GPR was used to determine the internal structure of the mounds, but due to high water saturation of sediments it suffered penetration problems.

Soil samples were taken every 100 m in the centre of the agricultural fields and selected mounds. Ten centimetres cores were also drilled to register the main stratigraphic changes caused by the building of the mounds (Terreros et al., 2017). In addition, semi-quantitative chemical tests were applied to 269 soil samples based on the Laboratory's analysis protocol (Barba et al., 1991, 2009b). This study made it possible to obtain distribution maps of chemical residues and to relate: proteins to fish and insect consumption areas; carbohydrates to accumulation of decomposing cellulosic material around the mounds; carbonates to lime; and phosphate residues

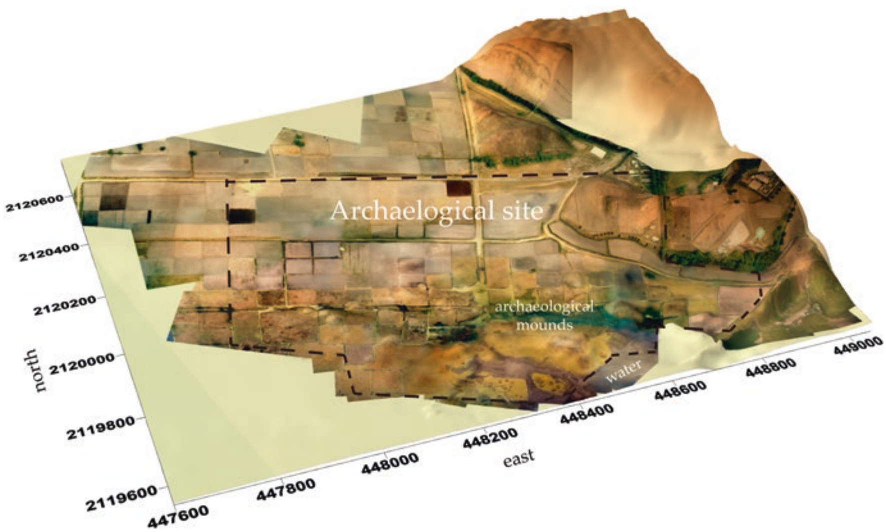

Fig. 5 Balloon aerial photography mosaic, overlapping digital terrain model in Santa Cruz Atizapán. (Blancas et al., 2017a)

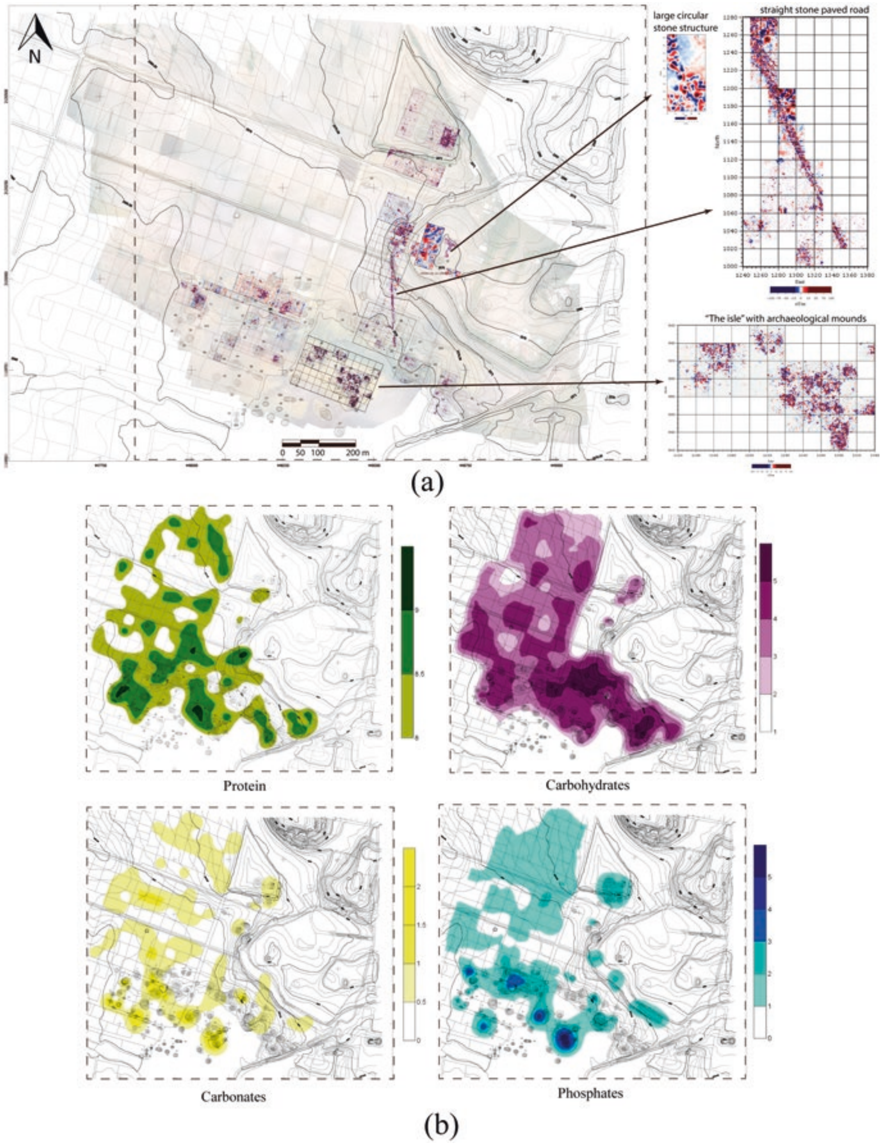

Fig. 6 (**a**) Results of the magnetometer survey at Santa Cruz Atizapan showing three areas with important archaeological remains: small section of a large circular structure, straight stone-paved road, and an isle with a complex of archaeological mounds. (**b**) Distributions of protein residues, carbohydrates, carbonates, and phosphates concentrations expressed on arbitrary scales (Barba, 2007). Their enrichment correlates with the larger mounds and suggests that more intense activities were performed in these areas

to areas inhabited by human groups. Figure 6b shows that the distributions of these residues are clearly associated with the area occupied by the pre-Hispanic mounds, especially in the area called “The Isle”, and in the areas related to waste and food consumption activities.

2.4 Tlajinga, Teotihuacán

Tlajinga is in the southern part of the large Teotihuacan complex, north-east of Mexico City, following the Avenue of the Dead, the city’s main pilgrimage route and its N-S axis, 1.5 km from the Citadel. Spanning roughly 1 km^2, it is set on a gentle slope of vertisol soil farmland. It receives water from the Patlachique range that spill to the north towards the San Lorenzo River (Fig. 7).

Arising from the work of Nichols (1988), Storey (1992) and Widmer and Storey (1993, 2012) in the Tlajinga quarter, an interdisciplinary research project was undertaken combining remote sensing, geophysical survey, soil physicochemical analysis, and excavations (Blancas et al., 2019).

Multi-spectral satellite imagery was helpful in identifying the locations of archaeological structures owing to the way their degraded building materials had combined with the surrounding soils and sediments. In the processing of this imagery, which included atmospheric correction by Chavez’s method (1996), the multispectral and panchromatic images were merged, giving a 41 cm’s spatial resolution, but with the same chromatic contrast of the multispectral images (Blancas, 2012). Using principal components analysis, anomalous patterns appearing with greater brightness and contrast were detected, which in some areas correlated with structures reported by the Teotihuacan Mapping Project (Millon, 1973) (Fig. 7). The distinctive reflectance was due to calcium carbonate from partially destroyed and buried structures that had mixed with the original soil (San Pablo Black Paleosoil (SPBP)) (Sánchez et al., 2013; Solleiro-Rebolledo et al., 2011). This study was extended by spectroradiometrically to determine the spectral signature of soil samples taken across the site. Those with high reflectance due to the presence of stucco or lime-based plaster were associated with collapsed archaeological structures.

The subsequent magnetometer surveys covered a total of ~6 ha and revealed landfills, heated surfaces, wall foundations, and other structures built mainly of volcanic stone. At the eastern part of the map (Fig. 7, right) there was an exceptionally large hill with a linear arrangement of magnetic dipoles related to the volcanic stones in walls. Other disordered dipoles were associated with debris. The magnetometer survey results from the 34: S3W1 complex showed a large platform and a other structural remains to the south (Fig. 7, bottom).

Besides, we collected reference materials to compare the geophysical results with the stuccos pf the Teotihuacan structures, caliches (natural carbonates) and soils, such as San Pablo Black Paleosoil (SPBP) upon which the Teotihuacan culture was developed (Fig. 8b).

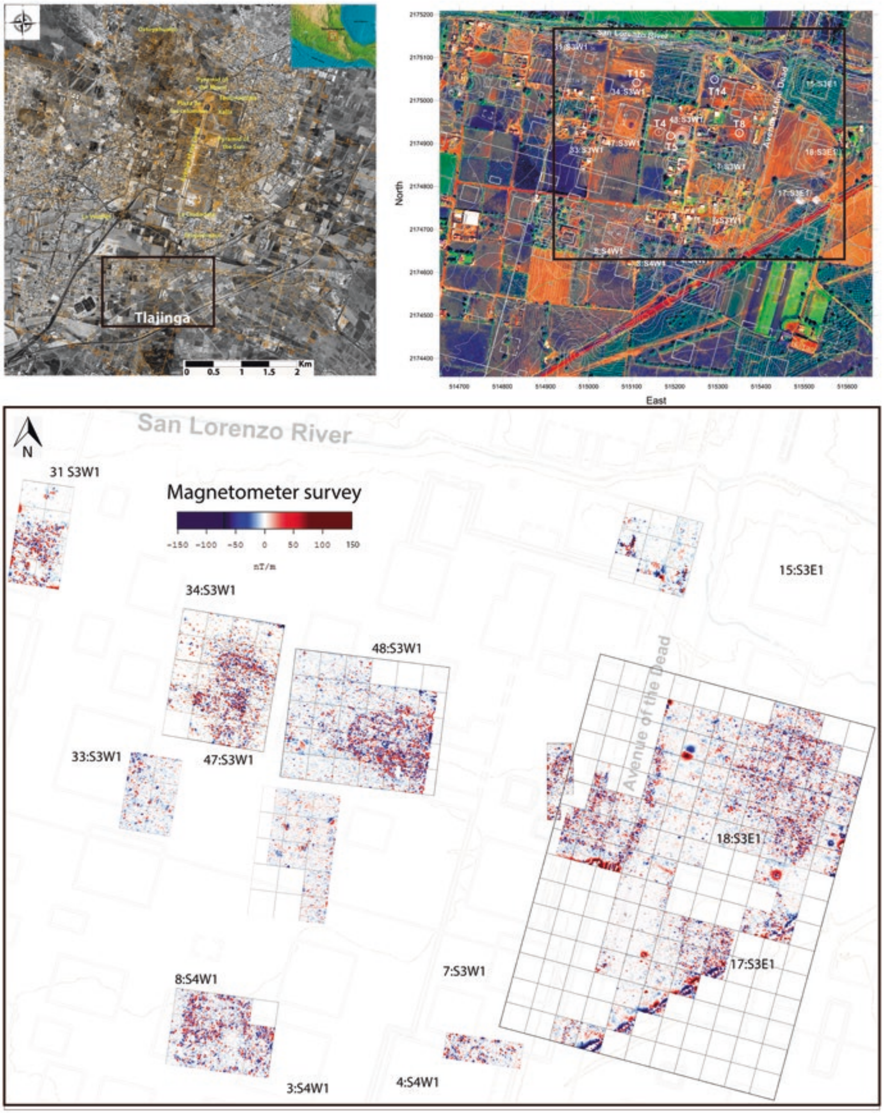

Fig. 7 Upper left, area of study location. Upper right, RGB satellite composite colour image of principal components (PC1, PC2, PC3), the shallow material of archaeological structures shows in orange colour, vigorous vegetation is related with green colour, and zones with greater moisture in blue colour. The soil samples (T4, T5, T6…) were analysed with FRX, DRX, micromorphology and FTIR. Below, magnetometer survey map of main archaeological structures (3:S4W1, 4:S4W1, 7:S3W1 …)

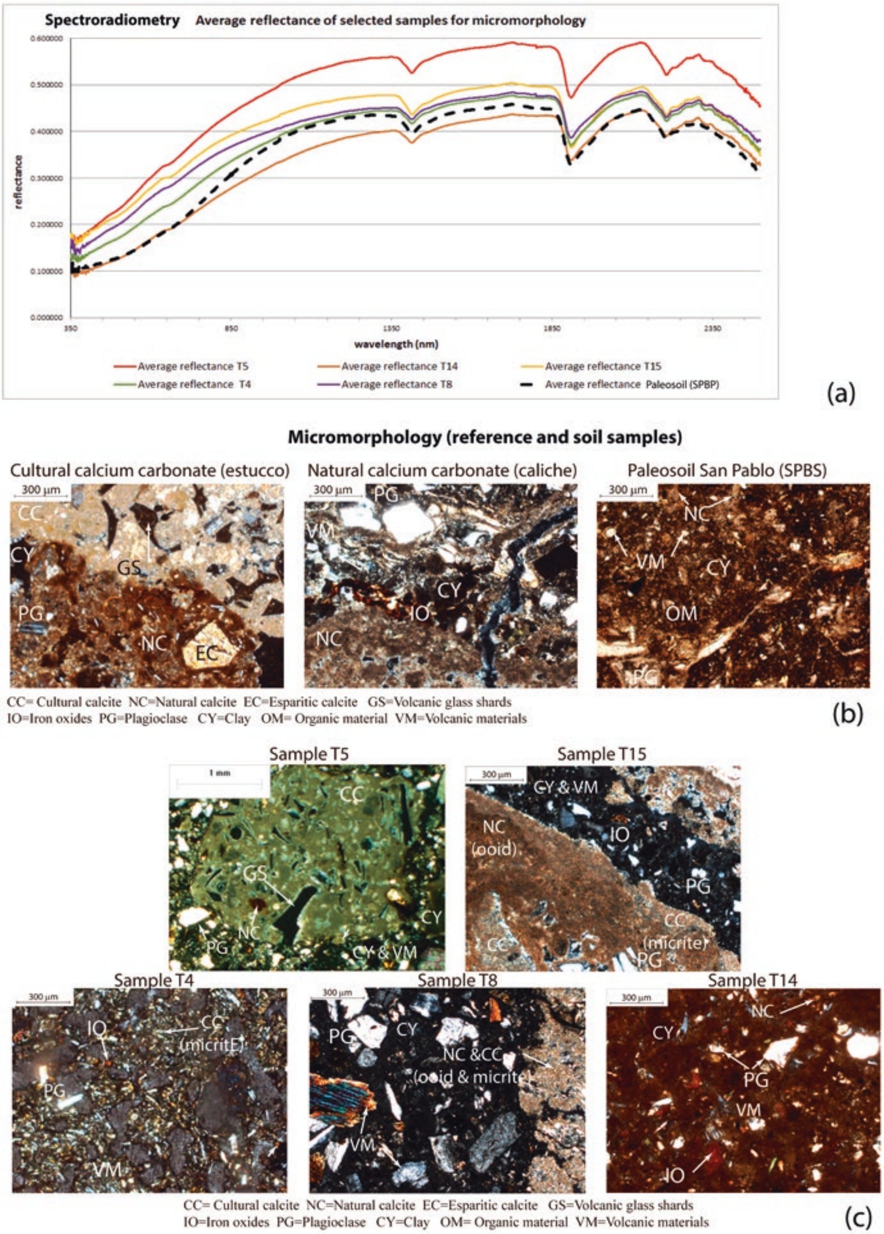

Fig. 8 Reflectance and micromorphology results. (**a**) Spectroradiometric measurements. Micromorphology in crossed polars of (**b**) reference and (**c**) archaeological samples

Petrographically, the soil samples were taken from the central part of Tlajinga (Fig. 8, upper right) contain assorted materials, of volcanic origin and related to cultural activities. Cultural calcium carbonates with well classified volcanic glass sherds were identified. Those were added for the preparation of flooring, and walls are mainly made of volcanic materials, such as ferromagnesium, plagioclases, or volcanic glass in different amounts. Stucco and caliche are chemically similar since both have calcium carbonate (Fig. 8c). However, caliche contains eolithic calcium carbonate as well as volcanic clays and minerals, while stucco has as aggregate sorted volcanic glass shards and calcite micritic crystallisation (Barca et al., 2013; Barba et al. 2009a, b; Guillén, 2018).

X-ray fluorescence (XRF) for caliche and stucco revealed an elementary chemical composition with a larger calcium concentration in comparison to soil samples (T4, T5, T8, T14 and T15). Conversely, soil samples had larger quantities of elements, such as Si, K, Ti, Mn, and Fe, all volcanoclastic origin. The elementary chemical content of the San Pablo Black Paleosoil (SPBP) layer and selected soil samples was basically the same. This is explained by the volcanic origin of these soils (Fig. 9a). The chemical concentration of the caliche and the stucco had remarkable differences in Ti, Mn, and Fe if compared to the soil samples and the SPBP.

Volcanic minerals found in the soil samples by micromorphology and X-ray diffraction (XRD), such as ferromagnesians, plagioclases and even glass, are in different proportions in the aggregates used for the preparation of the bases in Teotihuacan floors and walls. A striking difference between stucco and caliche, both calcium carbonates, is that caliche contains not only calcium carbonate, but also clays and minerals of volcanic origin. In contrast, stucco has sorted volcanic glass sherds as aggregates in the mixture (Barba et al., 2009a, b; Guillén, 2018). According to the results of this study, the calcium carbonate particles, mixed with the upper layer of the soil in this region of Tlajinga, modified and enriched the mineralogical content of the soils, and increased the reflectance of the upper soil horizon. Due to the intrinsic reflective properties of this mineral, mainly in the visible and infrared band, many of these anomalies come from the destruction of archaeological structures from the Teotihuacan period.

Finally, Fourier-transform infrared spectroscopy (FTIR) was applied to the stucco and caliche samples to determine whether the calcium carbonate was of geological or cultural origin (i.e. if the calcium carbonate crystal formation was related to an anthropogenic heating processes) (Chu et al., 2008). Looking at the three main infrared absorption peaks in the FTIR spectra in Fig. 9c, the caliche reference sample had a $\nu2/\nu4$ ratio of 3.01 indicating a natural geogenic origin. The stucco had a ratio of 5.86 that revealed a great atomic disorder and a larger probability of being of cultural origin. Soil T5, classified as of high reflectance, had a $\nu2/\nu4$ ratio of 5.72, consistent with a probable cultural origin. Soil T15 has a $\nu2/\nu4$ ratio of 4.23, which is intermediate and an indicator of a mixture of calcium carbonates both cultural and geogenic. The medium reflectance samples, T4 and T8, had more geogenic calcium carbonates, as most of the caliche could have been brought over from nearby natural

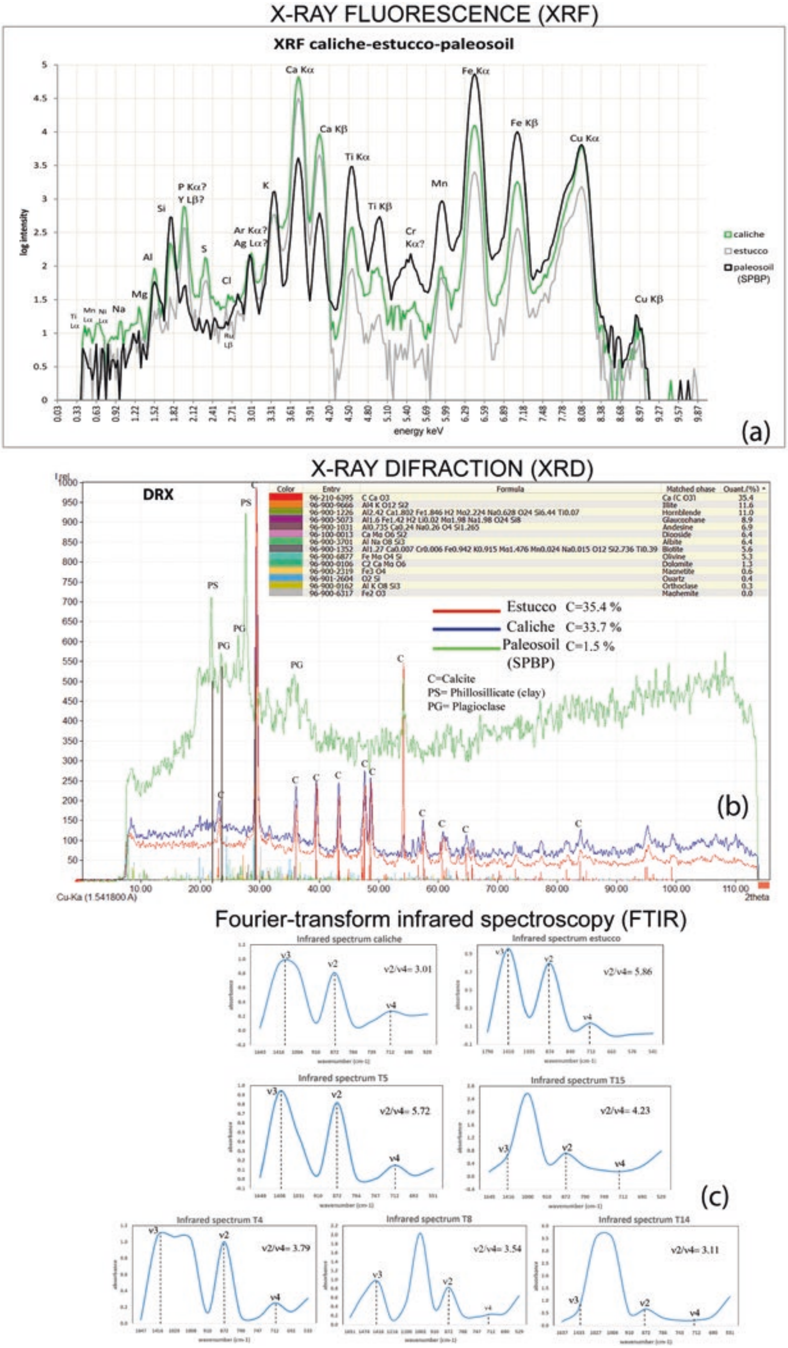

Fig. 9 Results of (**a**) XRF, (**b**) XRD and (**c**) FTIR analyses on soil and reference samples

sources. The T14 low reflectance sample was micromorphologically like the SPBP layer, with a $\nu 2/\nu 4$ value of 3.11, suggesting a clear geogenic origin.

3 Conclusions

This chapter has briefly reviewed the 40-year progress of the Archaeological Prospection Laboratory, of the National Autonomous University of Mexico's Institute of Anthropological Research. The early experiences and observations have over time been enriched with new equipment and the integration of a wide variety of technologies that provide a more robust information for the interpretation of buried sites. The soil, as packing material of archaeological remains, preserves a great deal of information that deserves our attention. In the examples presented here the calcium carbonate particles are a remarkable cultural material that plays a key role in understanding the buried sites studied with satellite imagery and land-based techniques. This is important since the presented case studies are in volcanic environments, then most of the carbonates detected are from anthropic origin.

San Jose Ixtapa was the first case study to test the proposal of prospection techniques integration. For the first time, it was established the direct relationship between clear spots in terrain and high values in carbonates, in this case, as a by-product of past activities. In our second experience in Oztoyahualco, Teotihuacan, the clear spots in terrain revealed the existence of archaeological structures once covered by lime plasters and was confirmed by high topographic and earth resistance survey values. In Santa Cruz Atizapan, carbonates were almost absent but the distribution of some other chemical indicators revealed the areas of more intense occupation, while magnetic survey was successful to detect the presence of the volcanic stones used as building material and at the end, we had the active participation of earth resistivity and ground penetrating radar as verification techniques.

At Tlajinga, which is the most recent and successful application of our study methodology, the results show that calcium carbonate mixed with the upper layer of the soil modifies the soil's mineralogical composition, increasing reflectance due to the properties of this mineral, which is visible in infrared light. Therefore, many of the anomalies in the processed satellite images come from the destruction of the Teotihuacan archaeological structures covered by lime plaster (Fig. 8). By gathering and analysing spectroradiometric, petrographic, chemical, and mineralogical data, we can assess the relationship between calcite in the soil's upper horizon and reflectance in satellite images to establish their correspondence. The location and characteristics of the destroyed archaeological structures were verified indirectly using geophysical survey with magnetometer survey, earth resistance survey, and ground penetrating radar. Later, archaeological excavations have been conducted in certain selected zones to verify results.

The results of Tlajinga study are applicable to all of Teotihuacan's spaces, since they shared the same building techniques, and were built over the same type of soil. Thus, most of the clear spots seen on the surface should be attributed to collapsed archaeological structures, especially spots on low hills. The origin of this observation in Teotihuacan was at Oztoyahualco in 1985, when for the first time these clear spots were seen on the ground surface and confirmed by chemical spot test. It can be concluded that the calcium carbonate particles in the soil are an inorganic compound that can be observed by remote sensors, verified by chemical tests as well as seen through a microscope, although thus far it has not been detected by geophysical measurements.

We have emphasised the role of carbonate particles because lime was an important material in Mesoamerica and on the other hand, it is quite common in literature to have reports of geophysical studies but is rather unusual to combine archaeo-geophysics and chemical data. Among more than 300 projects we have at present participated, we selected those cases where most of the techniques included in our methodological proposal were successfully applied and provided part of the information that at the end, produced a more integrated and better interpretation of the studied site.

In Mexico, there is just one Archaeological Prospection Laboratory (celebrating its 40 anniversary) full time devoted to applying geophysical techniques to the study of archaeological and cultural heritage sites. In addition, there are a couple of groups in research laboratories, that sometimes use geophysical techniques in cultural heritage projects. Occasionally, some teams from abroad come to Mexico to participate in some specific projects. There is just one commercial company in Mexico that provides this kind of services, the rest of the surveys have been performed by research laboratories. As a consequence, the great majority of the geophysical studies have been part of research work but in recent times some cases have involved federal government institutions and large infrastructure projects. By far, the most popular technique is magnetometer survey, but GPR is becoming more common every day. Less popular is the earth resistance survey.

Most of the studies have been carried on detecting and studying buried archaeological remains, but in recent times applications increasingly involve cultural heritage buildings diagnostic, sometimes to detect pre-Hispanic remains below colonial or modern buildings, some others, to define materials and construction techniques before historic buildings interventions.

For the future of archaeo-geophysics in Mexico, it will be necessary to increase funds to acquire geophysical equipment, as well as to promote the training of young geophysicist who want to be involved in cultural heritage studies.

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Part XIII
Moldova

Looking Through Earth: Archaeo-Geophysics and Soil Science in the Republic of Moldova

Mihail Băț, Octavian Munteanu, and Mariana Vasilache

Abstract The research carried out by co-opting the natural sciences opens a special perspective on studying the archaeological sites. In the Republic of Moldova, several legislative and normative acts currently regulates the use of the soil sciences and the non-invasive methods in archaeology. The beginning of geophysical investigations dates back to the 70s and 80s of the last centuries, and the prehistoric sites of Cucuteni-Trypillia culture have been researched at first. After a pause that lasted until the end of the first decade of the new millennium, the involvement of magnetometer surveys, in the activity of archaeologists in Moldova took on a new dimension. Currently, about 40 Neo-Eneolithic sites can be studied based on magnetometer survey data maps. Some of the images obtained are truly spectacular, such as, for example, those of Stolniceni or Petreni, which provide a clear picture of the internal organisation of the settlements, the types and dimensions of the archaeological structures, but more importantly, opening new opportunities for the development of targeted research strategies. Along with the Neo-Eneolithic sites, the sites from the Iron Age and those from the Roman Imperial era also aroused the interest of archaeologists. The Getic fortifications, whose defensive systems began to be understood in all their complexity, caught special attention. We should also mention the interest shown by the researchers of the Middle Ages, who, being at the beginning of the path, managed to open new perspectives for the study of medieval cities and fortresses.

In memory of Stanislav (Stas) Țerna

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At the same time, in all types of sites, regardless of the periods to which they refer, the experiences of soil scientists who come to offer new perspectives in interdisciplinary research, such as the determination of element concentrations of archaeological deposit for assessing past activity areas, are also increasingly used. In other words, even if we still have a lot to achieve in this field, the direction and increasing rhythms through which soil analysis and geophysical methods are embraced by archaeologists, makes us look optimistically at the future of research in the Republic of Moldova.

1 Introduction

Non-invasive methods of researching archaeological sites in the Republic of Moldova were first applied as early as in the late 1960s, when V. Dudkin carried out geophysical measurements at a number of sites of the Cucuteni-Trypillia culture (Dudkin, 1980). Later, in the 1970s–1980s, K. Shishkin made the first reconstructions of large sites of the Cucuteni-Trypillia culture based on aerial photographs (Bicbaiev, 2007).

After a break of two decades, due to mixed projects with international participation, non-invasive research of archaeological sites in the Republic of Moldova at the beginning of the new millennium was developing sweepingly, which led to the discovery of new sites and a reassessment of the archaeological potential. To date, magnetometer surveys were undertaken about at 60 archaeological sites, and their number continues to grow.

From the first instruments used—caesium magnetometers (Sava & Kaiser, 2011; Niculiță et al., 2012; Asăndulesei, 2016; Țerna, 2016), to systems with 5 or 16 sensors (Sensys MAGNETO®-MX ARCH) (Rassmann et al., 2016), coupled to GPS systems (Leica RTK-DGPS (base/rover) (Țerna et al., 2019), the quality and speed of data collection has evolved, finally providing overviews of the archaeological structures that formed the basis for the subsequent research strategy.

2 Good Practice in Archaeological Diagnostics: Non-invasive Survey of Complex Archaeological Sites

In the following lines, we will review the most important actions through which geophysical and soil research methods have come into use in archaeological investigations in the Republic of Moldova. In order to provide a clearer picture, let us trace the evolution of non-invasive archaeological research in chronological order: from the oldest to the most recent, or from the Neolithic to the Middle Ages.

2.1 Neolithic

Although they were fewer, Neolithic sites have undergone magnetometer surveys since the early 1980s. The settlement of the Starčevo-Criș culture Săcărăuca I was the first of its kind. V. Dudkin provided the first image of the underground structures (Dudkin, 1980); the results of the magnetometer surveys were used for comprehensive archaeological research by excavating the site (Țerna, 2016). In the period from 2014 to 2019, six other sites of the Neolithic era, single or multi-layer ones, were partially or completely explored: Sîngerei XIX, Mihailovca VII, Chișcăreni XIV, Nicolaevca V, Bumbăta III, Găureni I, which confirmed, following archaeological surveys and excavations, the presence of remains of the Starčevo-Criș, Linear Pottery, and Pre-Cucuteni cultures (Țerna, 2016). Particular attention should be paid to the Nicolaevca V site, which has a special archaeological potential confirmed by geophysical surveys and archaeological research in 2014 and 2019. Even though the Neolithic settlement attributed to Linear Pottery culture is located in an area with anthropogenic impact, the site was investigated during two research campaigns. The first geophysical prospecting campaign covered an area of approx. 4 ha. On the magnetometer survey results, two clear areas were distinguished: the first, located in the northern part, contained anomalies from structures placed in a circle (attributed by means of excavations to the stage Pre-Cucuteni—Trypillia A); the second, located in the south, represented elongated anomalies from four dwellings of the Linear Pottery culture (Fig. 1, red circle). We should note here that on the territory of the Republic of Moldova, the site of Nicolaevca V, attributed to the Linear Pottery culture, is the first to be discovered using magnetometry in the eastern area of this cultural horizon. The 2019 geophysical surveys covered an area of approx. 4 ha. In order to identify the southwestern border of the settlement, the measurements revealed the remains of at least 13 longhouses with related longitudinal pits (Saile, 2020).

2.2 Copper Age

As we have indicated in the introductory part, large-scale magnetometer surveys on Copper Age sites in the Republic of Moldova began in the late 1960s. In the next 20 years, magnetometer surveys were carried out at 12 sites of the Cucuteni-Trypillia culture (Țerna, 2016). These sites are different in terms of size, location, and dating. Thus, out of the total number of settlements, only one site belongs to the Pre-Cucuteni—Trypillia A culture (Sevirova II), three sites refer to Cucuteni A—Trypillia BI (Brînzeni-Ostrov, Trifănești, Putinești III), one site belongs to Cucuteni A–B—Trypillia B1/B2 (Old Orhei), and six sites to Cucuteni B—Trypillia B2, C1 (Racovăț, Ivanovca, Sofia-La Moină I, Sofia-La Moină II, Glavan I, Sofia II-Găvan) (Țerna, 2016: 192). This trend of interdisciplinary research was maintained in the

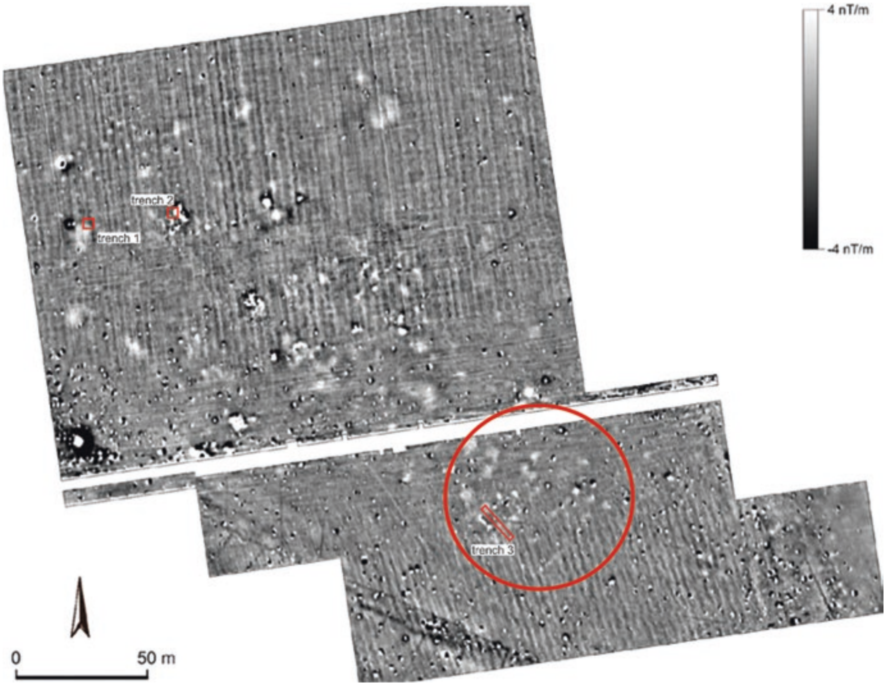

Fig. 1 Results of the magnetometer survey at the Neolithic site Nicolaevca V. The red circle indicates the area of LBK (Linear Pottery culture) longhouses. (From Țerna, 2016)

next ten years, until 2011. Consequently, magnetometer surveys were performed at five settlements belonging to the Cucuteni culture (A, A–B and B): Horodca Mare, Ochiul Alb, Cobani, Sîngerei, Petreni (Rassmann et al., 2016). In the recent period (2011–2021), the settlements of the Cucuteni culture at all phases of its development (Brănești, Stolniceni I, Cunicea I, Cunicea II, Cunicea III, Cunicea IV, Putinești III, Trinca-La Șanț, Gordinești II-Stânca Goală) and those of the Bolgrad-Aldeni/Gumelnița culture (Cucoara I, Cealîc, Chioselia Mare, Taraclia I) have been researched (Mistreanu & Przybyla, 2020).

Further, it is worth mentioning in more detail two sites of the Cucuteni-Trypillia culture, which stand out, on the one hand, by the size and spatial distribution of structures, and on the other hand, by the extent of archaeological research that followed the geophysical surveys.

Petreni. This site is indicative for the Southeast European Copper Age. It has a round shape in plan and covers an area of about 33 ha (Fig. 2(1)). The site has been known since the beginning of the twentieth century, being researched by E. von Stern during 1902–1903. In that first research campaign, eight structures were revealed: three in the central part of the plateau; two in its southern part; two in the western part; and one in the northern end of the settlement. In 1943–1944, archaeologists R. Vulpe and V. Zirra made several excavations in the southeastern part of the settlement; the results of the investigations have not been published. In 1947 the settlement was researched by T. Passek, during an exploration in the region. Later, in 1981, the site came to the attention of researchers V. Markevich and K. Shishkin, who also deciphered the first aerial photographs of the settlement. In 2009–2012, thanks to a Moldovan-German partnership between the Eurasia Department of the Roman-Germanic Commission of the German Archaeological Institute and the National Museum of Archaeology and History of Moldova, multidisciplinary research of the site was carried out. Amongst the most important results, we should first of all note, the obtaining of the geophysical and topographic plans of the settlement. The information provided by the magnetometer results was confirmed by excavations on several archaeological structures: dwellings, pits, and a ditch. Also, soil sampling and performing a new series of analyses (palaeobotanical, palaeozoological, pedological, radiocarbon) have contributed to the replenishment of databases on the phenomenon of proto-urban settlements in Southeastern Europe (Rassmann et al., 2016; Uhl et al., 2017).

Stolniceni I. Magnetometer surveys and archaeological excavations conducted in 2015–2019 revealed a large new site (27 ha), with a complex concentric structure (Fig. 2(2)). During the investigation, modern documentation methods were applied including the use of an electronic tachometer, photogrammetry, the use of differential GPS and a drone. Radiocarbon samples were taken for dating, as well as soil samples to determine element concentration to identify past activity areas using X-Ray fluorescence spectroscopy (XRF). The magnetometer survey results revealed about 370 dwellings, hundreds of pits, three ditches, a palisade, approx. 15 pottery kilns, access roads to the site, as well as areas of extra muros activity. The archaeological excavations undertaken in Stolniceni aimed to provide a more accurate interpretation of the result of the magnetometer survey by probing different types of geophysical anomalies, knowing the internal chronology of the settlement, and obtaining data on the social organisation of the prehistoric community. Thus, the remains of a surface dwelling, two pottery kilns and several pits in the enclosure were fully investigated. Along with the research of the fortification elements (ditches and palisade), the archaeological investigations revealed for the first time for the Cucuteni-Trypillia culture the existence of an access road. The data obtained as a result of archaeological excavations now make it possible to accurately interpret the geophysical plan, as well as to outline general guidelines regarding the internal chronology of the settlement and the way of organising economic activities, such as pottery production in certain areas of the site. Given the complex structure of the Stolniceni site, in which there are almost 30 quarters of dwellings of different sizes, the choice of research strategy was to be conditioned by the possibilities of detailed investigation of these stratigraphic units. Therefore, in 2019, a new working methodology was tested, based on minimally invasive archaeological research, which combines the systematic collection of surface archaeological materials with pedological drilling. This method allows, on the one hand, the collection of samples and materials for various types of analysis (chemical analysis of soil, human and animal DNA, botanical and palynological analysis, radiocarbon dating), and on the

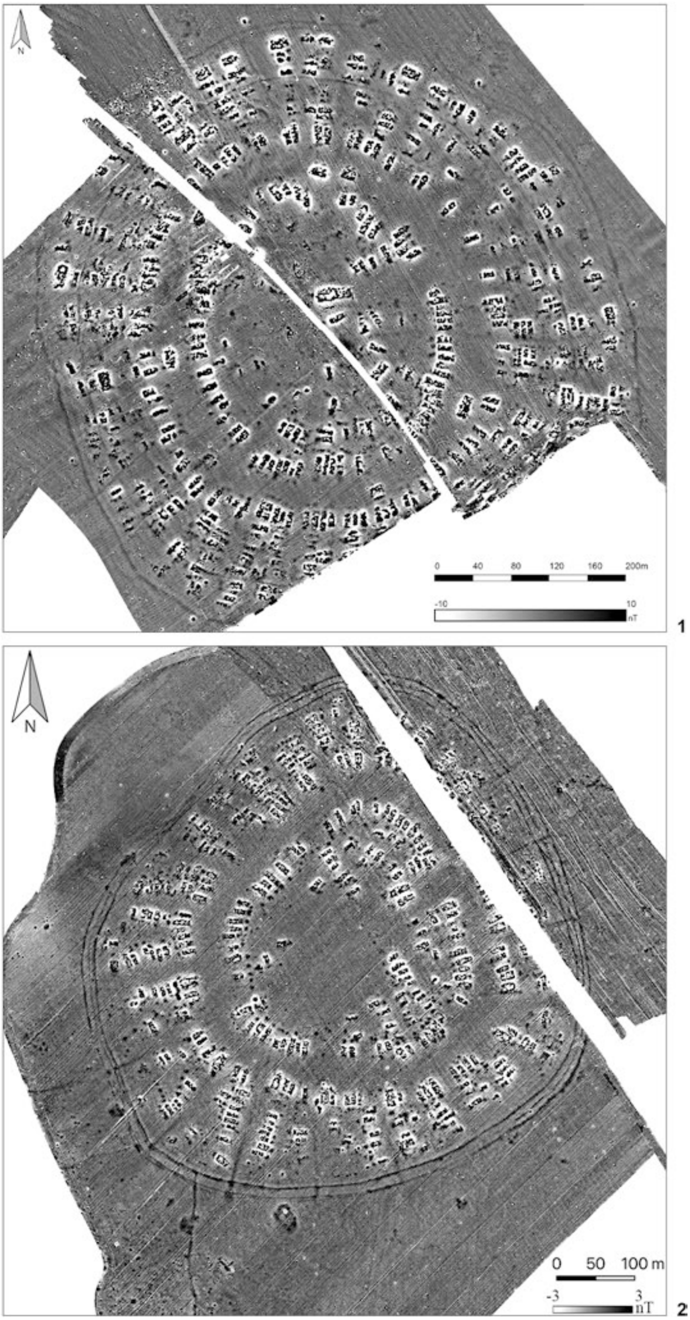

Fig. 2 Results of the magnetometer survey: 1—Petreni (From Rassmann et al., 2014); 2—Stolniceni I (From Ţerna et al., 2019)

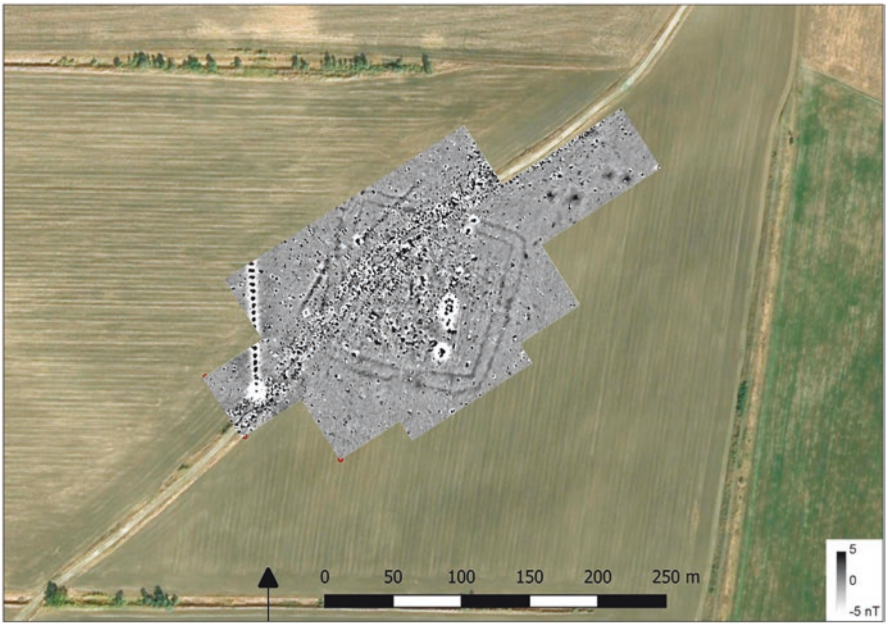

Fig. 3 Results of the magnetometer survey at Gumelniţa site—Taraclia I. (From Mistreanu and Przybyla (2020), licensed under CC-BY 4.0)

other hand, the investigation of many archaeological structures in a short time (Ţerna et al., 2019).

The only Gumelniţa site that has benefited from a complex approach and an archaeological research strategy involving several methods (from excavation in 1982–1985 to magnetometer surveys in 2019) is the settlement of Taraclia I (Fig. 3). The results of a joint project with the University of Rzeszów (Poland) allowed a full site scan and revealed an important information about the defensive system (double-sided quadrilateral enclosure and access roads on each side) and residential area. Although difficult to interpret, the result of the magnetometer survey of the Taraclia I site provided important data on Copper Age settlements in southern Moldova, completing the settlement database of the Gumelniţa-Kodjadermen-Karanovo VI cultural complex and laying the groundwork for new research (Mistreanu & Przybyla, 2020).

2.3 Bronze Age

Although there are numerous Bronze Age sites in the Prut-Dniester region, the amount of interdisciplinary research carried out on them has been limited. However, it should be noted that in the past two decades, special attention has been paid to the Noua-Sabatinovka complex, where interdisciplinary research was carried out on several archaeological sites. The research, coordinated by E. Sava (National Museum of History of Moldova) and E. Kaiser (Free University of Berlin), was aimed at investigating objectives in two different areas of the Late Bronze Age archaeological heritage: the northern part (Noua culture) and the southern area (Sabatinovka culture). Regarding the sites of the Noua culture in the north of the Republic of Moldova, we note that 12 became known thanks to aerial photography carried out by K. Shishkin in the 60s and 80s of the last centuries, and the subsequent interpretation of the aerial photographs by V. Bicbaev. One of them is the Miciurin-Odaia settlement with ash lenses, which offered the most important results. The site, known since 1986, is multi-layered with cultural heritage from different eras, among which there are the remains attributed to the Copper Age (Cucuteni-Trypillia culture) and the Bronze Age (Noua culture). The latter are represented by the hillocks of "ash mounds", the number of which varies depending on the stage of research and the consequences of anthropogenic activity, since this area has been affected by agricultural work overtime. Initially, based on aerial photographs taken in the late 1960s and satellite photographs, about 40 ashen spots were counted. The 2003 topographic map shows 25 "ash mounds", the remains of which can be identified. In the same year, a quarter of the area occupied by the remains of an "ash mound" in the eastern part of the site was surveyed. Subsequently, the site research strategy aimed at conducting geophysical explorations, which covered an area of 7.50 ha in 2005, where 16 "ash mounds" were identified and confirmed, in the central and western part of the site. Interpretation of geophysical data made it possible to associate some anomalies in the space adjacent to the "ash mounds" with the line of a ditch, and others with the supposed access roads. In general, magnetometer surveys gave modest results compared to the expectations of the researchers, due to the lack of burned structures and other features able to provide enough magnetic contrast to be detected with such geophysical method (magnetometry). On the other hand, a number of pedological and mineralogical analyses provided particularly important information on the origin and functionality of the "ash mounds". Element concentration analysis of soil samples from the "ash mounds" structures indicated a high content of calcium, phosphorus, and potassium. These results confirmed, in the opinion of the authors, that the "ash mounds" are the ruins of some structures made of clay, limestone and other materials of organic origin, which in the process of gradual degradation and mineralisation gave the soil a grey colour. On the other hand, the presence of carbohydrates confirmed the authors' hypothesis that the ash-coloured soil, which gave its name to this type of structure, is the result of the action of pedogenetic factors, which excludes the thermal origin of "ash mounds" (Sava & Kaiser, 2011; Kaiser & Sava, 2014). Regarding the sites in the steppe region of the south of the Republic of Moldova, we note that recently (2016–2017) geophysical surveys were conducted at two sites attributed to the Sabatinovka culture: Taraclia-Gaidabul and Cazaclia II (Sava et al., 2017). As a result of the geophysical exploration, the identified anomalies will guide the choice of a future archaeological research strategy.

2.4 Early Iron Age

The impetus given by modern research to study the sites attributed to this chronological sequence is currently an isolated phenomenon, with many cases originating from the Middle Dniester region. The first geophysical surveys were carried out in 2010 at the multi-layered site of Saharna Mare (Fig. 4) by a mixed team consisting of specialists from the Moldova State University and the Arheoinvest Center of the "Alexandru Ioan Cuza" University of Iași (Romania). In 2015, the results of the first magnetometer survey campaign were complemented with new datasets (Asăndulesei, 2016). In total, the measured area was about 6 ha out of a total of 13 ha occupied in the Iron Age. Among the positive magnetic anomalies identifed in the area, two semi-circular anomalies were associated with the remains of a hillfort (Fig. 4, red arrow). The subsequent archaeological excavations coordinated by I. Niculiță

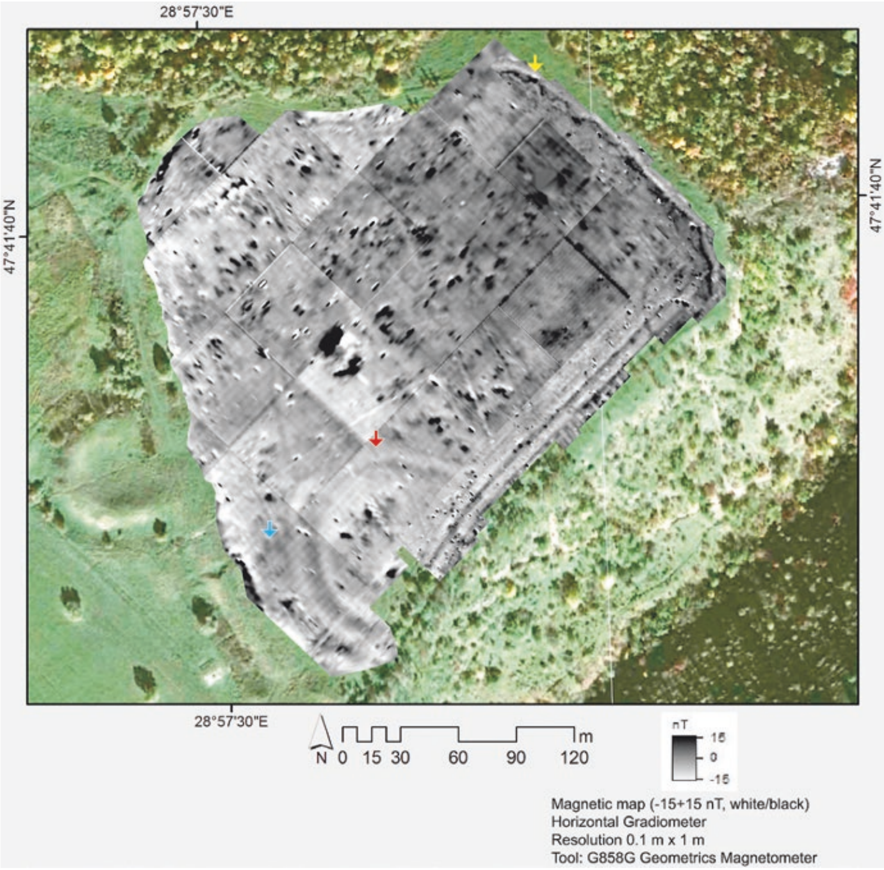

Fig. 4 Results of the magnetometer survey at Saharna Mare. The red arrow marks the Early Iron Age fortification, and the blue arrow marks the anomaly investigated in 2017–2019. (Adapted from Asăndulesei, 2016)

confirmed the existence of a hillfort with two components: a “citadel” of quasi-round shape in plan, ~74 × 76 m in size; and a semi-oval “enclosure”, 55 × 78 m in size on the north side. It should be mentioned that it is the first discovery of a fortification in the eastern area of the Saharna culture in the Early Iron Age. Subsequently, a group of researchers from the Moldova State University identified in the vicinity of the Saharna Mare site a new fortification of this period, Saharna “Rude”. As a result of a magnetometer survey covering an area of ~3 ha, several anomalies of archaeological potential were found, including one located at the northern edge of the settlement. It is circular in shape and consists of two concentric lines, the first of which has a diameter of ~50 m, and the second of 75 m. Also, this survey confirmed the presence of a large open settlement (~10 ha), and probably synchronous with the fortification, that was preliminarily identified by field observations. Future investigations are to clarify the time of the construction of the two defensive lines, as well as the stages of occupation of the promontory (Zanoci et al., 2020a).

Following this model and verifying the available information, in 2021, researchers discovered two other fortifications in the region (Saharna “Țiglău” and Țahnăuți), both of which were subjected to geophysical prospection. These initiatives, carried out within the project “The archaeological heritage of the Iron Age in the Middle Dniester region and the Cogâlnic River basin: interdisciplinary research and scientific development”, were strengthened by a bilateral research cooperation between the State University of Moldova and the German institutions—Friedrich Schiller University Jena, Philipp’s University of Marburg, and the Roman-Germanic Commission of the German Archaeological Institute. In 2019, as part of this project, magnetometer surveys were conducted at four Iron Age sites near the village of Horodiște (Fig. 5). Among the studied sites, the habitation on the Horodiște promontory with the two fortified sites—“La Șanț” and “La Cot”—stands out. If it was initially considered that the habitation area included the entire plateau (28 ha), the geophysical results limited the living area to about 6 ha. In the intra muros space, the magnetometer survey results identified numerous anomalies, which can be grouped in three or four clusters of ~1 ha, which correspond to a scattered habitation with several cores of spreading of archaeological remains (Zanoci et al., 2020b). One of these anomalies, linearly arranged in the northwestern part of the promontory, was excavated in the summer of 2021. The results confirmed the presence of an Early Iron Age ditch and a rampart. It is worth mentioning here that it was initially believed that the plateau was inhabited mainly in the Late Iron Age. Along with the clarification of the period of operation of the defensive structures built on the promontory, further research will aim to understand the stages of occupation of the space during the Iron Age. The analysis of soil samples has shown that deposits in the cultural layer contain traces of carbonates, phosphorus, and potassium, which may indicate the decomposition of animal and plant waste, as well as the ash resulting from the burning of remains (Nagacevschi et al., 2019).

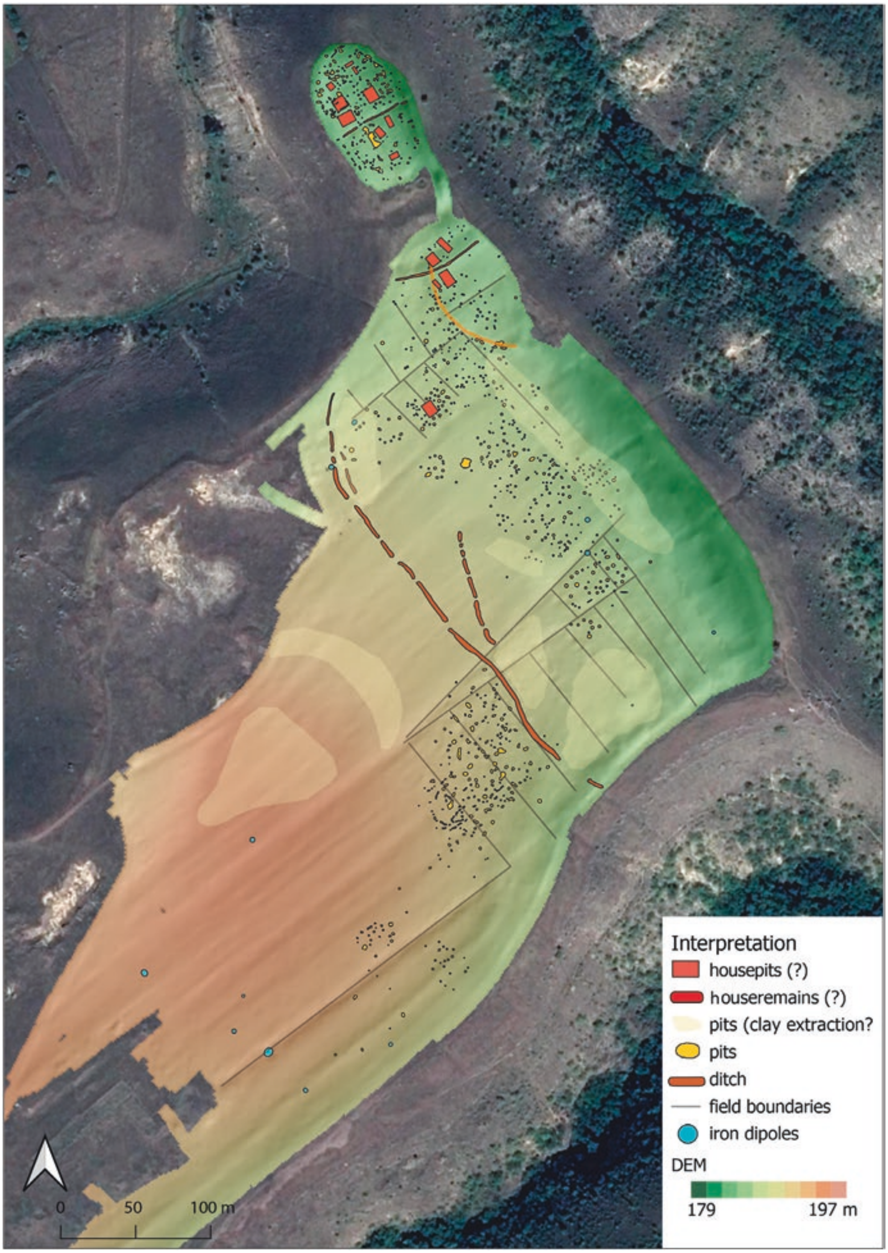

Fig. 5 Horodiște. Ortophotoplan of the site combined with interpretation of the results of the magnetometer survey. (From Zanoci et al., 2020b)

2.5 Pre-Roman Iron Age

Among the sites from the fifth to third centuries BC, the site on the Saharna Mare promontory is one of the few archaeological sites that have been investigated by non-invasive methods. As mentioned above, the Saharna Mare site is multi-layered; the promontory had been inhabited uninterruptedly for a millennium (twelfth to third century BC). This is an aspect that may challenge the interpretation of the results of magnetometer surveys (and other geophysical techniques) due to the complexity of the deposition of the cultural remains. In this regard, the case of the targeted study of an anomaly in the western part of the site, which has an oval shape with dimensions of about 20 × 16 m, is indicative (Fig. 4, blue arrow). Three successive excavation campaigns (2017–2019) aimed at clarifying the nature of this anomaly, which turned out to be in fact, an overlap of several archaeological structures of the Early and the Late Iron Age (Niculiță et al., 2019). Of interest are the remains of a heavily burnt surface structure. The daub covered a pit house with a fire installation (hearth) and a burial structure. In the place of a burial, a grave pit with a catacomb was dug, purified by fire. A man over 60 years old is buried in the catacomb. Later, a clay-coated wooden superstructure was built in the pit. It seems that this structure was later burnt down. It is worth mentioning here that the first radiocarbon data for this site were obtained from this stratigraphic context. Among the archaeologically confirmed anomalies, mention should be made of the defensive line on the eastern side of the promontory, consisting of a rampart and eight semicircular bastions arranged four on each side (Fig. 4, yellow arrow).

The sites characteristic of the last two pre-Christian centuries began to be investigated quite recently. In 2015, the first magnetometer survey was carried out at the Poienești-Lucașeuca site at Brănești, covering a total area of ~4 ha (Meyer et al., 2020). Along with a few Copper Age dwellings, several structures attributed to the Poienești-Lucașeuca culture were identified, which were verified by small-scale excavations, thus opening the way for possible interpretations of the types of anomalies and non-invasive research of the sites belonging to this era. This was followed in 2016 by limited explorations at the Poienești-Lucașeuca site in Ivancea Sub-Pădure, which, despite its small size, provided an extremely expressive picture (Fig. 6), which made it possible to identify anomalies that even reflect pits from pillars of wooden structures as verified by test trenches (Meyer et al., 2020). The results obtained opened up new research prospects, already within the DFG (Deutsche Forschungsgemeinschaft) project "Ausgrabung der Siedlung der Poienești-Lucașeuca Kultur von Ivancea-sub Pădure" (a joint project of the Free University of Berlin with the Ion Creangă State Pedagogical University of Chișinău). Among them, we highlight the priority and most important directions: magnetometer exploration of a larger area to capture the periphery of the site, as well as delimit the space where materials from other chronological horizons appear (the surveys were carried out in 2021 by a German service provider); collection and mapping of surface material in a GIS to pursue and complement the same goal; soil sampling to

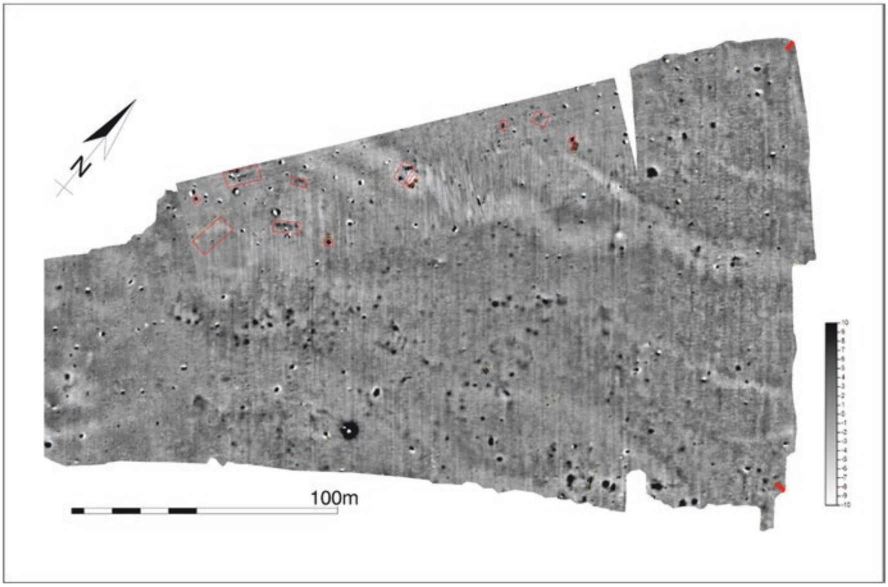

Fig. 6 Results of the magnetometer survey at Ivancea-sub Pădure, Poienești-Lucașeuca culture. (From Meyer et al., 2020)

study phosphate concentrations, archaeobotanical remains, and soil erosion; 3D terrain modelling based on aerial photographs taken from drones. All actions are part of a broader strategy for preparing archaeological research over large areas and through the widest possible integration of interdisciplinary research methods.

2.6 Roman Period

The sites of the Roman era began to be studied from the moment when the first recent projects of non-invasive research appeared on the territory of the Republic of Moldova. The first site to which they paid attention was the Sântana de Mureş-Černjachov settlement in Sobari. A stone enclosure with stone and wooden structures was discovered at its western end. In 2009, an area of ~1 ha was surveyed, covering the space inside the enclosure, as well as to the south of it. The preliminary image obtained from the magnetometer survey confirmed previous observations on the internal structure of the settlement, with relatively good traces of three sides of the stone enclosure in the northwestern part of the settlement (Musteață et al., 2017). In 2013–2016, a mixed team of researchers from the Moldova State University and the National Archaeological Agency carried out archaeological excavations, which were largely due to the degradation of the site (unauthorised sand mining) and were carried out in places of maximum risk. The results confirmed the site's potential,

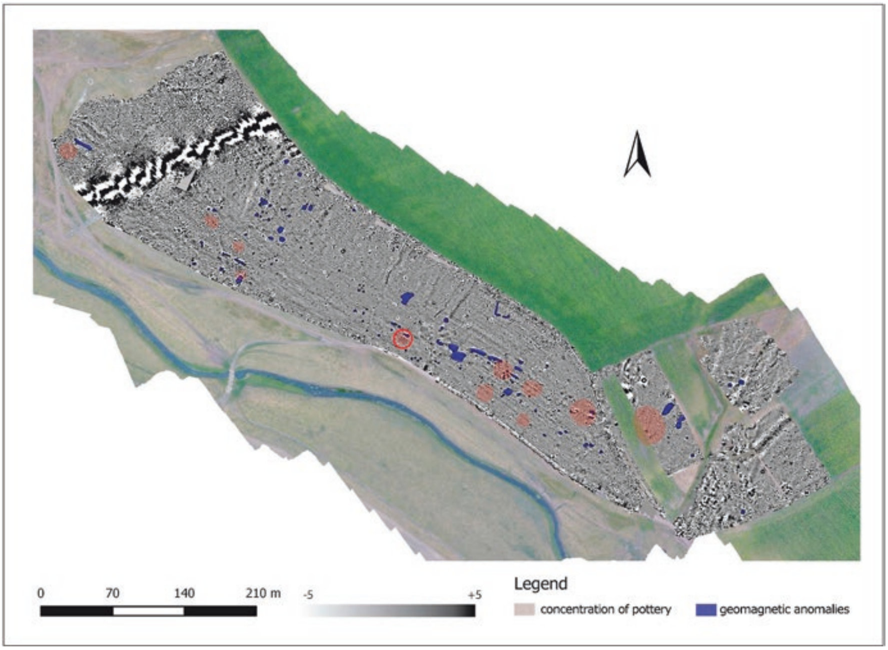

Fig. 7 Results of the magnetometer survey of the site Putinești, the Late Antiquity. (From Voß et al., 2015)

revealing several well-preserved kilns (Matveev & Vornic, 2017). Among the large-scale magnetomer survey, the ones carried out at the site at Sângerei (2010) stand out, where more than 20 ha of the area were explored (Musteață et al., 2017). The results revealed an elongated magnetic anomaly, with a length of about 28.0 m. We conclude the presentation of the research for this period by mentioning the site from Putinești, where 8.2 ha were explored, and among the many anomalies of archaeological interest there was a ceramic kiln (Fig. 7, red circle) (Voß et al., 2015).

3 Middle Ages

Regarding the medieval sites, the first non-invasive investigations were carried out at the medieval site of Old Orhei (Orheiul Vechi), which, in addition to several cultural layers, preserves traces of the Tatar medieval town of Shehr al Jedid and the Moldavian town of Old Orhei. The research was a collaboration between the Ion Creangă State Pedagogical University of Chișinău, the German Archaeological Institute and the National Museum of the Eastern Carpathians, Romania. At the first stage, in 2009, an area of 30 × 40 m inside the medieval citadel was explored

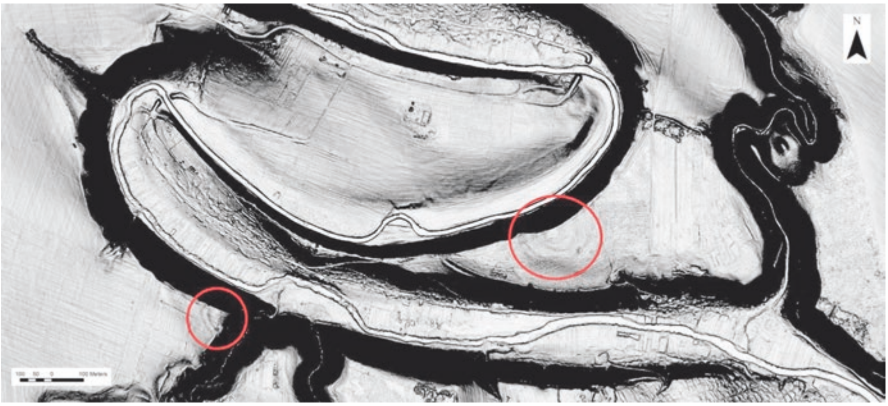

Fig. 8 Orheiul Vechi. The LiDAR derived hillshade (red circles indicate the remains of the hill-forts). (From Musteaţă et al. (2017), licensed under CC-BY 3.0)

(Popa et al., 2010). Numerous anomalies of archaeological potential have been identified, including the contours of rooms with walls up to three meters, most likely made of stone, adjoining the enclosure and partially open to the inside of it (Popa & Musteață, 2019).

In the autumn of 2014, the same team carried out a new magnetometer survey of the medieval site of Old Orhei as part of a study to include in the application for the inclusion of the Old Orhei cultural landscape in the UNESCO World Heritage List. The surveys covered 29 research units revealing several anomalies that require additional field verifications to determine a more accurate interpretation, but also to determine the strategy of further research (Popa & Musteață, 2019). Also in 2014, the American College for Cultural Site Research and Management (CSRM) (Baltimore, USA) carried out a study at the same site focused on LiDAR data. The results revealed two enclosures and landscape features, confirming and refining the information already available, but also providing information previously unknown (Fig. 8). The team from the Ion Creangă State Pedagogical University, in collaboration with the Free University of Berlin and a service provider of geophysical surveys (Eastern Atlas, Berlin), returned to the same site in 2021, conducting targeted magnetometer surveys in the area of the first defensive rampart at the promontory. The results outlined a rectangular structure of imposing dimensions in the intramuros area.

The second medieval Tatar town, located near the village of Costești, even though it is of great interest and was included in the list of priorities of the project "Geophysical surveys in Moldova" (collaboration of the Ion Creangă State Pedagogical University of Chișinău with the Roman-Germanic Commission of the German Archaeological Institute), was not subjected to magnetometer surveys due to unfavourable weather conditions during the planned period. The third medieval site of national importance—the medieval fortress of Soroca—became the object of geophysical prospection in the fall of 2012 and in the summer of 2013, within the project "Non-destructive investigations in complex archaeological sites. An integrated model for applied research of the immovable cultural heritage". It was developed by several institutions from the Republic of Moldova and the Arheoinvest Research Center of the "Alexandru Ioan Cuza" University and Museum of the Eastern Carpathians (Romania). The techniques used included ground penetrating radar (GPR) and magnetometry. The surface surveyed with the magnetometer was about 4650 m^2, and an area of about 1500 m^2 was investigated by measuring the electrical resistance of the soil, the authors managed to draw a complex research perspective of this important site for the Republic of Moldova, which partially began to materialise, providing extremely valuable information (Musteață et al., 2018). The geophysical results guided the subsequent 14 targeted archaeological excavation that covered an area of more than 200 m^2. These investigations resulted in the registration of a rich collection of archaeological material and resolve some problems related to the architecture, stages of construction and dating of the site.

4 Conclusion

Summarising the above, we find that the stereotypical picture of a sharp lag in the use of geophysical and soil science methods in Moldova requires a radical correction. We pay special attention to the activities of researchers in the Republic of Moldova in recent years, which come to confirm an increasingly clear connection with the modern methods aligning with the general trends of the development of modern archaeology. Obviously, the actions taken so far are relatively modest, even if some of the results are impressive, for example, at the sites of the Copper Age, which provide clear images of the internal organisation of settlements, types and sizes of archaeological structures, but what is more important opening up new opportunities for the development of research strategies. At the same time, in all types of sites, regardless of the periods to which they belong, the experiences of soil scientists are increasingly used, which offers new perspectives in interdisciplinary research. In other words, even if we still have a lot to do in this area, the direction and growing pace, with which geophysical and soil research is being adopted by archaeologists, make us look optimistically to the future of research in the Republic of Moldova.

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Part XIV
Morocco and Tunisia

The State of Archaeo-geophysics in the Maghreb: Case Studies from Tunisia and Morocco

Abir Jrad, Stephen A. Collins-Elliott, Aomar Akerraz, and Hamden Ben Romdhane

Abstract North Africa possesses a rich archaeological heritage, which to a significant degree remains to be investigated. This chapter reviews the current state of archaeo-geophysical research in Tunisia and Morocco, tracing its earliest development in the 1970s up to the present. While geophysical surveys were implemented in both countries within a fairly short amount of time, the uptake has been slow, increasing only in recent decades. Archaeo-geophysical research has also largely been focused on ancient and medieval contexts. From the perspective of rescue archaeology, many sites are threatened by increasing urbanisation and modern development. Geophysical survey offers a key tool to obtain fast, economical, and non-destructive observations on subsurface archaeological remains, allowing for targeted archaeological excavations in the future. Developing training programs in geophysics for archaeologists will help to promote the continuity and health of the field of archaeo-geophysics in both countries in the future.

1 Introduction

Geophysical methods provide a non-invasive, non-destructive means of studying subsurface archaeological remains, and have been methodologically well developed in archaeology as a new field. In the context of the archaeology of Morocco and

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Tunisia, geophysical methods have not been consistently applied since their earliest introduction in the 1970s, in marked contrast to their use in geological and hydrological research.

This chapter provides an overview of the history of archaeo-geophysical fieldwork in Morocco and Tunisia. After a synopsis of the history of the region and of the development of geophysical methods in archaeology, we review their application in the fields of archaeology in Morocco and Tunisia.

Geophysical investigations have been conducted as part of pre-excavation assessments to determine where to locate trenches. Also, these methods have been used at ancient and medieval settlements with visible remains to complete their urban layout. North-western Africa has an extensive prehistoric record: Africa as a whole is generally regarded as the cradle of humanity, from which *Homo habilis* (ca. two million BP) first began to migrate to other continents, and the recent discovery of *Homo sapiens* at Jebel Irhoud near Marrakesh in Morocco has pushed back the earliest attestation of modern human beings in north-western Africa to ca. 300,000 BP (Hublin et al., 2017).

1.1 Brief Introduction to the History of the Maghrib

The premodern history of the Maghrib, of which Morocco and Tunisia are a part, is conventionally divided into three periods, prehistory, antiquity and the Middle Ages (Laroui, 1970; for Morocco, see Kably, 2011). There are several forms of chronology in place, based on geological epochs, material cultures, and, beginning from antiquity, dated events or periods, like those of ruling dynasties. Such chronologies are often not universal, but are bound to specific contexts and cultural expectations, as with the Neolithic and its implications with a settled way of life dependent upon agricultural and domesticated animals (Barich, 2021). This chronological particularity is also related to the geographical variability of the natural landscape. Even though the complex of mountain chains that form the Rif, Atlas, and Aurès may be viewed as a coherent and unifying geographic feature, diversity in the forms of human adaptation and material culture is evident from prehistory onward (Camps, 1974; Linstädter, 2008).

1.1.1 Prehistory

Prehistory is commonly held to begin ca. one million BP, with the first evidence of *Homo erectus*, up to the eighth century BCE, when the coasts of north-western Africa were frequented by traders and settlers from Phoenicia (approximately modern Lebanon). This period therefore comprises an extremely long duration of time. Generally speaking, in the Palaeolithic, human begins domesticated fire, used lithic tools, practised funerary rituals and formed the earliest communities, while the subsequent Neolithic saw the domestication of animals, the spread of agriculture and the adoption of a sedentary way of life (Roche, 1963; Strauss, 2001; Hublin & McPherron, 2012; Hublin et al., 2017). The relationships between the Palaeolithic/Neolithic transition, climatic conditions and the particular definitions of material cultures are complicated, as is the question of whether distinctions between post-Neolithic ages like the Copper, Bronze or Iron, which are a basis of periodisation elsewhere in the Mediterranean, should apply (Lucarini et al., 2021). Around the end of the second or start of the first millennium BCE, though, local societies in north-western Africa were adept at mobilising sufficient labour to construct monumental building projects, such as the cromlech at Mzora in Morocco (Bokbot, 2020), and to practise oleiculture and viticulture, as at Althiburos in Tunisia (Kallala & Sanmartí, 2011; Sanmartí et al., 2012; Mattingly, 2016).

1.1.2 Antiquity

Antiquity generally covers the period from the first centuries of the first millennium BCE up to the fifth century CE. During this time north-western Africa attests the earliest phases of urbanisation and the development of political societies, as at Lixus in Morocco and Carthage in Tunisia, which were originally Phoenician colonies (Lancel, 1995; Aranegui & Hassini, 2010). The latter city emerged as an imperial power over the course of the sixth to fourth centuries BCE. In the course of its wars against the Carthaginians, the Roman state became implicated both diplomatically and militarily in the region, and by the mid-first century CE Rome had annexed the coasts and plains of north-western Africa up to the Atlantic coast (Briand-Ponsart & Hugoniot, 2006; Lassère, 2015). The Roman period has traditionally been seen as a period of great economic prosperity, with flourishing urban societies and a high level of rural production (Hobson, 2015). The exportation of products from north-western Africa, such as *garum* (fish sauce), olive oil and wheat, both for the city of Rome and for the broader Mediterranean economy, as well as the diffusion of ceramic fine ware (African Red Slip ware), represent well the region's Mediterranean connections. Recently, however, the coherence of such vitality is being revisited, to highlight regional variation (Stone, 2019).

1.1.3 Middle Ages

The division between antiquity and the Middle Ages is situated in the transition between the disintegration of the western Roman Empire in the fifth century CE and the campaigns of the Umayyad Caliphate in the seventh century CE (Leone, 2007; Fenwick, 2013, 2020; Bockmann et al., 2019). The region's political and military landscape underwent modifications pursuant to conflicts between local kingdoms and external agents, such as Vandals, Byzantines and Arabs. Some urban centres were abandoned or destroyed, such as Simitthu, Carthage and Utica in Tunisia, and Banasa, Zilil and Lixus in Morocco. Other cities continued to be inhabited, however, showing that there was not a complete rupture with the past. That said, the sociopolitical makeup of the region changed considerably, even if gradually, as new political and economic relationships became established (Boone et al., 1990). New centres of power emerged and shifted from one to another, such as at Kairouan, Raqqada, Mahdia and Tunis in Tunisia, or at Fes, Marrakesh and Meknes in Morocco, over the course of the first to sixth centuries AH / seventh to twelfth centuries CE. The most noteworthy changes of the medieval period are found in the domains of religion and language, with the introduction of Islam and Arabic. Such a shift is apparent in importance of the later geographies and accounts of conquest (*futūḥ*) that form the mainstay of evidence for understanding the political events around the Umayyad conquest, the subsequent rebellions and the birth of states governed by local dynasties (Ṭāha, 1989; Siraj, 1995).

2 Geophysical Surveys in Moroccan & Tunisian Archaeology

While geophysical techniques have been well developed methodologically in archaeology as a global discipline (Aitken, 1974; Atkinson, 1953; Hesse, 1966, 2005; Tabbagh, 1974), the application of geophysics within national and collaborative international archaeological fieldwork projects in Morocco and Tunisia has historically not been as robust. The following sections present a summary discussion of the history of archaeo-geophysical surveys in each country, outlining primary case studies in the application of geophysical methods in archaeological contexts. To be sure, geophysics found ready application in both countries starting in the 1970s, but the frequency of geophysical projects has not been consistent over time, increasing only recently. The application of geophysical methods has largely focused on the investigation of ancient and medieval (Roman and Islamic period) sites, and rarely on prehistoric ones.

2.1 Morocco

In Morocco, the study of cultural heritage falls under the purview of the Framework Law No. 99-12 under the National Charter for the Environment and Sustainable Development Dahir No. 1-14-09 of 4 Jumada I 1435 (6 March 2014) (B.O. No. 6240 of 18 Jumada I 1435 AH, corresponding to 20 March 2014). There are no mentions nor recommendations on the use of geophysical surveys in archaeological heritage documentation and preservation. Since its foundation in 1985, the Institut National des Sciences de l'Archéologie et du Patrinoine (INSAP, the National Institute for Archaeology and Heritage) has been a leading institution for the study of archaeology in Morocco and has undertaken collaborative projects using geophysical methods to investigate archaeological sites. Prior to INSAP, the Service de l'Archéologie (Archaeological Service) was the central institution for archaeological fieldwork in Morocco (Papi, 2006).

Geophysical survey was first used in Moroccan archaeology in the 1970s, with magnetometer and electrical resistivity being the most common methods used. Between 1971 and 1972, at the important medieval centre of Sijilmasa in the Tafilalt region of Morocco, a project of archaeological and ethnological research was directed by the Ludwig Keimer Foundation and the Moroccan government. As part of this work, Boris de Rachewiltz conducted an electrical resistivity survey that revealed a network of underground pipelines that linked vessels and wells buried under the sand (de Rachewiltz, 1972). Another pioneer of geophysical survey on archaeological sites in Morocco was carried out by Alain Kermorvant, who conducted fieldwork under the auspices of the French Ministry of Cultural Affairs (Ministère d'État Chargé des Affaires Culturelles) as part of the Franco-Moroccan excavations at Dchar Jdid (the ancient Roman colony of Zilil). Between 1977 and 1980, Kermorvant carried out a geophysical investigation using magnetometer and electrical resistivity methods (Akerraz et al., 1981–1982). Kermorvant also conducted a magnetometer survey in 1996 under the direction of another Franco-Moroccan collaboration at Banasa, a Mauretanian and Roman period site, where archaeological excavations confirmed the effectiveness of this method for the detection of pottery kilns (Arharbi & Lenoir, 2011). The use of magnetometer surveys to locate potential kilns had already been demonstrated by Patrice Cressier in 1977 at the medieval site of Ain Kerouach, where an electrical resistivity survey was also conducted using with a 1 m electrode-spacing on a Wenner array configuration to locate the walls of the site (Cressier, 1981–1982).

More recent surveys includes the magnetometer explorations at Sidi Ali ben Ahmed (ancient Thamusida), conducted between 1999 and 2001. These surveys were carried out using a fluxgate gradiometer, covering an area of about 14 ha. These surveys were highly effective in detecting the subsurface remains of walls and mapping the buried city, some of the results are presented in Fig. 1 (Cerri, 2008). Kermorvant carried out magnetometer surveys at Kouass in 2009 as part of strategy of targeted excavations (Bridoux et al., 2009). In 2010, Cerri also

Fig. 1 Archaeological structures revealed by the magnetic anomalies in Sidi Ali Ben Ahmed, ancient Thamusida (Cerri, 2008)

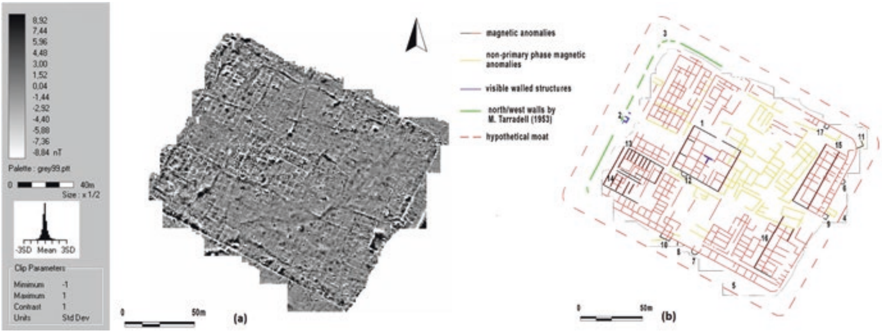

Fig. 2 (**a**) Gradiometric map obtained in the military camp el Benian in Morocco with a range from +9.12 to −8.84 nT (**b**) Interpretation of the magnetic anomalies (Martorella, 2021)

conducted magnetometer surveys at Lixus (Shoumish), a major urban centre during the Roman period, under a collaborative project between INSAP, Mohammed V University of Rabat and the University of Siena (Italy), to delineate the architecture and built infrastructure of the site (Mascione et al., 2016). Between 2013 and 2017, Francesco Martorella and Laura Cerri investigated the Roman military camp at El Benian, south of Tangier. The results derived from the magnetometer survey (Fig. 2) shed light on the organisation of space internal to the fort in late antiquity (Martorella, 2021). In 2016, electromagnetic surveys were conducted around the eastern gate of the medieval fortress of Ighram Aousser, located south of Meknes (Cozzolino et al., 2016, 2018; Manfredi et al., 2019). The medieval site of Ain Kerouach was revisited in 2018 by researchers from Abdelmalek Essaadi University in Tangier to conduct a magnetometer survey, reassessing the depth of the aforementioned kiln features (Ayad & Bakkali, 2018). Finally, as part of Morocco-American fieldwork in the Loukkos valley under the direction of Aomar Akerraz and Stephen Collins-Elliott, Abir Jrad has carried out magnetometer surveys on several rural sites using the Grad 601-2 magnetometer.

2.2 Tunisia

In Tunisia, legislation on cultural heritage can be found under article 94-35 from 24 February 1994 on the Code of Historical Archaeological Heritage and Traditional Arts, which serves to organise and protect Tunisia's cultural heritage. There are currently no protocols regarding the use of non-invasive methods of geophysical methods.

Geophysical surveys within the domain of cultural heritage have been carried out under the supervision of the Institut National du Patrimoine (INP, National Heritage Institute) of Tunisia and in collaboration with foreign institutions from Poland, Germany, Italy, France and more recently Britain. The first geophysical survey in Tunisia was a microgravimetry investigation of the site of the Roman circus of

Carthage in 1972 by a Polish team (Kolendo et al., 1973; Iciek et al., 1974). Carthage was revisited in 2003–2004 for another campaign of geophysical investigation, using both magnetometer and ground penetrating radar (GPR) surveys. This was a collaboration between Tunisia and Italy (Piro & Capanna, 2006). The most recent geophysical survey of this area was conducted in 2015 by a Tuniso-German team, which used three methods: GPR, magnetometer and electric resistivity (Ben Romdhane et al., 2016). The electrical resistivity survey (using a Geoscan Research RM15 resistance meter) did not provide useful results because of the high soil aridity and lack of soil moisture during the survey. The GPR results proved to be the most effective, allowing for the identification of several buried features (Bockmann et al., 2018). The GPR survey was carried out using 200 MHz and 400 MHz central frequency antennas, while the instrument use for the magnetometer survey was a G858 caesium magnetometer. Four caesium probes, spaced 50 cm apart, were placed on a wooden wagon to be towed. This made possible to acquire ten measurements per metre in the direction of travel and four measurements each two metres in the transverse direction.

Geophysical explorations have become more frequent in recent decades in Tunisian archaeology. In 2004, a collaboration was established between the Tunisian INP and the French research program Sisyphe at the Université Pierre-et-Marie Curie Paris VI to conduct a geophysical survey at the site of Ṣabra al-Manṣūriya in Kairouan, one of the capital cities of the Fatmid Caliphate. A combination of methods was used to counteract adverse conditions (such as scrap metal that obstructed results from the magnetometer and high soil salinity that impeded electrical resistivity survey). Results revealed axial alignments of anomalies that were used to target excavations (Cressier & Rammah, 2004).

In 2010, geophysical surveys were conducted at two sites, Chemtou and Utica, in collaboration with the German Archaeological Institute (DAI) and the British School at Rome respectively. Chemtou (the ancient Simitthu) is situated in the governorate of Jendouba in north-western Tunisia. The goal of the GPR survey was to locate the buried walls of the medieval city. Utica, a Phoenician colony and primary urban centre throughout the pre-Roman and Roman period is located at the North of Carthage city. The aim of the survey at Utica was to assess the viability of magnetometer characterisation of the site and the preliminary results proved quite promising as many structures related to the ancient city plan were revealed (Kallala et al., 2010). Since, Utica has been the target of more intensive geophysical survey work. The initial magnetometer survey has been extended and further GPR surveys has been performed in the framework of the Rome's Mediterranean Ports project of the University of Southampton and the British School at Rome (Hay et al., 2010; Ben Jerbania et al., 2015, 2019; Keay & Hay, 2017).

In 2012, three sites at Carthage (under the supervision of Pr. Aounallah and Dr. Achour), at the North-East of the capital Tunis, and one in Hergla (the ancient Horrea Caelia) at the South of the capital Tunis (under the supervision of Pr. Ghalia), were surveyed (Jrad, 2014). The first one, the Malga archaeological park in front of Carthage-Zaghouan aqueduct, was explored combining electrical resistivity tomography (ERT), magnetometer and seismic surveys. The correlations between the geophysical anomalies allowed the identification of potential archaeological features at ~1 m depth. A magnetometer survey was conducted at the Punic port of Carthage to search for a potential kiln structures as evidence of pottery industry at is area. The third site, a burial ground at Tophet, was surveyed using a G858 magnetometer. The objective of the survey was to understand the magnetic signature of the graves (Jrad, 2014). The last site, the commercial harbour of the city of Hergla, belonging to the governorate of Sousse, was also explored though a magnetometer survey to locate the ancient city walls. In situ magnetic susceptibility measurements of different materials of the walls were also taken using SM30 susceptibility meter and also recorded the archaeological materials at the site to better define magnetic anomalies (Fig. 3).

In the same year, a Tunisian-German team conducted a geophysical survey at the site of Meninx on the island of Jerba in south-eastern Tunisia, the most important city on the island in antiquity. The German team used a Cesium-Smartmag SM4G-special-magnetometer to cover an area of 120,000 m². In situ magnetic susceptibility measurements were also taken by a handheld Kappa-meter SM30 (Zh-Instrument)

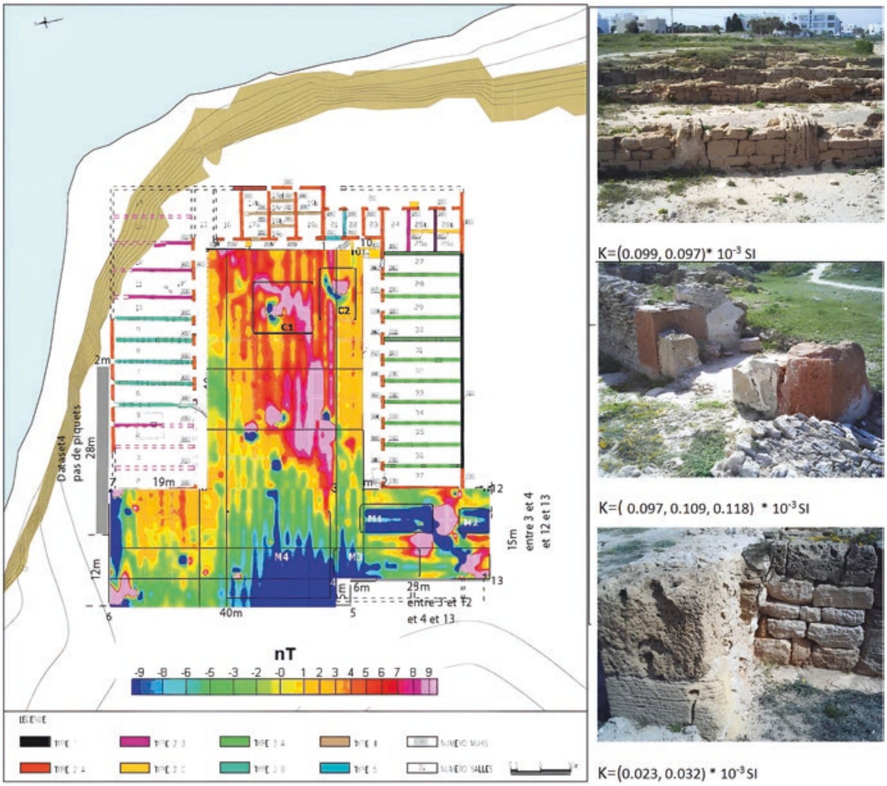

Fig. 3 Results of the magnetometer survey of Hergla in Tunisia with some susceptibility measurements (Jrad, 2014)

to estimate the magnetic susceptibility of the building materials (Fig. 4) (Ritter et al., 2018; Ritter & Ben Tahar, 2020). The objective of this study was to complete the city plan of Meninx and stablish suitable areas for future archaeological excavation. In 2019, an electrical resistivity survey was carried out also at Jerba island using vertical electrical soundings and ERT to locate remains related to ancient olive oil production infrastructure with promising results (Azaiez et al., 2019).

In 2019, a Tunisian team carried out a magnetometer survey at the archaeological site of Ourazla in Zaghouan (under the supervision of Dr. Ben Romdhane), in eastern Tunisia. Previous rescue archaeological excavations revealed structural remains extending on the course of a modern highway. As a preventive measure, the survey aimed at mapping the total extension of the site. The team was composed by archaeologists from the Heritage Institute of Tunis and a geophysicist from the Water Researches and Technologies Centre. Some preliminary results are shared here. The instruments used was a dual sensor Bartington Grad601-2 magnetic gradiometer which was operated in a scanning mode to do a fast sweep of the study area and locate hotspots where to conduct higher resolution survey. These more detailed surveys were conducted in 40 × 40 m grids collecting data along parallel lines with 1 m line separation and in-line of 1 m, covering a total area of ~1 ha, with a rate of 8 samples/m. The results showed linear anomalies, oriented north-west/south-east and north-east/south, likely to be linked to subsurface remains of wall foundations (Fig. 5). This hypothesis finds support from the fact that part of the alignments detected by the magnetometer survey are known to correspond to a wall within the

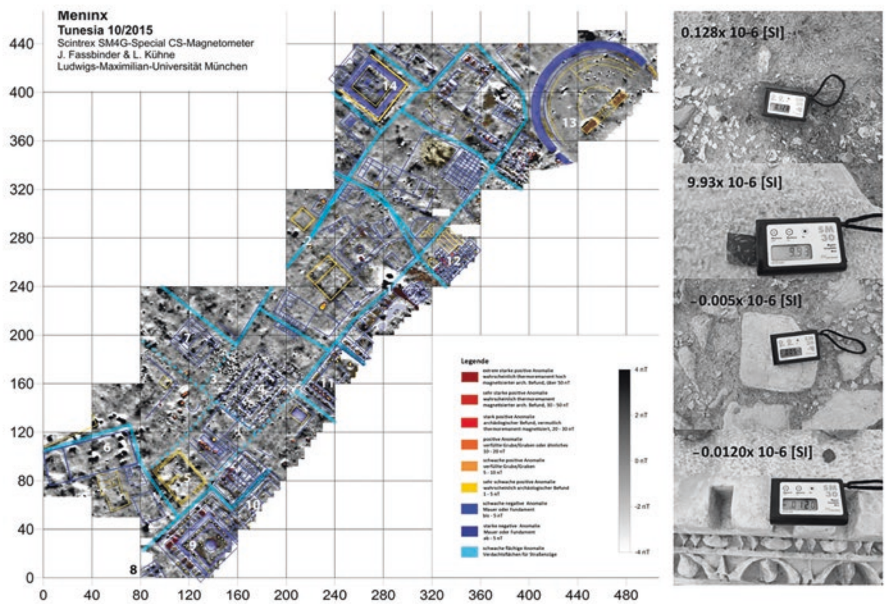

Fig. 4 Magnetic gradient of Meninx (Jerba, Tunisia) and susceptibility measurements from Ritter et al. (2018)

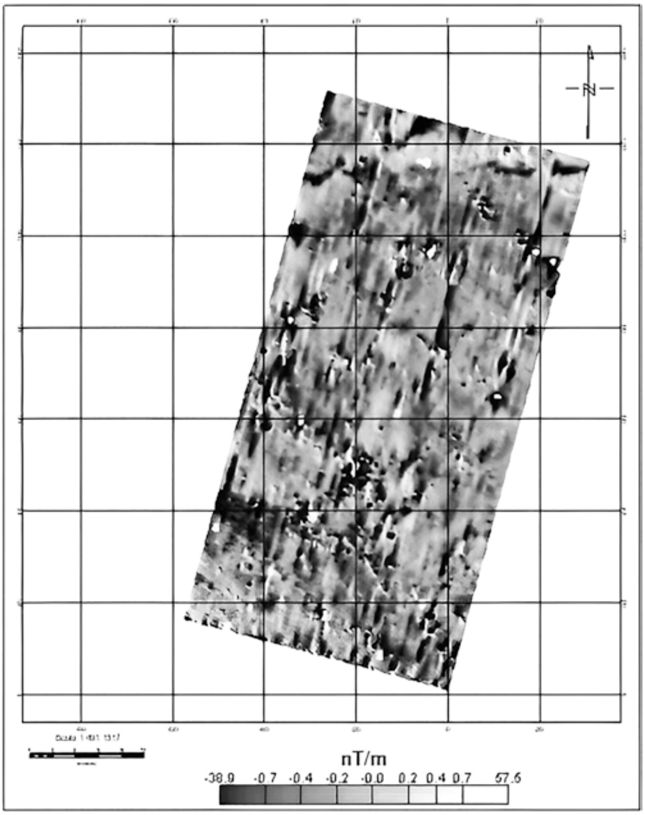

Fig. 5 Results of the magnetomer survey at Ourazla (Zaghouan, Tunisia)

excavated area. These promising results must necessarily be supplemented and confirmed by additional geophysical survey, and future plans entail the use of parallel and perpendicular ERT profiles to the linear magnetic anomalies to better assess the geometry of these structures.

3 Conclusion

This chapter has sought to present an overview of geophysical applications within archaeological fieldwork in Morocco and Tunisia. The 1970s saw the earliest application of geophysical methods, but with only a score of surveys for archaeological purposes in the preceding half-century in both countries combined. The practice of archaeo-geophysics would therefore appear to have been slow to develop, and is, in some respects, still in its infancy. While geophysical surveys have become more frequent in recent decades, the condition of geophysics in archaeology stands in marked contrast to the regular application of geophysics in other fields, i.e., for both geological and hydrogeological purposes. The extent to which geophysical fieldwork can address prehistoric questions deserves further investigation.

It is clearly desirable to promote and develop geophysical methods as a cornerstone of archaeological fieldwork, especially in the domain of rescue archaeology. Central to this objective is the development of an interdisciplinary pedagogy, to ensure that archaeologists receive training in geophysical methods as part of their university education, whereas currently in Tunisia geophysical methods are taught only to geoscientists. Providing training to archaeologists in geophysical methodologies on a national level will help ensure the place of geophysical surveys as part of the regular process of conducting archaeological fieldwork. Such a goal has several benefits, such as the ability to map entire cities without the need for excavation, or at least reducing the number or extent of excavations to a targeted amount based on specific research questions. Furthermore, fostering training in archaeo-geophysical methods in both Morocco and Tunisia can enhance the frequency of exchanges between both countries and quality of fieldwork to the benefit of protecting our universal heritage.

Finally, bringing the results of geophysical survey into communication with soil analyses will further enhance our understanding of surface anomalies and produce a better reading of the results from geophysics. This domain of research has not yet been sufficiently developed at sites in either Morocco and Tunisia. To be sure, magnetic susceptibilities of archaeological features in Tunisia have been measured, such as with ceramics from surveyed sites at Carthage to find their natural remanent magnetisation (Jrad, 2014), but there have been no results that have combined observation from other type of soil analyses with those from geophysical fieldwork. Addressing this lacuna is imperative. Geophysical surveys using multiple methods that are coordinated with soil analyses will serve to enhance our understanding of past on-site functions (Graham & Scollar, 1976; Cuenca-Garcia et al., 2018), and, being a primary goal of the Soil Science and Archaeogeophysics Alliance (SAGA), deserves more widespread implementation in the Maghrib.

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Part XV
Romania

Back to the Roots. Ablest Prospection Techniques for Rediscovering the Chalcolithic Settlement of Cucuteni—*Cetățuie*, Romania: A Short Retrospective, Novel Recent Data, Prospects for the Future

Andrei Asăndulesei, Felix Adrian Tencariu, Dragoș Alexandru Mirea, Radu Gabriel Pîrnău, and Radu Ștefan Balaur

Abstract In this chapter we discuss the important contribution of non-invasive surveys, along with minimally invasive pedological analyses, in the evaluation, re-evaluation and rigorous documentation of buried archaeological heritage. We propose also an overview of the research background, especially by discussing some key moments in promoting these interdisciplinary methods and techniques in Romanian archaeology. Therefore, we consider a review of the contributions to geophysical research, as well as the main initiatives in the field of pedological studies applied to archaeological contexts. The aim is to highlight the indisputable need for such initiatives in a modest national historiographical landscape.

In support of our approach, we have chosen to focus on one of the most well-known and publicised prehistoric archaeological monuments in Romania, the eponymous site of the Chalcolithic Cucuteni Culture (toponym *Cetățuie*). The site has benefited from special attention over time, but still with multiple questions without an answer.

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138 years from its discovery and over 50 years from the latest archaeological research, the site is still surprising. Previous research, reflected in dozens of articles, studies and monographs and considered quasi-completed, is, as the latest investigations prove, away from an outcome. Older observations suggested the existence of a prolongation of habitation or satellite settlements near the known settlement on the *Cetățuie* promontory, but suppositions were not confirmed by previous research. Recent magnetometer surveys and pedological investigations have revealed that the Cucuteni settlement has expanded considerably at a time, with a few tens of highly fired dwellings arranged on rows, with accessways between them, enclosed by other ditches. The new information radically changes the conception over the planimetry and the dynamics of habitation on *Cetățuie*, opening the way for a large project on the research of this famous settlement, in the context of the European Chalcolithic.

1 Introduction

As we mentioned in the abstract, in this chapter we propose to discuss the important contribution of non-invasive surveys, along with minimally invasive pedological analyses, in the evaluation, re-evaluation and documentation of buried archaeological heritage. We propose also an overview of the research background, especially by discussing some key moments in promoting these interdisciplinary methods and techniques in Romanian archaeology. Therefore, we consider a review of the contributions to geophysical research, as well as the main initiatives in the field of pedological studies applied to archaeological contexts. The aim is to highlight the indisputable need for such initiatives in a modest national historiographical landscape.

In support of our approach, we have chosen to focus on one of the most well-known and publicised prehistoric archaeological monuments in Romania, the eponymous site of the Chalcolithic Cucuteni Culture (toponym *Cetățuie*). The site has benefited from special attention over time, but still with multiple questions without an answer.

1.1 Brief Retrospective About Interdisciplinarity in Romanian Archaeology: The Role of Geophysical Prospection

The assertion of modern prospection techniques, starting with the second half of the last century, and the special impact on international archaeological research, have caused an echo among specialists in Romania as well. We recall here, from the pioneering phase, the resistivity survey of Richard Atkinson, conducted at Dorchester-on-Thames, in 1946 and published for the first time in the work edited by Annette Laming (1952), those of Martin Aitken and Eduard Hall from Oxford

University (Aitken, 1958, 1986), Elizabeth Ralph at the Museum Applied Science Center for Archaeology (Ralph, 1964), Albert Hesse and Alain Tabbagh at the Center National de la Recherche Scientifique, Irwin Scollar at the Rheinisches Landesmuseum in Bonn, or Carlo Lerici and Richard Linington from the Lerici Foundation and the Milan Engineering School (Lerici, 1965; Clark, 1990; Gaffney & Gater, 2003).

Thus, in a paper published by Hadrian Daicoviciu in 1960 (Daicoviciu, 1960), inspired by the volume edited by Annette Laming in Paris (1952), the measurement of electrical resistance of the soil, one of the main methods of prospecting in archaeology to this day, is presented. The author highlights the indisputable quality of these type of studies and the need to standardise these applications in Romanian archaeology, emphasising the advantages that the archaeologist can benefit through these non-invasive interventions. In this regard, the following historiographical statements come from Aurelian Petre (1966a, b; Petre & Apostol, 1970), a good connoisseur of this subject, who, following the inauguration in 1964 of the annual international courses of archaeological prospecting, organised by the Milan Engineering School, takes part in one of these meetings. The first two articles of the above-mentioned author present synthetically, and in a manner accessible to the archaeologist, the methods debated during the course of 1965 that took place in Rome. The 1970 paper (Petre & Apostol, 1970) presents one of the first practical applications of magnetic and electrical methods in Romanian archaeology, more precisely the ones conducted in the perimeter of the ancient castrum of *Beroe* (Petre & Apostol, 1970).

In the following period, for various reasons, the application of recently developed techniques is manifested in Romanian archaeology only as a *desideratum*. References can be made, for the period of the '80s, to initiatives such as that of professor Gheorghe Lazarovici, who applied the method of electrical resistivity in the tumulus from Tureni (Dragomir et al., 1992) and took an interest in organising national seminars on archaeometry, in the period 1988–1992.

A new approach in archaeology, manifested during the '90s, directed mainly towards interdisciplinarity and driven, in particular, by numerous collaborations with specialists from abroad, encourages the intensification of the use of non-destructive methods in Romania, visible both by the appearance of scientific studies based on field applications—such as those from Scânteia, *Dealul Bodești* (Cucuteni culture) started in 1994 and 1995 (Ghiță et al., 2000) or the measurements of the same F. Scurtu (2014) for sites like Porolissum, Histria, Tropaeum Traiani, Orgame or Halmyris—as well as through the institutionalisation of research centres.

The problem that fundamentally characterises this period is the lack of an adequate logistical base, qualified staff and bibliographic material. The results, where they exist, do not exceed the scope of isolated tests. However, in 1996, at the initiative of a team from the National Museum of History of Romania, the National Centre for Multidisciplinary Research was established (Popovici et al., 2002). The University "1 Decembrie 1918" of Alba Iulia, with the help of a research grant, implemented in the period 2001–2003, starts the second attempt to establish an institutional body. Originally called Multi-Users Research Base and with the specific objective of developing a system of theoretical and practical training in the field of archaeology, conservation and restoration of archaeological materials and sites, it will be transformed in 2004 into the Institute of Systemic Archaeology, which currently bears the name of the initiator of this project, the late professor and archaeologist Iuliu Paul.[1] In Iași, interdisciplinarity was highly and early promoted. In this regard, mention should be made of the introduction, in 1987, of a section entitled "Interdisciplinary Research in Archaeology" in the prestigious journal *Arheologia Moldovei*, at the initiative of the journal's founder, professor Mircea Petrescu-Dîmbovița. In 2000, under the auspices of the Department of Ancient History and Archaeology of the Faculty of History, within the "Alexandru Ioan Cuza" University of Iași, the Interdisciplinary Centre for Archaeological Studies (CISA) was created, aiming to "establish contacts and collaborations with all those who can and want to contribute to the progress of archaeological research through interdisciplinarity" (Ursulescu, 2006). The founding of this centre, as well as the subsequent activity dedicated to issues related to multi- and interdisciplinarity (language standardisation, explanation of terms, etc.) was the foundation on which, a few years later, the Platform for Training and Research in Archaeology—Arheoinvest will be based. The latter, set up after obtaining a research grant, comes to solve one of the most pressing problems in Romanian archaeology—the alignment of research standards with the European ones, by acquiring an appropriate logistical basis for the interdisciplinary approach, including modern instruments for archaeological prospection.[2]

Along with these three main examples, we can list the National Centre for Multidisciplinary Research at the "Valahia" University of Targoviște, the Department of Computerized Archaeology at the National Museum of Transylvanian History in Cluj-Napoca, the Applied Geomorphology and Interdisciplinary Research Centre at the Department of Geography at the West University of Timisoara (with a strong geoarchaeological component) or the Tulcea Eco-Museum Research Institute, involved through the project "Archaeological Research and Prospecting with Optoelectronic Means (CARPO)" in the mapping of all archaeological sites in the county.

All this contributed to significant progress in the field, putting the Romanian archaeological research to an ascending direction.

Thus, in the last two decades, we can see an obvious increase in the application of non-destructive techniques in prehistoric and classical archaeology, based, in particular, on collaborations with foreign groups, but also through the contribution of local specialists (Ardelean et al., 2017; Asăndulesei, 2011, 2015b; Asăndulesei et al., 2011; Bennett, 2006; Cosac et al., 2014; Dragoș et al., 2020; Drașovean & Schier, 2010; Gogâltan et al., 2019; Gridan et al., 2017; Heeb et al., 2012, 2015; Hegyi et al., 2019, 2020, 2021; Maillol et al., 2004; Micle et al., 2010a, 2010b; Mischka, 2008; Mischka et al., 2015; Opreanu et al., 2013; Pisz et al., 2019, 2020;

[1] http://www.bcum.uab.ro/index.html

[2] http://arheoinvest.uaic.ro

Popa, 2017; Popa et al., 2009; Scurtu, 2005; Ștefan & Popa, 2017; Ștefan et al., 2010; Szentmiklosi et al., 2011; Țentea et al., 2018; Teodor & Dumitrașcu, 2019).

In direct connection with our case study, previous undertakings in the case of the Cucuteni culture include those carried out by our team from Arheoinvest Center (Asăndulesei et al., 2012, 2020a, b; Asăndulesei, 2014, 2015a, 2017), by teams of German researchers collaborating with Romanian specialists (Mischka, 2008; Hofmann et al., 2016; Mischka et al., 2016) or with groups from other Romanian academic or research centres (Dumitroaia et al., 2012; Micle et al., 2010a).

1.2 Short Overview About Pedo-archaeological Interaction

In Romania, although the relationship between archaeology and pedology has its roots in the late '50s, very few pedo-archaeological studies were carried out to date. The earliest attempts to study soils in archaeological contexts belong to Popovăț (1957), which aimed to establish a relative age of soil horizons buried under several Bronze and Iron Age sites from south-eastern Romania, and to Nicolăescu-Plopşor (1958), which focused on developing a chronological scheme of the Upper Paleolithic using soil and archaeological data. Later on, Protopopescu-Pache (1969) and Mateescu (1971) conducted several pedogenetic studies within Neolithic settlements from south Romania.

During the '70s and '80s, the sporadic collaborations between soil scientists and archaeologists resulted in several papers published by Asvadurov et al. (1970, 1972), which focused on the Paleolithic chronology using soil data, and by Lupașcu et al. (1987), who analysed the physicochemical properties of the thick heterogeneous deposits from a *tell* settlement from eastern Romania.

Over the last decades, the increasing demand for soil information in archaeological studies led to a slightly growing of published papers focused on the detailed physicochemical and mineralogical characterisation of soils from various archaeological sites (Lupașcu, 1996; Gâță et al., 2000; Rogobete et al., 2011; Dicu et al., 2015). In recent years, emphasis has been drawn to the use of proximal soil sensors and digital soil morphometric techniques, together with the multivariate statistical methods in the pedo-archaeological studies (Pîrnău et al., 2014, 2020, 2022). An overview of literature related with Romanian pedo-archaeological research can be found in Asvadurov and Florea (2002).

As can be seen from the paragraphs above, only recently can be noticed an intensification of integrated archaeological studies. The generalisation of non-invasive investigations based on the integration in a GIS environment, alongside spatial analysis, of the main prospecting methods (air photography, LIDAR surveys, geophysical prospecting, pXRF) arise new opportunities for understanding the complex phenomenon on the evolution of these Cucuteni communities.

2 Rediscovering the Eponymous Site of the Cucuteni Culture

In 1884, at 50 km from Iași, the archaeological site of Cucuteni was discovered, a site which was to become one of the eponymous settlements of the most renowned prehistoric civilisations in Europe, Cucuteni-Trypillia, whose area of spread exceeded 350.000 km^2 over nowadays Romania, Ukraine and the Republic of Moldova (Lazarovici et al., 2009).

The site (Lat: 47°17′55.12″N; Long.: 26°54′44.68″E) is located in North-East Romania (Fig. 1a), on the north-western part of Iași county (Fig. 1b) and in the upper sector of Valea Oii catchment (the last left tributary of the Bahluieț River), in a hilly area at the border between Moldavian Plain and Suceava Plateau (Fig. 1c). More specifically, can be found in the north-west of the Băiceni village (Fig. 2a, b) on a promontory east of the wide Laiu plateau (Petrescu-Dîmbovița & Văleanu, 2004).

The geology of the studied area is characterised by Sarmatian sediments, consisting of clay and sands deposits of ca. 200–300 m thick, overlaid by thin layers of limestone and sandstones, up to 4–5 m thick (Grasu et al., 2002). The investigated site is situated at the eastern edge of a large structural plateau, at an elevation of 325 m a.s.l., on a promontory bordered by steep slopes facing north and east, and by a large gully, up to 20 m deep with nearly vertical slopes, to the south (Fig. 1a). Towards the west, the terrain has a gentle slope shaped on a marl deposit of 2–4 m thick, that overlays a sandstone layer. The climate is temperate continental with mean annual temperature of 8–9 °C and mean annual precipitation around 530–560 mm (Dumitrescu & Bîrsan, 2015).

The settlement benefited from a particular attention on behalf of the academic environment due to its location near the city of Iași. By the contribution of the national and foreign researchers, the results achieved over time here were capitalised, both locally and internationally, through numerous articles and monographs (Beldiceanu, 1885; Schmidt, 1932; Petrescu-Dîmbovița & Văleanu, 2004). At *Cetățuie* the research was considered practically completed. Over 50 years after the latest excavation campaign in the renowned site of Cucuteni, benefiting from the new directions of interdisciplinary research in the field of archaeology, we resumed the investigations on this site and its landscape to finalise the research began 140 years ago.

The main argument that determined us to go on with a new research campaign for the site, primarily based on a multi-disciplinary approach of modern non-intrusive techniques of archaeological prospection, has been engendered by a series of novel recent results concerning site's planimetry achieved for other Chalcolithic (Cucuteni) settlements from North-East Romania, using similar field methods (Asăndulesei, 2017; Asăndulesei et al., 2020b; Mischka et al., 2016, 2019).

We direct the attention to the presence of an external habitation positioned outside of the main fortification/delineation works of the settlements and additionally to a diverse typology of the ditches. This was possible due to the enlargement of the areas measured in order to attain a broader general view and a close characterisation of the landforms on which the communities were settled.

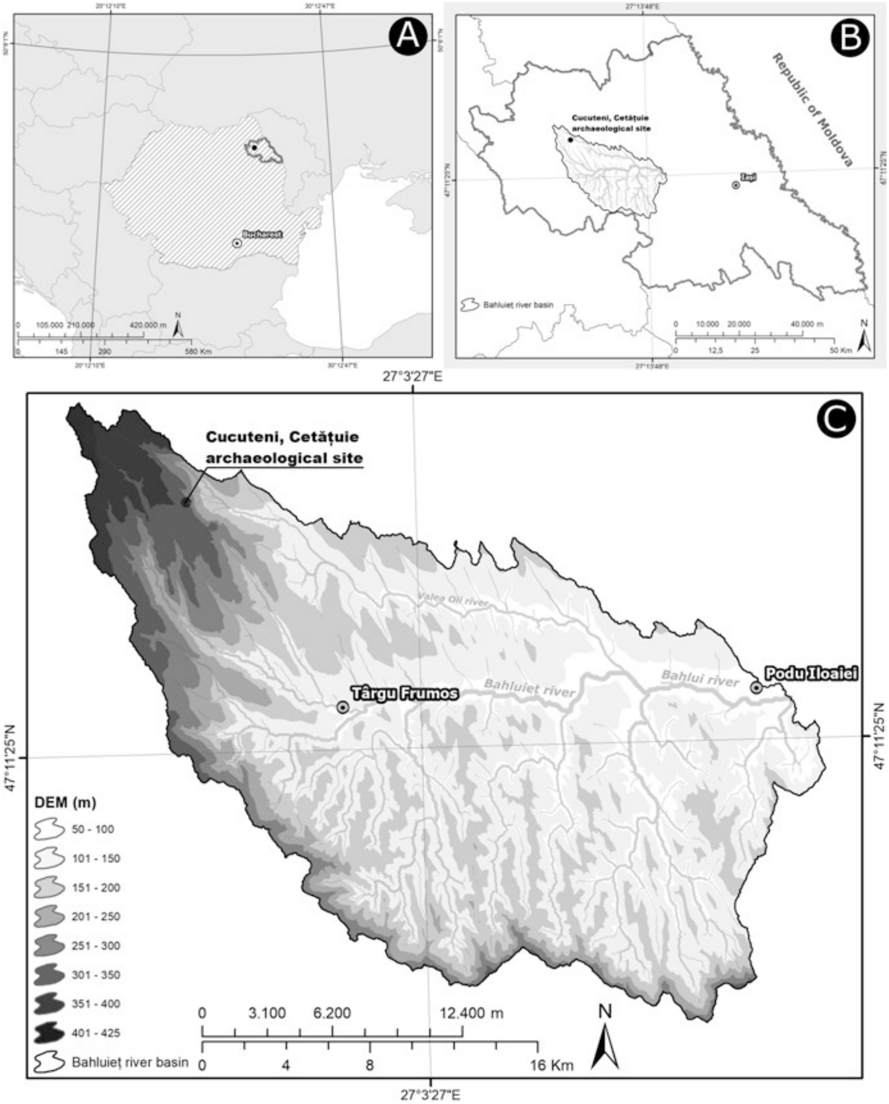

Fig. 1 The location of the case study in North-East Romania (**a**), within Iași county (**b**), and Bahluieț river basin (**c**)

The non-invasive surveys carried out in North-East Romania in recent years offered the possibility of prospecting much larger areas than had been covered by excavations, especially outside the anthropic boundaries. Rarely the archaeological trenches were positioned in order to prospect the outside areas adjoining the defensive works or, like in the present case, were placed, by mischance, in between of archaeological complexes.

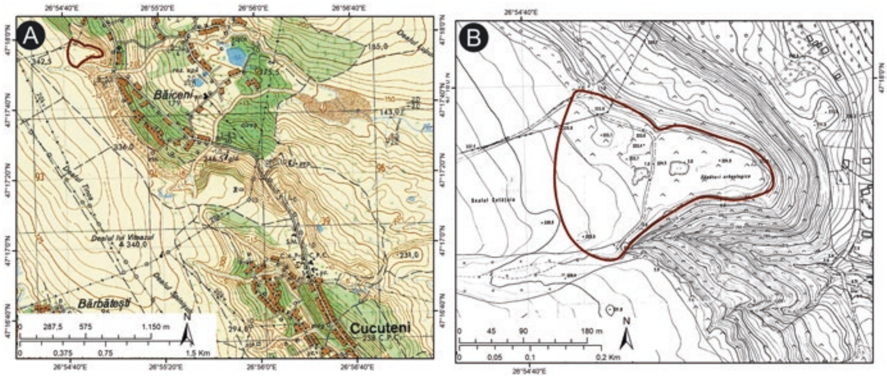

Fig. 2 Topographic maps (1984 and 1979 editions) of the area with settlement limit, scale 1:25000 (**a**) and 1:5000 (**b**)

Thus, as there were more validations in this regard for many other cucutenian sites (Asăndulesei, 2017; Asăndulesei et al., 2020b)—it was practically documented an initial fortified habitation followed by an extension outside of main enclosure works—the same question was raised up for the eponymous site as well, especially, as we will subsequently see, there were some assumptions according to which the habitation would be extensive. Settled on a high naturally defended promontory with steep slopes from three sides and only with a relatively flat area to the west, effortlessly accessible, supplementary argued a possible extension in this direction and a good reason for our endeavour.

In this study, complementary to magnetometer investigations, a soil survey consisting of seven auger cores carried out on the territory of Cucuteni-*Cetăţuie* settlement aimed to examine the morphological and geochemical characteristics of soil cover in relation to geophysical results and the archaeological site features.

2.1 Milestones of 140 Years of Research of the Cucuteni–**Cetăţuie**

As stated above, the Cucuteni settlement was discovered in 1884, thanks to the ethnologist Theodor Burada (1901), who was aware of the importance of the ancient remains of *Cetățuie*, stopped the destruction caused by the site's rock exploitation work. There followed, from 1885, surface surveys and small excavations conducted by Dimitrie Butculescu and Nicolae Beldiceanu (1885) (also, Gr. Tocilescu participated in the research of 1887). The first systematic researches took place since in 1888, due to the association of N. Beldiceanu with Grigore C. Buțureanu; George Diamandy also took part in the excavations, and later he presented two papers about the Cucuteni discoveries within the Society of Anthropology in Paris (Diamandy, 1889, 1890). The same year, Gr. Buțureanu participated with a paper at the

International Congress of Anthropology and Prehistoric Archaeology in Paris (Buțureanu, 1891), where the discoveries made at Cucuteni were enthusiastically received by the European archaeologists. The excavations continued in 1889, 1890, 1892 and 1895, the death of N. Beldiceanu marking the end of this first stage of research.

The next period of intensive research is due to archaeologist Hubert Schmidt from the Ethnographic Museum of Berlin, which carried out two vast excavation campaigns in the years 1909 and 1910 (Fig. 3). His research focused on the settlement of *Cetățuie* but also made some test trenches at *Dâmbul Morii*—“the settlement from the valley”. In 1910, H. Schmidt was accompanied by Gerhard Bersu, who investigated the defensive system of the settlement. Based on the findings from Cucuteni, the German researcher published a series of articles (Schmidt, 1910, 1911, 1924) and the famous monograph (Schmidt, 1932), building the chronological scheme of the evolution of Cucuteni civilisation, valid even today, with some nuances and additions.

The systematic researches were resumed between 1961 and 1966 (Fig. 3) by a team headed by Mircea Petrescu-Dîmboviţa (excavation leader) and Marin Dinu (assistant), with Adrian C. Florescu, Attila László, Eugenia Popuşoi, and many others. The excavations were eventually published extensively, as a monograph, under the signature of Mircea Petrescu-Dîmboviţa and Mădălin Văleanu (Petrescu-Dîmbovița & Văleanu, 2004).

Beyond the intrinsic significance, as the eponymous settlement of the Cucuteni culture, the older and newer researches from Cetățuie contributed decisively to the

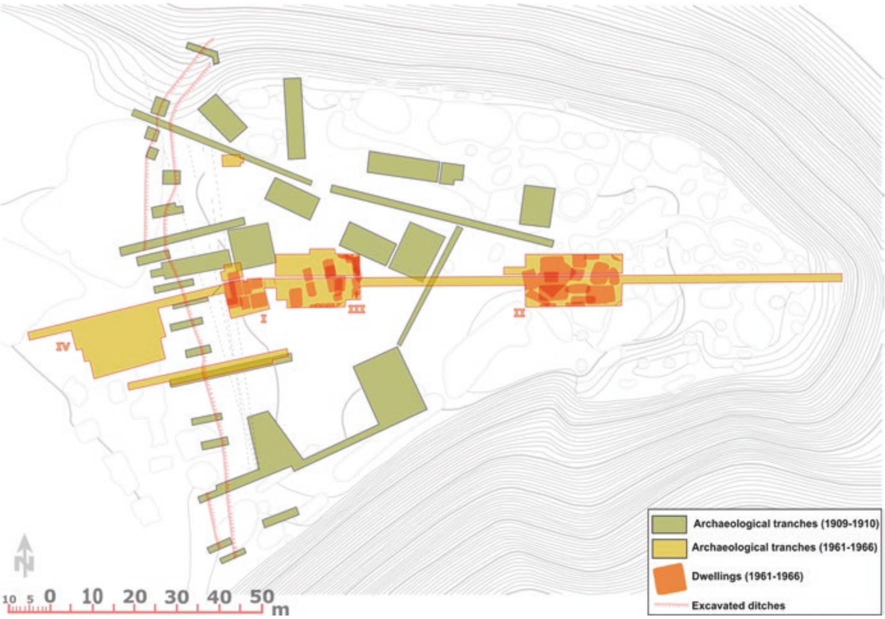

Fig. 3 *Cetățuie* archaeological site—excavation plan with the main archaeological complexes

establishment of the chronology of the Cucuteni civilisation, by combining Hubert Schmidt's observations with the information obtained through the systematic excavations from the '60s.

On the *Cetățuie* there were attested all three main phases of the Cucuteni culture (A, A–B and B). There were sporadic traces of habitation from Horodiştea-Erbiceni culture, and others associated to with later periods (Early bronze age, La Tène period). The investigated dwellings did not provide exceptional construction details. Interesting and noteworthy are the dwellings dating from the beginning of subphase B1, with local stone (sandstone)-built platforms. They contained modest interior arrangements, mainly hearths and ovens, areas for household activities (grinders) and some cult structures, mostly destroyed, perhaps intentionally (Petrescu-Dîmbovița & Văleanu, 2004).

2.2 Extra **muros—***Old Assumptions*

Researches, both the initial and the subsequent ones in the twentieth century, focused only on the prominent part of the terrain (the *Cetățuie* itself), naturally defended on three sides by steep slopes, and on the fourth (westward)—through a system of ditches and ramparts. Previous surveys presumed that the habitation has expanded beyond this system, on the western plateau.

The first clue in this respect is provided, even since the end of the nineteenth century, by one of the pioneers of the site's research, the professor from Iași University, Gr. Bușureanu, who speaks about the extension of the habitation beyond *Cetatuie*, for about 500 m, but the topographical indications, as well as the cardinal directions, are very vague (Bușureanu, 1889). Moreover, he even considered that this extension might be true habitation, and the *Cetățuie* was only the refuge. His ideas were, more or less, taken over by the first German scholars who wrote about the discoveries of the Cucuteni (Bosshard, 1890; Hoernes, 1898).

One of the owners of the land at the beginning of the twentieth century, C.V. Gheorghiu, in the brochure he writes about Cucuteni (Gheorghiu, 1910), states that on the northern edge of the site there is a stone quarry and, in that area, where there is a forest, about 150 m from *Cetățuie*, several discoveries were made, including a two-edged blade of a copper dagger. The piece, of great archaeological importance, was given to H. Schmidt, who deposited it at the Berlin Museum.

The discovery is confirmed by the Berlin scholar Hubert Schmidt, who in the 1932 monograph about the excavations he made at Cucuteni in 1909–1910, also speaks of the traces of habitation beyond the fortifications. He states that, in the two test trenches he practised here, "a few discoveries of great importance" were made, but without nominating them, except for the dagger. The pottery found here dates the traces found in this *extra muros* area (including dwelling debris) in the Cucuteni B phase (Schmidt, 1932).

In the 1961–1966 excavations led by Professor Mircea Petrescu-Dimbovita, one of the four investigated areas (trench IV: 240 m^2) was placed immediately after the defence ditches in the *extra muros* area, but no dwelling remains were found here, but only isolated ceramic fragments. However, in the presentation of the general model of habitation, it is stated that "when the ditch, by filling it, did not fulfil anymore its defence purpose, the habitation extended also on the plateau beyond it, in the Cucuteni B2 sub-phase, on a quite large area, then continuing, somewhere nearby, in the first stage of Horodiştea-Folteşti culture" (Petrescu-Dîmbovița & Văleanu, 2004). The authors of the Cucuteni monograph have attached some aerial photographs, some of which present the area beyond the western fortification system but without any comment, although they could have been edifying for the possible extension to the west of *Cetățuie*.

3 Materials and Methods

As Holliday et al. (1993) pointed out, soil science and archaeology are closely allied in their temporal and spatial scales, and among the earth sciences, pedology is most similar to archaeology in scales of operation and process. This similarity is also reflected at the methodological level, especially in recent years, when various methods and techniques have been adopted as standards in both archaeological and pedological research.

The case study has been visited with on many occasions by researchers, but, as we stressed above, both surface surveys and excavation have focused on the promontory area. As Binford (1982) said, *a landscape archaeology is an archaeology of place*, which is why we considered it useful to have a much broader approach to the landscape near the site on the *Cetățuie*. A multi-disciplinary approach of modern, non-intrusive or minimum invasive techniques of pedo-archaeological prospection and documentation were applied during the research.

3.1 Aerial Prospection and LiDAR Data

The 2004 monograph (Petrescu-Dîmbovița and Văleanu) includes some archival cadastral aerial photographs for the site from 1971 and 1981. The tip of the promontory is mainly focused here, but also a wide area with the surroundings of the site. Important things can be seen on the images concerning the old excavation trenches, fortification ditches or the open area from west and north disturbed by stone extraction.

Another aerial survey from a small aircraft was conducted in 2012 (Asăndulesei, 2014). In recent years (2017, 2021), many other flight missions were performed using UAVs (unmanned aerial vehicles) (DJI's octocopter S1000+ or Phantom 4 Pro v.2) in order to acquire up to date oblique and perpendicular images for the site and its proximity.

The Digital Elevation Model (DEM) can provide important information regarding the micro-topography of the study area. For our project, in order to obtain a good terrain model, we used ALS (Airborne Laser Scanning) data with 4 points/m^2 resolution (Stular et al., 2012; Doneus, 2013; Kokalj et al., 2013). Light Detection and Ranging (LiDAR) data were mainly used in RVT (Relief Visualisation Toolbox) to interpret the geomorphological parameters and some possible cultural anomalies.

3.2 Vertical Gradient Magnetometer Survey

One of the most intriguing characteristics of the Cucuteni settlements refers to the strongly burned archaeological structures. Most of the dwellings found in the excavation are burned, sometimes to vitrification. For this reason, we chose magnetometer survey as a main technique of prospection for this site, being known the efficiency of the method in similar contexts (Kvamme, 2006; Aspinall et al., 2008; Fassbinder, 2015). A 5 probe SENSYS gradiometer connected to a Leica GNSS receiver was used. The traverse spacing was set up to 0.5 m. The total area prospected with the use of magnetometer was about 5 ha (Fig. 6a). Magnetic data were processed using AGT (Archaeological Geophysics Toolbox) plugin in QGIS 3.18.1 and subsequently transferred in ArcMap 10.6.1 for integrated interpretation.

3.3 Soil Samples Collection and Geochemical Analysis

Portable X-ray fluorescence spectrometry (pXRF) has already shown strong capabilities for archaeological site prospection and in pedogenesis studies related with to past human activities and environmental conditions (e.g., Oonk et al., 2009; Dreibrodt et al., 2017; Horak et al., 2018; Smejda et al., 2017, 2018). Nevertheless, while pXRF became intensely used as a proxy for quantifying various soil physical and chemical properties, in Romania this technique has rarely been applied in pedo-archaeological studies (Pîrnău et al., 2020, 2022). In this study we attempt to identify the anthropogenic signatures at the Cucuteni-*Cetățuie* site by quantifying on-site and off-site enrichments or depletions of elements by means of employing pXRF measurements.

A transect of 300 m length, consisting in seven soil sampling points distributed in a range of altitudes of 325–338 m a.s.l., was established along the northeast-southwest direction, starting from the known archaeological site (P1), crossing the adjacent inhabited area revealed by the recent geophysical investigations (P2 and P3) and the off-site soils (P4, P5, P6 and P7) (Fig. 8a, b). A total of 72 soil samples were collected using a Dutch auger from each of the seven sampling points, at every 10 cm depth, from the surface to approximately 1.1 m depth, depending on the substrate (Fig. 8c).

A portable XRF device was used to perform a multi-elemental soil analyses in order to assess the geochemical signatures of past human occupation. Prior to pXRF analysis, all samples were air-dried in the laboratory and disaggregated to pass a

2 mm sieve and each sample was homogenised and compressed into a pellet using a 25-ton automated hydraulic press (Specac). The compressed pellets obtained were placed into cleaned plastic holders until the analysis was performed. Energy Dispersive X-ray Fluorescence (ED-XRF) analyses were performed using a portable Bruker Tracer S1 Titan spectrometer. This spectrometer uses a Rhodium (Rh) anode tube to generate an X-ray beam to probe the samples. The generated beam has a maximum energy of 50 keV, but was limited at to 40 keV. The incident beam is characterised by a spot with 8 mm in diameter on the selected samples. A Silicon Drift Detector (SDD), positioned backwards at an angle of approximately 45° with respect to the Rh-anode tube, is used to record characteristic X-ray spectra. One point randomly selected was analysed on each sample. Each point was exposed to the incident X-ray beam for 60 s. The spectrometer was used in *soil* workflow which provides measurements for 24 elements from which 12 elements (Si, Al, Ti, Zr, Ca, Sr, K, Rb, Fe, Mn, Cu, Zn) were retained for subsequent analysis due to non-detectability or the lower limit of detection of the other elements. The work-mode used to achieve the presented results was tested using NIST 1646a and NIST 679 standard reference material.

4 Results

Thus, it is noted that the extension of the settlement was postulated and even partially documented, but a thorough investigation of the problem has never been undertaken. In this context, the main purpose of our field evaluation was to open a much broader perspective on living near the most famous settlement of the Cucutenian civilisation.

4.1 Aerial Prospection and LiDAR Data

The old aerial photographs do not give indications regarding the planimetric extension of the site to the west, but they bring relevant information regarding the condition of the settlement in the 70s and 80s (Fig. 4a, b). Also, recent aerial images (Fig. 5a), as well as LiDAR data (Fig. 5b), provide information in this direction.

We can clearly see the area disturbed by the stone extraction from the north, apart from the main defence ditches (Fig. 4a). Here, the northern half of the external habitation is completely erased. Similar recent anthropic interventions can be correspondingly observed on the northern edge of the promontory itself (Fig. 5a, b). Also, the old excavation trenches are well outlined (Fig. 4b and 5a). To the south of the main habitation an active gully affects the integrity of the settlement (Fig. 5b).

Fig. 4 *Cetăţuie* archaeological site—Aerial images from 1971 (**a**) and 1981 (**b**) (Petrescu-Dîmboviţa & Văleanu, 2004); on the northern part of the upper image the stone extraction disturbances can be seen; excavated ditches representing the main fortification system can be observed on the lower image

4.2 Vertical Gradient Magnetometer Survey

The magnetometer measurements (Fig. 6a, b) on the large plateau highlighted the existence of a much different planimetry than what was known to date. Although excavations have taken place outside the known ditches (Fig. 3), it seems that the bad luck has made the planned sections to fall into the free space (without archaeological structures) between two rows of dwellings. This area lacking constructions is probably one of the two access ways in the settlement, which separates the rows of dwellings (Fig. 7). Only the southern row remains entirely today, but the layout of disturbed structures towards the centre and north of the external habitation suggests the presence of three alignments of Chalcolithic dwellings (Fig. 6b).

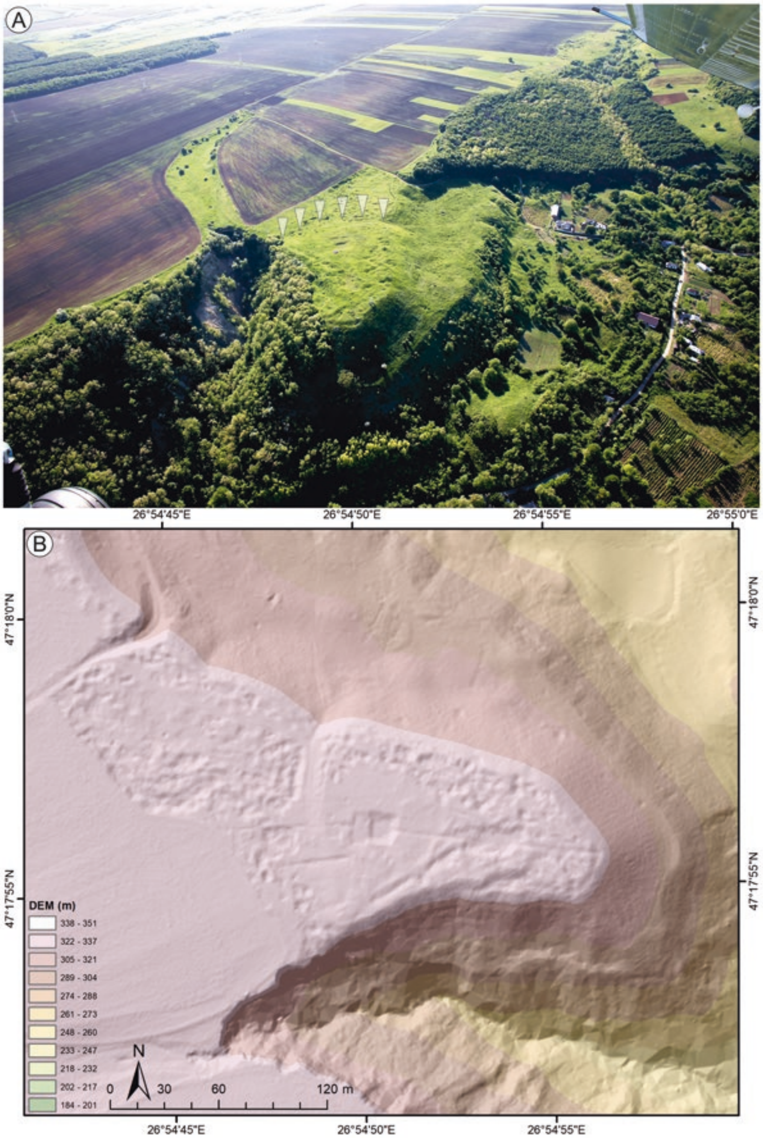

Fig. 5 Oblique aerial image of the *Cetățuie* site with the known ditches marked (**a**); hypsometric map of the site where archaeological trenches and other anthropic or natural disturbances can be observed (**b**)

The initial settlement was fortified with two defensive ditches, confirmed by the archaeological excavation. They are followed by another ditch, well individualised, with an average width of about 2.5 m, whose filling has, in certain sectors, a high degree of magnetic susceptibility (Fig. 7).

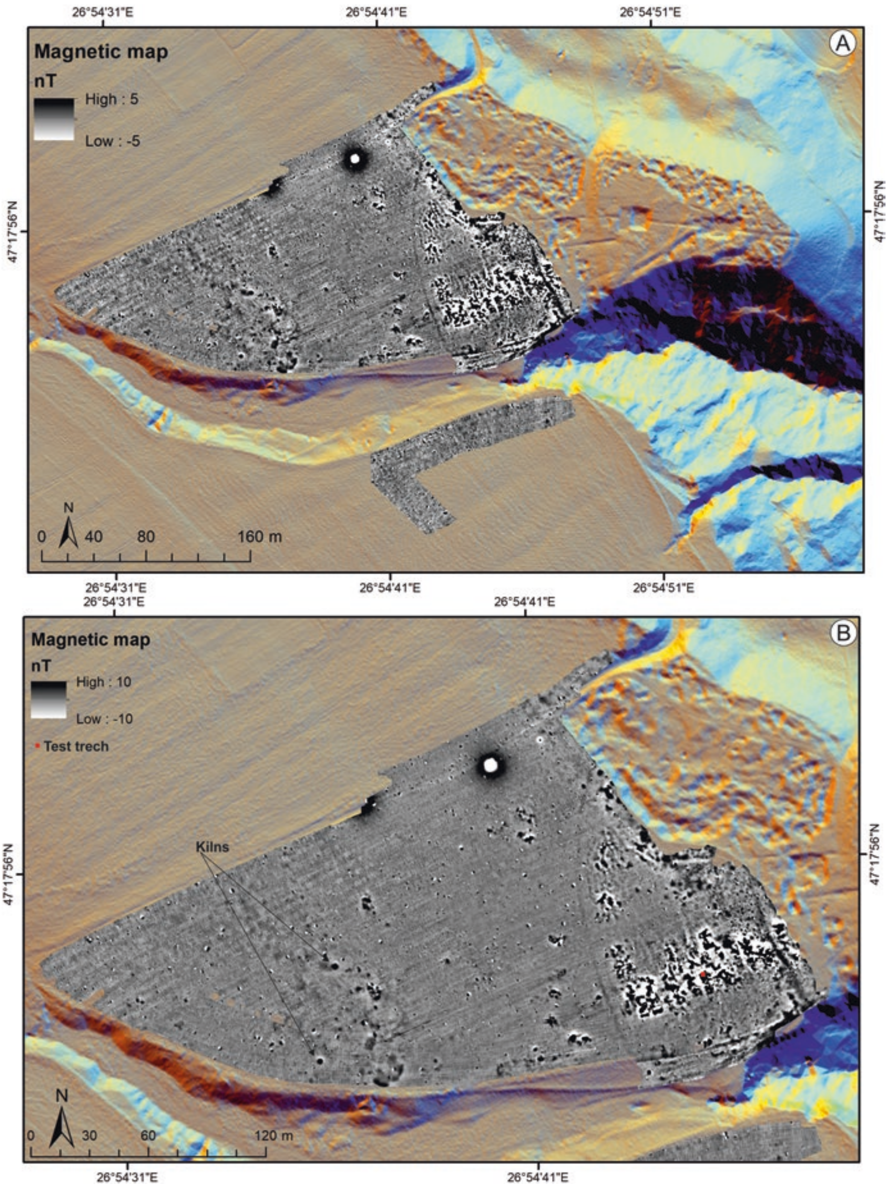

Fig. 6 Results of the magnetometer survey superimposed on multi-direction (16) RVT hillshade (**a**); a detail of results of the magnetometer survey where two possible kilns can be observed (**b**)

The southern row consists of at least 12 heavily burned dwellings (with values that may even exceed ±100 nT), some of which are visibly disturbed (Fig. 6b). Most seem to be north-northwest—south-southeast oriented, with a few exceptions. The latter may be a category of special constructions. Here too we can include the

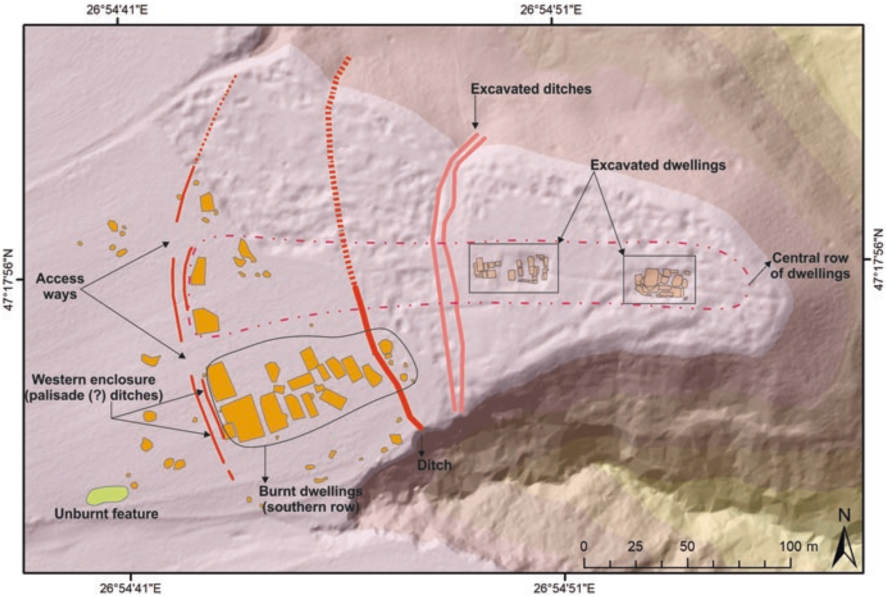

Fig. 7 Interpretation of the results of the magnetometer survey together with the excavated features

anomaly at the western end of the row which, although deranged, seems to have a surface that exceeds 300 m^2 (Figs. 6b and 7). Structures on both sides of the access-ways could also be classified as "bastions" or observation points.

The settlement also has a system of ditches arranged in a circular arc, narrow (not more than 1.5 m wide) and not very deep, which delimits the western side. The interruptions on their route, alongside the space without dwellings, suggest access areas in the settlement. We can probably talk about the ditches of a palisade system (Fig. 7).

Positive anomalies with relatively high dynamics, are visible outside the western ditches in the vicinity, but without a clear arrangement. Further on, to the west, a set of many positive, burned or unburned anomalies, possibly pits, is still visible. It is difficult to tell whether they have any connection to the Cucuteni habitation. There are also two circular anomalies in this sector, which exhibit a thermoremanent magnetism (signal intensity of about 35–55 nT), which may suggest the presence of kilns (Fig. 6b).

4.3 Soil Morphology

Among the seven sampling points, P1 and P2 occur within the inhabited area of the site, P3 intersects the rampart of the second ditch of the settlement, whilst P4–P7 occur off-site on the soils from the middle and upper parts of the catena sequence (Fig. 8a).

P1 has a very dark brown to black A chernic horizon (10 YR 2/1–2/2) in the upper 40 cm, followed by a buried A mollic horizon (10 YR 3/2), which gradually changed at ca. 70 cm depth to a thin Bw horizon having a very dark greyish brown colour (10 YR 3.5/2). The Bw horizon is rich in coarse limestone fragments and is followed by a continuous limestone layer at 90 cm depth. Small fragments of potsherds and other artefacts are common from the topsoil to the bottom, with a maximum content at 30–90 cm depth (Fig. 8c).

P2 occur in the adjacent inhabited area, recently revealed by the geophysical investigations, and exposes similar characteristics with P1 in the upper and middle part, but a more developed Bw horizon formed on a marly calcareous parent material that overlay the limestone layer. The topsoil is characterised by a thin colluvial layer mixed with the buried Ah horizon, both having a black colour (10 YR 2/1). The artefact content reaches a maximum in the 20–50 cm interval (Fig. 8c).

The topsoil layers of the P3 are similar with P2 to 30–40 cm depth, where abruptly change to a buried A molic horizon, with colour shifting from 10 YR (2/1–2/2) to 10 YR 3.5/2. The horizon sequence is followed by a Bw horizon with a dominant paler yellowish-brown colour (10 YR 5/4–5/6), mixed with mollic colours (10 YR 3/2). The morphological characteristics indicate that this profile cut through the rampart remains of the adjacent to the second ditch of the settlement. Artefacts are present in the middle and bottom part of the profile, with elevated accumulation at 50–60 cm and 90–100 cm.

In the case of P4, a colluvial layer of 40 cm thick, having a very dark greyish brown colour (10 YR 3/2), underlying a buried A chernic horizon (10 YR 2/1) to 70 cm depth. The underlaying Bw horizon has a dark yellowish colour (10 YR 4/4) and contain a small number of artefacts at 80–90 cm depth (Fig. 8c).

In the middle and upper parts of the catena (P5–P7), soils display some features different from all other profiles, like the presence of mollic surface horizons (10 YR 3/3–3/4) instead of chernic ones and a low content of artefacts fragments. Moreover, in the highest part of the catena (P7), the subsurface Bw (cambic) horizon gradually changes to Bt (argic) horizons characterised by clay coatings observed on some aggregates and stagnic properties shown by the presence of the redoximorphic features. In the case of P5, due to its location on the steepest slope, the surface horizon is strongly affected by erosion.

Taxonomically, the soils distribution along the analysed catena shows a succession of Technosols (Archaic, Cernic), in the case of P1–P3 profiles, followed by Cambic Phaeozems (P4–P6), in the transitional zone, and by Argic Phaeozems (P7) in the upper part of the slope (soil names according to IUSS Working Group WRB, 2015).

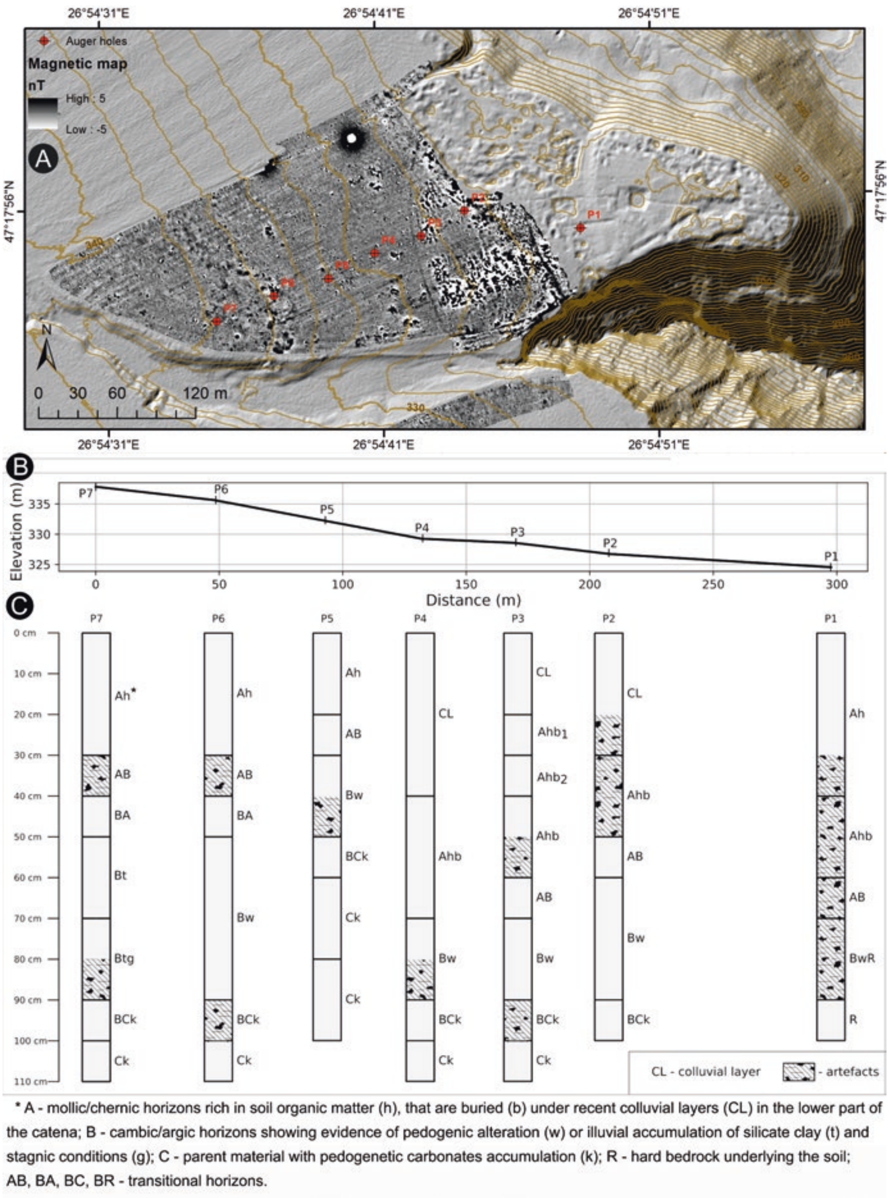

Fig. 8 Location of the investigated auger holes on the magnetometer survey results (**a**); topographic profile (**b**); simplified stratigraphy of the investigated profiles (**c**)

4.4 Results of the pXRF Elemental Analysis

The depth distribution of measured element values by pXRF is presented in Fig. 9. The results of the pXRF elemental analysis show clear differences in element concentrations in archaeological site areas compared to the off-site soils. Overall, the concentration of Si, Al, Ti, K, Rb, Fe, Mn, Cu and Zn are elevated in P1–P3, from topsoil to the bottom part, except for some values of P1 that can be attributable to the soil disturbance caused by the previous archaeological excavation.

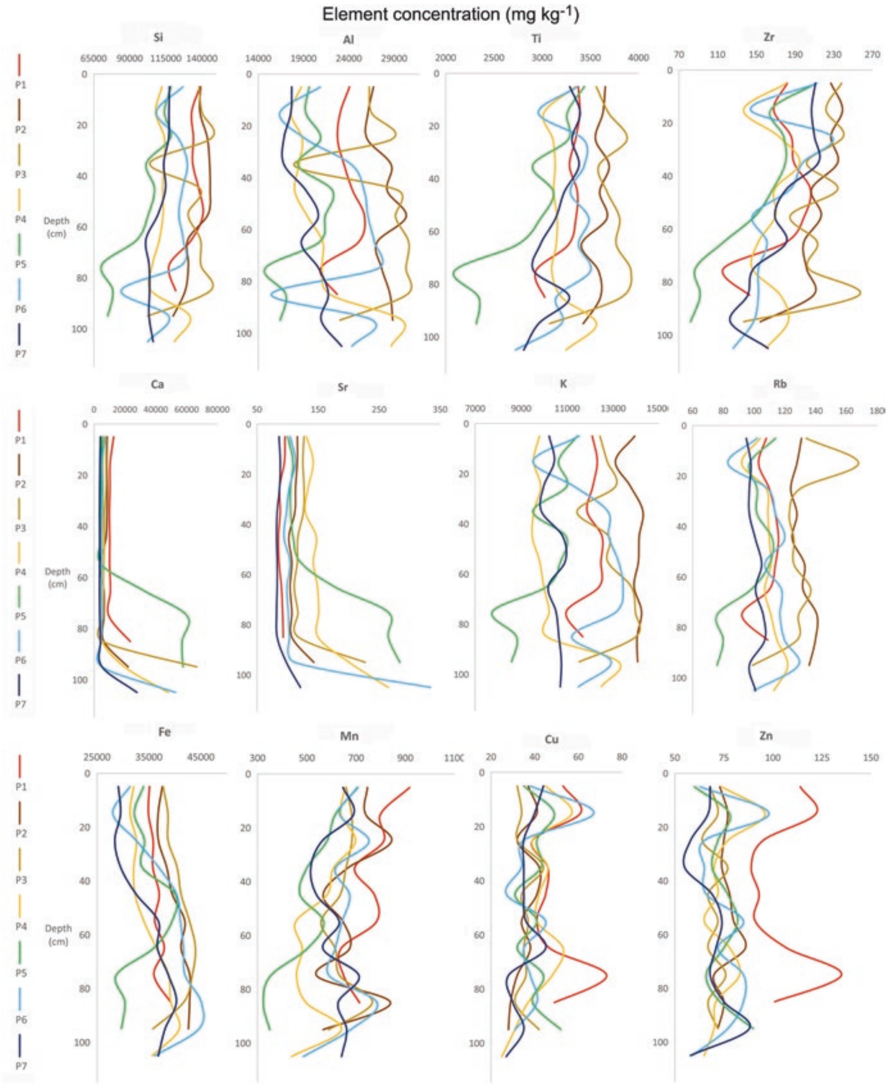

Fig. 9 Concentrations of elements measured by pXRF

The ratio of Si, Ti, Zr and Mn show a similar distribution and a decreasing trend down to the soil profiles. In the case of P3, concentrations of the Si and Al decrease sharply at 30–40 cm depth, indicating a threshold between the upper part and the middle part of the soil. Due to the position of the sampling point in the proximity of the western ditches of the settlement, revealed by the magnetometer investigation, it can be presumed that this threshold reflects the contact between the remains of a possible ditch rampart and the buried soil beneath it.

The Fe and Al concentrations are relatively constant down the profile, in the case of archaeological soils, but have slightly elevated values in the B horizons of the off-site soils, which reflects the accumulation of clay by argilluviation processes, in the case of P7, or by in situ clay formation, for the other analysed soils with Bw horizons.

The depth distribution of Rb and K elements, which are strongly correlated with the clay content, as shown by numerous studies (Zhu et al., 2011; Tóth et al., 2019; Croffie et al., 2021, among others), demonstrates also increased values in the B horizons of the off-site soils. In the case of the soils situated within the archaeological site (P1–P3), the higher values of K and Rb are more likely related with to ancient anthropic influence and catena processes that led to the concentration of these elements at lower elevations.

As expected, Ca and Sr show a similar behaviour with depth, being highly correlated with the presence of calcium carbonates. Due to the leaching processes, both elements' concentrations are uniformly low throughout the upper and middle parts of the analysed profiles. The elevated concentrations below the 80–90 cm depth are consistent with the presence of the carbonate marls. In the case of P5, which is located on the steepest slope of the catena, the concentrations of Ca and Sr increase from 60 cm, due to the erosional processes which removed the upper part of the soil.

In the case of Cu and Zn, a prominent spike occurs in the topsoil of all analysed points, which is related to the recent anthropogenic activities. A second spike in Cu and Zn content is characteristic only for the P1 profile, at 0.6–0.7 m depth, which is related to the presence of a consistent layer with artefacts fragments, reflecting the ancient anthropogenic influence.

5 Discussion

The catchment area or the exploited territory of a settlement is understood as an area where the Chalcolithic communities carried out their everyday activities, from where they ensured their food and resources. In the absence of a precise chronology that would make it possible to understand the contemporaneity of the settlements, their territoriality can only be determined by an attempt to analyse the type of habitation, which will subsequently show indications of their functionality. Analysing closely the characteristics of the place where the communities sat (geomorphological parameters, soils, etc.), we have seen that areas with a high concentration of settlements can be detected (Asăndulesei, 2015b). Of these, the long-standing settlements, such as *Cetățuie*, where all three major phases of the Cucuteni culture are present, have definitely been key positions in the development of the proximity and population dynamics. Through its position, dominates the upper course of the Valea Oii creek, benefiting from a high potential of visibility, polarising at the same time many settlements situated on low relief near the watercourses, with which has intervisibility relations.

The determination of a territory exploited by the communities of this culture should not be done through a steep delimitation of areas around the settlements without a prior proper interpretation of planimetry, a rigorous cultural analysis of artefacts, ecofacts or natural resources in their proximity. The delimitation of a reservoir of resources must be made from the inside of the site towards the dynamic habitat of interaction between the Chalcolithic communities.

As it can be seen, the recent research from Cucuteni—*Cetățuie* provided new interesting data worth of a thorough future investigation. It is about the existence of habitation in a much larger area than the one that was researched 50 years ago, with many new interesting archaeological situations (double fortifications, dwellings, possible kilns).

It seems that the tip of the promontory constituted the initial nucleus of the settlement, which probably developed to the west in several stages, in the context of demographic growth. Several stages of evolution of the Cucutenian site can be distinguished, for which we cannot define chronological intervals, in the given state of research (Fig. 7). Similar situations are known e.g., Războieni—*Dealul Mare* (Asăndulesei, 2017), Fulgeriș—*La trei cireși* (Asăndulesei et al., 2012), Ghelăiești—*Nedeia* (Mischka et al., 2016), Drăgușeni—*Cetățuie* (unpublished) constituting solid arguments, especially in case of high promontories settled habitations, for a possible existence of some particular patterns. Correspondingly, the lower situated settlement could have such an extension of habitation: Cucuteni—*Dâmbul Morii* (Asăndulesei et al., 2020a, b), Ripiceni—*Holm* (Asăndulesei et al., 2020a, b).

From a pedological point of view, overall, the variation of elements content with depth is consistent with the geophysical results and soil morphology. The results of pXRF measurements shown the enrichment of all measured elements at the lower part of the investigated area, which coincides with the archaeological site occurrence. Although a significantly higher concentrations of anthropogenic elements, such as Cu and Zn, was expected in the case of archaeological soils, the increased values of the geogenic elements can be explained by the post-Chalcolithic catena processes that led to the formation of a colluvial layer above the site and implicitly the concentration of these elements at lower elevations. Moreover, the depth distribution of elemental contents in the settlement area, highlighted a pedogenic threshold at ca. 40 cm depth, at the transition between the colluvial deposit and the buried chernic horizons developed at the Chalcolithic land surface. For the off-site soils, the vertical distribution of most elements shown a sharp change at the same depth, which is related with to the presence of B horizons and a second threshold at 80–90 cm depth, coincident with the depth occurrence of the parent material, consisting mostly in carbonate marls. The carbonate-rich parental material had a strong impact on soil development, leading to the formation of deep chernic/mollic horizons on the Chalcolithic land surface, which can also explain the preference of Chalcolithic inhabitants for this area. The colluvial cover explains the good preservation of buried soils and the relatively limited degree of soil evolution, despite a recent relatively humid climate.

The specificity of the investigated area is given by the dominance of the Cambic Phaeozems at the lower slopes, linked with the prehistoric habitation, that gradually changes to Argic/Stagnic Phaeozems and Haplic/Stagnic Luvisols, which occur in the upper hill region, outside the investigated area. The soil distribution suggests an open landscape at the archaeological site and its proximity, bordered at the west by a forested area, that favoured the development of the Bt (argic) horizon.

6 Conclusions

The Cucuteni-*Cetățuie* site has been the focus of much archaeological research over the last hundred years. Nevertheless, the non-invasive investigations carried out in this study allowed the identification of some previously unknown features related to site boundaries and the characteristics of the proximity area.

The results obtained are extremely important because they offer the possibility of a new, more efficient, approach to site research strategy given that it is increasingly threatened by anthropogenic, but especially natural, destructive factors.

With a total area of around 3.5 ha, the *Cetățuie* site belongs to the small settlements category, but with a dense and complex internal spatial organisation of archaeological features. Apart from the two main excavated ditches, on the magnetometer survey results a third one having the same size and orientation can be observed. This delineation could be interpreted as one of the first extensions of the settlement. Other two small ditches enclose the western side of the site; these remains here could have been generated probably by a palisade system. Two interruptions on the way of these anomalies could be interpreted as entrance into the settlement through some possible alleys situated in between the dwelling rows. At least 12 dwellings are visible in the western enlargement of the settlement, on the southern row, and many other small positive anomalies attesting the presence of pits (Fig. 7).

A test trench excavated in late November 2017 was intended to partially frame chronologically the extension of the eponymous settlement from *Cetățuie*. For this purpose, we have partially investigated a section (S I – 2 × 2 m), located at the centre of a magnetic rectangular anomaly that suggested a typical Cucuteni burned dwelling. About 25 cm below the ground surface, we have already reached the destruction layer of a dwelling, with wattle and daub fragments from its collapsed walls. The few painted pottery fragments indicate the Cucuteni B1 phase.

It was found that the soil morphological features and quantitative data of elemental contents measured by pXRF may add further information to geophysical results due to their ability to offer an insight on the vertical variation of soil properties and to address the complex issues of stratigraphical relationships between in-site and off-site area. The integration of results of magnetometer and soil survey may provide more answers for a better understanding of the extent and function of Chalcolithic sites. Furthermore, this approach has implications in archaeological sampling strategy by constraining the requirements for further excavation.

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Part XVI
Scotland

Geophysical Survey in the Archaeology of Scotland: Recent Developments and Results

Richard Jones

Abstract This paper reviews the current state of geophysics in Scottish archaeology, considering the scope of the surveys, the range of targets investigated and techniques deployed, as well as the practitioners and commissioners of surveys. Several issues of methodology and interpretation are illustrated through case studies taken from mainland Scotland, Orkney and the Isle of Lewis. One of these focuses on the relative frequency of poor magnetic and earth resistance responses recorded over ditch and pit features due to drift geology and soil conditions, and the efforts to explain those responses in terms of soil properties. This leads to the recommendation that archaeo-geophysics can only benefit from aligning itself on a regular basis with geoarchaeology since their respective subject areas often converge more than is usually recognised. Another recommendation is the need for fuller dissemination of the graphical output of surveys as well as access to raw data to encourage a more critical view of how interpretations of individual geophysical anomalies are made.

1 Introduction

Scotland's heritage offers considerable scope for the application of geophysical survey: to set the scene, there is the chronological range of its sites and monuments that have been explored in this manner, from potential Mesolithic seascapes linking the Minch (Fig. 2) bordering the Isle of Harris and the Atlantic (Bicket et al., 2017; MBS—see Table 1 for abbreviations), Mesolithic shell middens on Colonsay (Finlay et al., 2019; M, R), the Heart of Neolithic Orkney (Brend et al., 2020; Table 1), Roman military presence (Hanson et al., 2019; Table 1), potential royal tombs in Dunfermline Abbey (Penman & Utsi, 2016; GPR), nineteenth century lime kilns (Bishop et al., 2017; G, MS) to WW I warships scuttled in Orkney's Scapa

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Table 1 Case studies: sites, targets, and techniques (M- magnetometer survey, R- earth resistance, GPR- ground penetrating radar, MS-magnetic susceptibility, ALS- Airborne laser scanning or LiDAR, EMI- electromagnetic induction, MBS-multibeam sonar, P- phosphate)

Site	Target	Techniques	Publication
Heart of Neolithic Orkney	Neolithic to Iron Age (and later) Loch of Stenness	M, R, GPR, EMI MBS	Brend et al. (2020) and Bates et al. (2016)
Forteviot	Late Neolithic ring-ditch	M, R, GPR, EMI, P, multi-element analysis, texture, pH, conductivity, organic content & MS	Cuenca-Garcia (2012, 2018) and Poller (2020)
Dalswinton	Roman fort, annexe, enclosure and camp	M, R, MS, ALS	Hanson et al. (2019)
Bothwell Castle	Castle and environs	M, R, GPR	Rose Geophysics (2015)
Galson, Lewis	Graveyard	GPR	Rose Geophysics (2019)

Flow (Dean, 2006; MBS). This range also reflects the diversity of natural environments (lowland, upland, wetland, aeolian) that have hosted human activity, as well as the variable preservation of that activity over the course of time. Judged in this light, it may be fair to say that geophysics is now well established in most sectors of Scottish field archaeology and as such has overcome the perception, prevalent until the start of the present millennium, that its performance was uneven (Jones & Sharpe, 2006; Cuenca-Garcia et al., 2020, 6–7). This brief contribution attempts to give an overview of the current status of geophysical survey in Scotland, considering some of the routes by which geophysical surveys have been carried out and on what scale, and using case studies to highlight specific issues of methodology and interpretation.

An impression of the frequency with which geophysics was deployed up until the early 2000s can be gleaned from the Scottish Archaeological Geophysical Survey Database Project undertaken by the Department of Archaeology, University of Glasgow, and funded by Historic Scotland. From some 600 entries in the database Rennie (2006) reported that research-led surveys including those forming part of a broader project, such as the Traprain Law Environs Project (Hale et al., 2006; Hale & Cowley, 2009), were significantly more numerous than those relating to development proposals; prehistoric (i.e. pre-Roman) sites received the most attention. This picture seems to have altered in the intervening period to judge from the entries in *Discovery & Excavation in Scotland*, published annually by Archaeology Scotland. For the years 2016–2018, geophysical survey features 41, 50 and 47 times respectively as a component of fieldwork undertaken in the commercial sector, by universities and other institutions and in initiatives made by local archaeology societies and community archaeology groups. The size of the survey varies considerably, from the landscape level (up to 520 ha on the Aberdeen bypass project (see below) to a few thousand square metres in advance of targeted excavation. These numbers for 2016–2018 may be significant in themselves but should be considered in context: some 800 entries of fieldwork (including watching briefs, but excluding metal detector finds) feature, for example, in 2018. Figure 1 presents the proportions of different types of target investigated during those 3 years.

In the commercial sector, developer-funded archaeology has traditionally made some use of geophysical survey (Leslie & Banks, 2006), but recent years have seen a more critical approach to its role in guiding excavation strategy. In essence, the planning authorities in Scotland, advised by their heritage/archaeology advisor, consider *all* the options that non-invasive assessment can offer. The size of the development area and its location (urban, rural) are two of the many factors impacting on the suitability of deploying geophysics. For instance, the combination of large size and rural location encouraged reliance on gradiometer (hereafter magnetometer) survey in recent major road projects (for example, A9 Killiecrankie to Glen Garry section (8 ha) Headland Archaeology, 2018a; Aberdeen bypass (520 ha) https://molaheadland.com/project/aberdeen-western-peripheral-route/, Headland Archaeology, 2018b; A96 Nairn bypass (30 ha) AOC Archaeology Group, 2016). It is worth noting here the few cases of surveys, undertaken separately as developer- and research-led, that have combined to good effect, for instance at the Pictish centre at Kinneddar (Noble et al., 2019) (Fig. 2). As for the excavation strategy, the evaluation area of a proposed development site in Scotland has, since the 1990s, typically been 5–10%, compared to 2–3% elsewhere (Hey & Lacey, 2001, 43, Fig. 27). Of relevance in Hey and Lacey's account, based on data from sites in south-east England, is the valuable assessment by Linford and David (2001) of the effectiveness of the geophysical surveys carried out at five of those (prehistoric to Roman) sites in the light of their excavation.

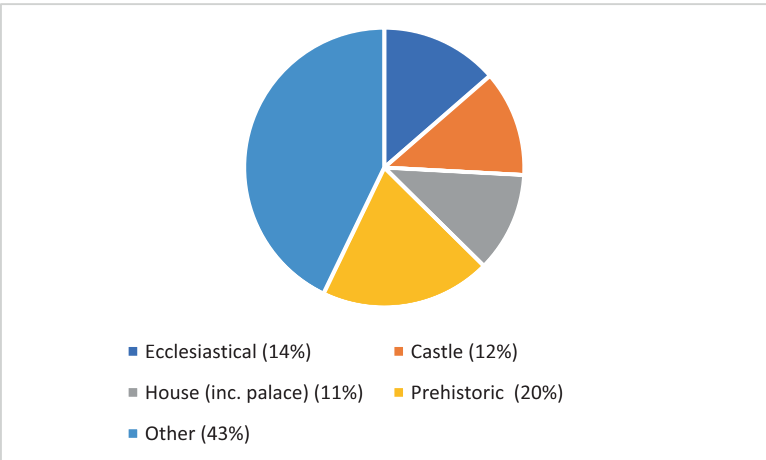

Fig. 1 Indicative relative proportions of geophysical survey targets reported in *Discovery & Excavation in Scotland* in 2016, 2017 and 2018

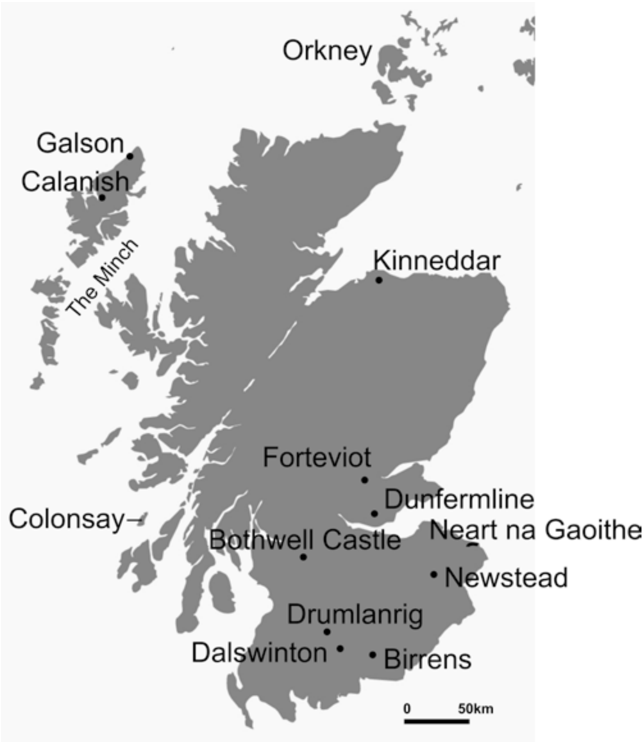

Fig. 2 Map of Scotland showing the locations of some of the sites mentioned in the text

Undertaking the surveys are specialised Scottish or UK-based geophysics companies, commercial archaeology units, university departments and local archaeological societies. Prominent among the many organisations commissioning such work is Historic Environment Scotland (HES), which has a diverse estate of properties in care (Sagrott, 2021); here geophysics is used as a management tool to build up a picture of the immediate environs of those properties. Indeed, they are well represented in the ecclesiastical, castle and house/palace categories shown in Fig. 1.

The planning of geophysical surveys and interpretation of their results in Scotland continues to make much use of the rich aerial photographic record, and this can now be supplemented by the availability of high-resolution ALS (Airborne Laser Scanning or LiDAR) data covering many parts of Scotland. HES, the leading body in Scotland promoting aerial survey, has recently extended its practical capability to include geophysical survey (multi-sensor magnetometer and electromagnetic sensor). This welcome development has seen the appointment of a full-time geophysics officer (Hannon, 2021).

In terms of instrumentation, one major development has been the deployment of multi-sensor gradiometers with integrated GPS capability placed on a vehicle-towed (or operator-pushed) cart, well suited for high-resolution landscape level surveys. Recent locations include Rousay (Orkney) (Beusing & Rassmann, 2018), Roman Newstead (Beusing et al., 2018a) and Roman-Iron Age Birrens/Burnswark (Beusing et al., 2018b) and the Antonine Wall (Hanson et al., forthcoming). But more generally geophysical survey has relied on the traditional trio of techniques: gradiometry, electrical resistance and ground-penetrating radar (GPR) in that order; this point is taken up in the Discussion. Methods such as electrical resistance imaging have found limited application (but see Sutherland et al., 1998 and Neighbour et al., 2001 for surveys on Shetland and in south-west Scotland respectively, and more recently Brend et al., 2020, Fig 5.29).

2 Case Studies

The case studies presented below have been selected to illustrate recent surveys. Confronting all of them is the fundamental issue of interpretating individual geophysical responses. As is demonstrated below, this has followed the traditional pragmatic approach, yielding archaeologically meaningful results without, except at Forteviot (see Fig. 2), recourse to validating those results by excavation. By contrast, there are surveys, undertaken as part of research-led and commercial projects, that have been followed by excavation; Sects. 16.2.3 and 16.3 briefly treat two such examples. However, they are in a minority and furthermore may not include a full post-excavation re-evaluation of the geophysics. In this situation in which excavation has not taken place, an awareness of the circumstances that may complicate interpretation is necessary. Notable among these is the nature of the drift geology and topsoil/subsoil conditions that may give rise to noisy data, partially masking the detection of remains of archaeological interest. It is the combination of the many natural factors likely to determine the nature of a geophysical response together with the realisation that those factors may be unique to a given location and its associated archaeological feature that has tended to undermine attempts to find helpful explanations. And to these natural factors should now be added the effects on magnetometer data of 'green waste' (biodegradable and organic materials) which form part of commonly used fertilisers and soil conditioners (Gerrard et al., 2015). In principle then, one way forward would be to build up a fuller characterisation of the soil that takes account of the soil's textural and chemical attributes. The application of chemical methods to soil analysis has already played valuable roles in geoarchaeology, particularly in defining activity areas within either ancient to recent settlements or individual buildings and in determining anthropogenic soil development (see overview https://scarf.scot/thematic/scarf-science-panel-report/4-people-and-the-environment/4-2-geoarchaeology/), but it has not interacted sufficiently with the corresponding geophysical data, as discussed in 3. below. An exception, alone of its kind in Scotland, is the study by Cuenca-Garcia (2012, 2018) who monitored the combined geophysical and geochemical responses to some archaeological features present in contrasting burial environments. Part of her enquiry, which finds parallels with soil chemical responses at sites in Scotland defined by cropmarks observed in aerial photographs (Sharpe, 2004), is discussed below.

2.1 The Heart of Neolithic Orkney

In terms of scale and output, pride of place must go to the 10-year landscape study of the UNESCO World Heritage Site, The Heart of Neolithic Orkney, comprising the most well-known Neolithic settlement on Orkney, Skara Brae, and, 5 km away, a remarkable array of Late Neolithic and later monuments of the Stenness-Brodgar area on Mainland Orkney (Brend et al., 2020). Situated in that area, much of it lying on a narrow isthmus between Lochs Harray and Stenness, are upstanding stone circles and henges, the chambered tomb of Maeshowe, the settlement of Barnhouse and the Neolithic complex of the Ness of Brodgar. But the knowledge that this area is known from surface and other indications to be rich in a variety of other prehistoric sites presented a unique challenge for geophysical prospection. Covering an area of some 285 ha, the survey, conducted primarily with the magnetometer (Table 1), indeed delivered on the title of its publication: *Landscape Revealed*; not only are its results of major archaeological importance, but both the manner they are presented in, and the methodology employed set new standards. In brief, the combination of terrestrial survey with, on the one hand, the aerial photographic and ALS records and, on the other, historical documentation and antiquarians' observations on past land use proved to be a powerful interpretative tool. Second, the project was able to draw on the results of marine survey on- and offshore of the two lochs just mentioned as well as sampling for microfossil and sediment analysis (including C^{14} dating) (Bates et al., 2016) to provide palaeo-geographic reconstruction; this approach is explored further in the Discussion. The corresponding work inland from Skara Brae in the Bay of Skaill employed conductivity survey and coring.

A selected sample of the results, from the Bay of Skaill area (Fig. 3), highlights the magnetic anomalies arising from the landscape viewed as a palimpsest: (a) prominent near-surface igneous dykes, (b) agricultural activity mainly of the rig and furrow type and (c) prehistoric and later occupation. Magnetically quiet areas in Fig. 3 are seen as former land surfaces now overlain by wind-blown sand. Of archaeological significance are first the detection of a continuation of the Skara Brae settlement and, further south, possible domestic structures; second, the inset in Fig. 3 shows the detail within the Iron Age broch of Loupandessness and, to the west, contemporary roundhouses/double houses. The post-medieval rig and furrow is prominent in this area of Iron Age occupation, yet hardly features towards the N and NE.

The results from the larger Stenness to Brodgar area were no less rich or informative. The marine survey concluded that by the Early Neolithic the isthmus was wider, Loch Stenness was smaller and sandstone outcrops suitable for monumental building were exposed at that time. This raised the possibility of the existence of early occupation phases on the isthmus as a whole. The agriculturally worked soils—rig and furrow—so prominent throughout the survey, deserve attention here because their magnetic signature was far from uniform. The nature of the underlying soils and deposits being brought into cultivation and the nature of the additions being made to the soil were both factors regulating the detected magnetic enhancement. As Brend et al. (2020, 102–4, Fig. 4.26–27) explain, where rig and furrow survive and weathering has been minimal, the ridge is a positive magnetic anomaly,

Fig. 3 Results of the magnetometer survey (top) and interpretation plan (bottom) of the World Heritage Area from Skara Brae to Loch of Skaill, Orkney; results at the roundhouses/'double houses' and Loupandessness (inset right). From Brend et al., 2020, Figs. 3.4, 3.5 and 3.25 respectively. Graphics courtesy of Nick Card

correlating with higher earth resistance, but the reverse happens when the rig and furrow have become denuded over time. Furthermore, the authors report instances of ploughed rig and furrow passing over enhanced material belonging to earlier occupation; this manifested itself in terms of narrow positive responses due to the ploughed-out furrows 'swapping' to become pronounced negative responses as they pass through strong (magnetic) anomalies.

2.2 *Forteviot*

The corpus of geophysical, mainly magnetic responses from ditches that are part of enclosures, henges, cursus monuments and ring structures in Scotland of prehistoric date is large, as several contributions to the volume *Going over Old Ground* (Jones & Sharpe, 2006), more recent work in Orkney (see above) and in East Lothian (Hale & Cowley, 2009) make plain. The experience gained from those same studies also indicates that the responses from magnetometer survey over prehistoric ditches *usually* appear as positive anomalies, resulting from magnetic enhancement of the deposits that filled them. Efforts have been made to characterise the distribution of magnetic susceptibility across a ditch before and after excavation, notably by Kainz (2016) in Austria and now in Scotland by Cuenca-Garcia (2012, 2018).

One of Cuenca-Garcia's programmes of survey, complementing high-resolution geophysical measurements (Table 1) with very detailed soil analysis, was located at Forteviot where some of the sites observed as cropmarks in aerial surveys were clearly identified as a complex of Neolithic-EBA enclosures and henges. Several of those prehistoric features were the targets of excavation forming a major component of Glasgow University's long-term field project, Strathearn Environs and Royal Forteviot (SERF) (Brophy & Noble, 2020). Their presence had been confirmed by geophysical survey, which was itself undertaken at different scales, extending to one covering a 51 ha area (Poller, 2020, 44, Fig 2.27).

Working on a ring ditch, which appeared as a negative magnetic anomaly (Fig. 4 top), Cuenca-Garcia (2018) demonstrated the effect of removing the topsoil prior to excavation had on improving the quality of its resolution. The constituent ditches, which were detected more successfully by GPR, displayed lower MS values than the subsoil and topsoil and a depletion of Fe, Mn and anthropogenic trace elements; Fig. 4 (middle and bottom) shows their lateral and vertical distributions. Introducing the corresponding earth resistance measurements, higher water retention, correlating with higher organic content, in the outer ditch and the presence of a central cist burial explained their detection as resistance anomalies that were lower than the sandy surrounding soils. Thus, a picture is emerging of subtle mineralogical changes within the ditch resulting from redox reactions involving Fe and Mn oxides.

2.3 *Dalswinton Roman Fort*

The results of the magnetometer survey at the Roman military complex at Dalswinton were also affected by noisy background data as well as the effects of recent agricultural activity. Interpretation by Hanson et al. (2019) proved to be an object lesson in a combination of viewing its results in the light of highly informative aerial photographs (and to a lesser extent ALS) and close cooperation between surveyors and experienced Roman specialist. That the fort had undergone a major re-organisation of its interior layout in response to changing military conditions only emphasised the need for such an approach.

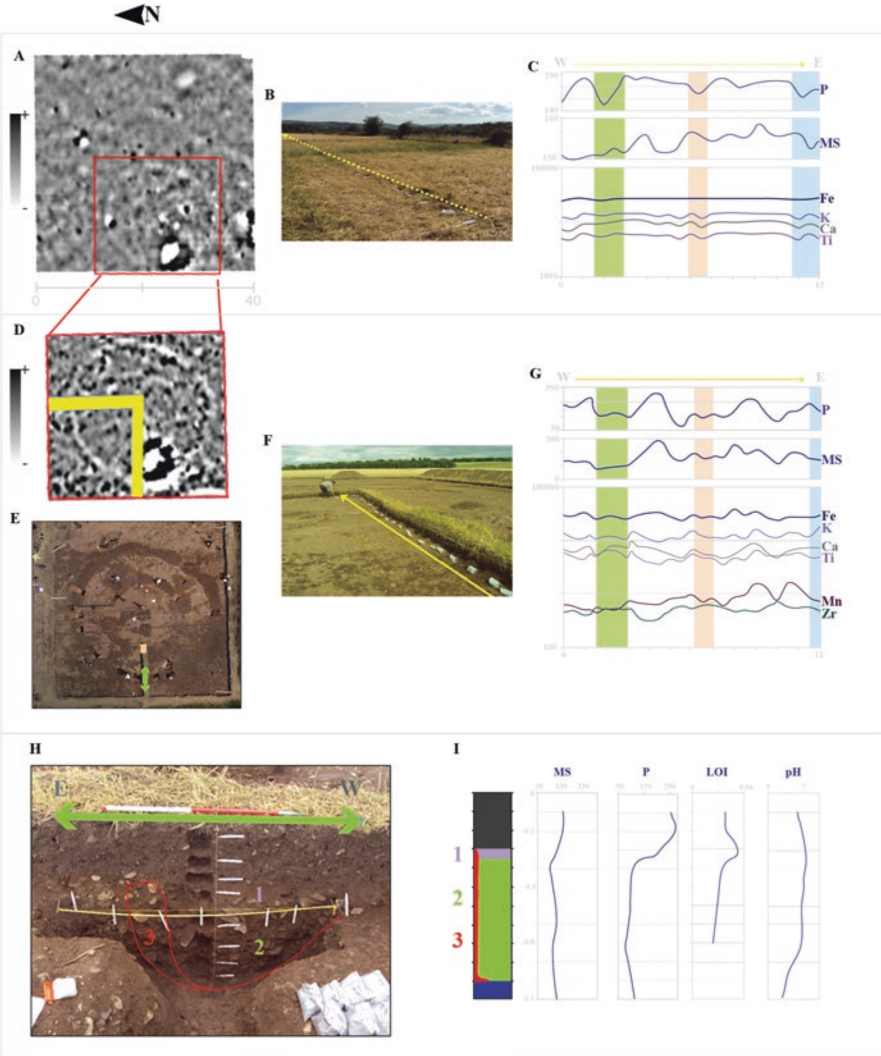

Fig. 4 Geophysical and geochemical responses at a ring-ditch enclosure at Forteviot. (**a**) results of the magnetometer survey before topsoil stripping (+/−10nT black/white). (**b**) Topsoil sampling over the enclosure before topsoil stripping (dotted yellow arrow). (**c**) Selected results of (continued) the soil analyses. Total phosphate (P in mg P/kg soil), magnetic susceptibility (MS in $\times10^{-6}m^3kg^{-1}$), and multi-element concentrations using portable X-ray fluorescence (pXRF). The coloured bars mark the location of the outer (in green) and inner (in light orange) ditches and the cist burial (in blue). (**d**) results of the magnetometer survey after topsoil stripping (+/−10nT black/white). The yellow bars indicate the baulks left after the soil stripping. (**e**) Validation of the results of the geophysical surveys and location of the trench where the outer ditch was further explored (green double arrow). (**f**) Soil sampling over the enclosure after topsoil stripping (yellow arrow). (**g**) Selected results of the soil analyses. Total phosphate (P in mg P/kg soil), magnetic susceptibility (MS in $\times10^{-6}m^3kg^{-1}$), and multi-element concentrations using pXRF. The coloured bars mark the location of features as in the cist burial (in blue). (**h**) Exposed north-facing section (green double arrow in **e**) and sketch of the three backfill deposits identified in the outer ditch. (**i**) Selected results of the soil analyses of the samples collected from the exposed north-facing section of the outer ditch (**h**). (Adapted from Cuenca-Garcia 2018, Figs. 10–12)

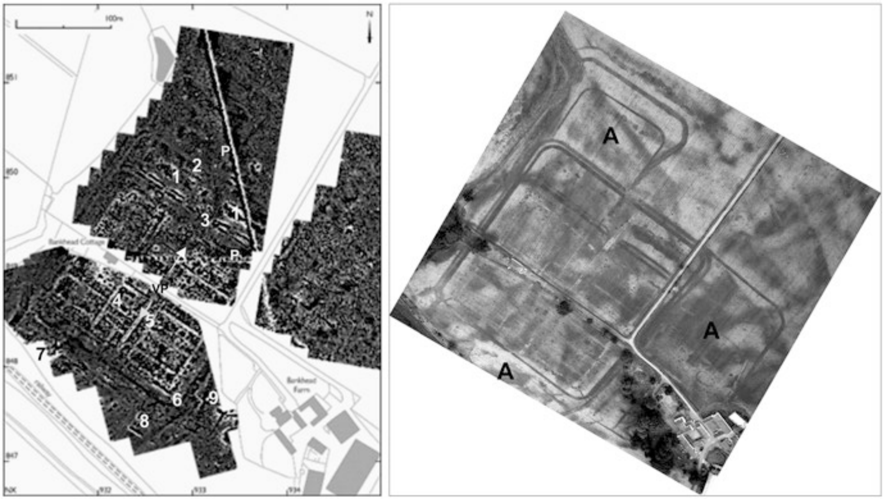

Fig. 5 Magnetometer survey (left) and aerial photograph (right) of the Roman fort and annexes at Dalswinton. **1** northern extension, **2** and **6** ovens or pits, **3** 'parrot's beak' configuration of ditch end, **VP** (with arrows) *via principalis,* **4** probably praetorium courtyard building, **5** phase 2 road running parallel to the VP, **7** possible remains of bath house, **8** possible furnace, **A** annexe. Greyscale plotted at -10nT (white) to 10nT (black). Images: (left) Hanson et al., 2019, Fig. 8; (right) SC 165876, Crown Copyright: HES

While the aerial photographs (such as Fig. 5 right) provided good definition of the defences outlining the fort and its annexes, the magnetometer data revealed more detail of the fort's interior (Fig. 5 left): the building blocks in the central sector, including two probable granaries and two courtyards (one of them the *praetorium*), the main gates, roads, and distinct areas of strong positive responses indicative of burnt debris reflecting the deliberate demolition at the end of the fort's occupation. Of the two halves of the fort, the southern sector yielded better quality results since it had been less ploughed and more in pasture. Collectively, the results speak of a fort, which was of major strategic importance in south-west Scotland during the Flavian period (first century AD), accommodating probably a mixed garrison of legionaries and auxiliary cavalry. The fort's expansion in the second phase need not have involved turning its orientation by 90°, as was originally suggested (Richmond & St Joseph, 1956, 13), but several adjustments were made to the interior. The probable legionary barracks occupying the new northerly extension (Fig. 5) may have been separated from the remainder of the fort. The *via principalis* (Fig. 5) continued in use, its route being altered only at the two ends to allow for the slightly changed position of the gates. The annexes, which were also expanded in the second phase, included space for animals, minor industrial activities such as metalworking but not civilian housing.

The magnetometer and earth resistance survey at the nearby Antonine-period Roman fort and annexe at Drumlanrig (Fig. 2) (Walker et al., 2005) should be mentioned here because the opportunity was taken to investigate some of the magnetic anomalies by excavation (Wessex Archaeology, 2005). Besides the 22 m long trench (T1) across the defences whose excavation confirmed the presence of the broad rampart and the V-shaped outer ditch (Wessex Archaeology, 2005, Fig. 1), six of the other eleven trenches targeted individual magnetic anomalies in the area of the *principia*. Here the experience was mixed, ranging from a large rectangular negative feature that neatly related to a probable cistern or trough to instances of incomplete interpretation due in large part to the complexity and limited spatial extents of the contexts encountered.

2.4 Bothwell Castle

This castle, one of Scotland's foremost medieval monuments, was built in the thirteenth century; it saw active involvement in the wars of Scottish Independence and as a result underwent much rebuilding only to be abandoned by the eighteenth century. As a monument in its care, HES commissioned a survey to assess some of the changes to the castle's interior and immediate environs, as well as much of the surrounding park (Rose Geophysics Consultants, 2015). A wide array of anomalies was detected (Fig. 6: A, B), those in the park being associated less with archaeology, more with the remains of such features as palaeochannels and recent interventions comprising roads, paths, drains and fencing. Particularly around the castle's north face, earth resistance identified some distinct structural, presumably foundation features. GPR time slices taken to a depth of 2 m were revealing; in the most shallow (Fig. 6: C) the strong responses are the result of the change from grass to paving and paths. But at 0.75–1 m (D) the time slice within the courtyard is able to show the distinctly linear high amplitude features which likely relate to drainage rather than to the amorphous shallow resistance feature. The clear message here may be well known but bears repeating: for a complex set of targets, deep and surficial, posed at a site like this castle the advantage of using complementary techniques is evident.

2.5 Galson, Isle of Lewis

The effects of coastal erosion on the NW coast of Lewis have prompted survey and excavation over the years (Dawson, 2015). While GPR has been generally well suited to elucidating the sequence of distinct stratigraphic layers in aeolian and coastal environments, its application to the detection of archaeological targets in such environments in Scotland has been limited (but see Parker Pearson et al. (2001, 64, 69) on survey on South Uist, also in the Outer Hebrides). Figure 7 illustrates how GPR, which has a long record of its ability to detect burials, produced some startlingly clear results at the thirteenth century chapel and associated graveyard of medieval to later date at South Galson (Rose Geophysics Consultants, 2015). High amplitude anomalies indicative of burials are evident owing to the good

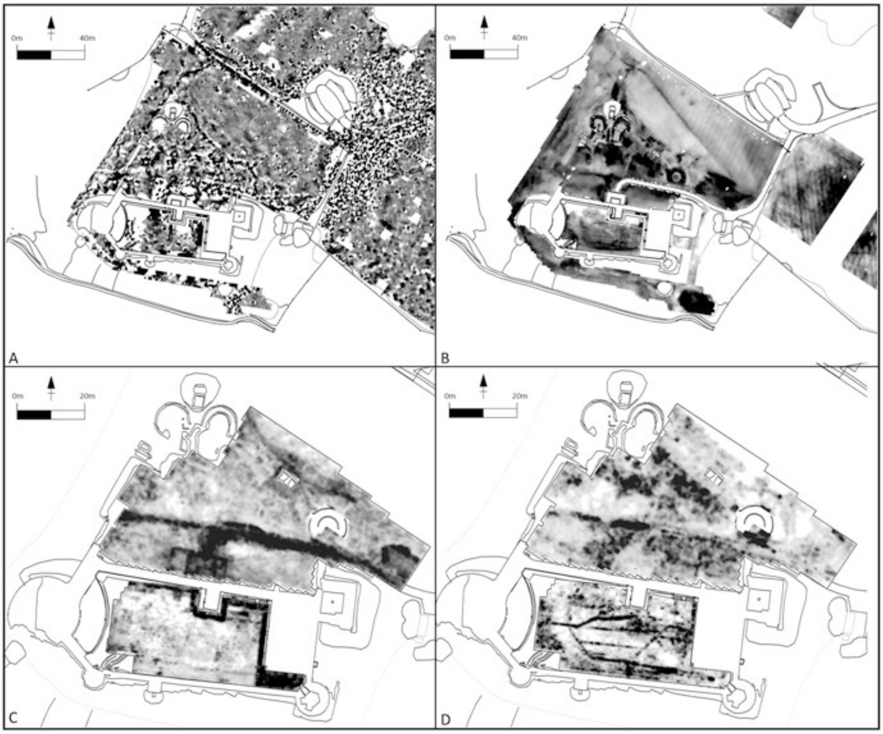

Fig. 6 Bothwell Castle. (**a**) Magnetometer survey data plotted at −6 nT (white) to 8 nT (black), (**b**) Earth resistance data plotted at −1SD (white) to 1SD (black), (**c**) 0.00–0.25 m GPR depth slice low amplitude (white) high amplitude (black), (**d**) 0.75–1.00 m GPR depth slice low amplitude (white) high amplitude (black). For scale, width of box **a** represents c. 180 m. (Graphics courtesy of Rose Geophysics and HES)

contrast between the sandy soil and the burial's top and base. In many cases these burials correlate with the (surface) presence of headstones and grave markers. But to the west, the responses are less clear, probably due to the presence of older burials in this area, some of them overlapping and consisting of multiple interments. Across the graveyard as a whole, some weak or poorly defined anomalies are likely to represent natural variations in the subsoil.

3 Discussion

The presentation above has outlined something of the current status of geophysics in Scottish archaeology. In turn, the case studies have served to illustrate issues of methodology and data interpretation that continue to remain central to the

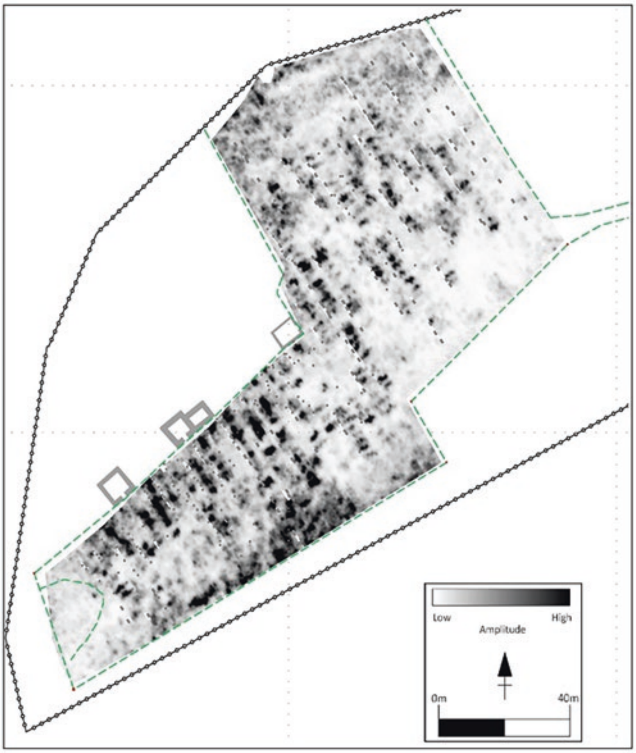

Fig. 7 GPR survey at South Galson graveyard. GPR time slice at 1.0–1.25 m. (Graphic courtesy of Rose Geophysics)

development of archaeological geophysics as much in Scotland as further afield. Ahead of that discussion, some of the key points arising from those studies can be summarised.

The importance of the landscape survey conducted on Orkney lies in its spatial scale, richness of archaeological information and attention to the signatures of agricultural activity that, although very common, usually receive minimal treatment. The deliberately science-based effort to explain a particular geophysical response stands out in the case of the multi-faceted characterisation of ditches at Forteviot; subtle, localised mineralogical changes are invoked. This approach now needs to be extended elsewhere to different targets and under the same opportunities of sampling before and after topsoil removal. At Dalswinton it was the coordination of geophysical and aerial data with detailed archaeological knowledge, in this case, of Roman forts, that was crucial for optimal interpretation. Such an interpretation emerged in a different manner at Bothwell Castle where the survey served as an example of advantageous interplay between the outputs of complementary techniques. Yet, under favourable circumstances, use of a single technique—GPR at Galson—was more than sufficient.

On methodology, reference has already been made to the way that the tried and tested techniques feature in most surveys. Although developments in instrumentation of a given technique, such as vehicle-driven multi-sensor magnetometers, are making their appearance in Scotland, there has been little evidence of trialling of novel instruments or their combinations. In that light, those research-led investigations that have departed from this norm stand out, one of which deserves mention because it highlights the recognition of the role of geophysics and analysis of cores in a situation that is not uncommon in Scotland: the burial of prehistoric (and later) landscapes in peat. Just as the investigation of the palaeo-landscape around the Neolithic monuments on Orkney discussed above used a combination of land- and marine-based techniques, so the same approach was adopted to good effect at Calanish on the Isle of Lewis (Fig. 2) (Bates et al., 2019). Here, the peat covering the original ground surface of the Neolithic standing stones was explored by targeted conductivity, magnetometry and electrical tomography, while the stones' proximity to lochs, as on Orkney, required bathymetric survey together with core analysis.

Regarding interpretation, the case studies have followed pragmatic, traditional routes: the identification of the main anomalies based on the combination of the geophysical response and archaeological criteria/experience, coupled with desk-based assessment of a range of information avenues from the aerial photographic record, historical sources to geological and soil conditions. Although its emphasis lay on detecting locations of prehistoric activity, the landscape survey on Orkney successfully took a fully diachronic approach, incorporating the recording of natural, pre-Neolithic phenomena through to agricultural and other activities of historical times. By contrast (and unsurprisingly), the priorities of the survey at Dalswinton (Hanson et al., 2019) and those at some thirty locations along the Antonine Wall (Hanson et al., forthcoming) have lain in identifying those anomalies that are known on the basis of morphology and context to be most likely related to Roman (military) presence. Such an approach only works because of the detailed and extensive knowledge of that presence derived from excavation along the Antonine Wall over the course of more than a century (Breeze & Hanson, 2020). Anomalies that did not 'fit' a Roman label were not ignored; indeed, they may be important in demonstrating, for example, immediate pre-Roman presence, but they were not classified with the same confidence.

This discussion can now look at a range of issues beyond the case studies. First is the experience of excavation in validating or otherwise the identification of geophysical anomalies. Acknowledging that this fund of information is limited in size, it is, however, instructive to look at two contrasting evaluations undertaken by Wessex Archaeology: Drumlanrig Roman fort, mentioned in Sect. 2.3 above, and a 30–40 m wide strip, 12.4 km long at Neart na Gaoithe (Fig. 2) (Wessex Archaeology, 2015). It is not surprising to find that the trends common to both of them arise from the criteria of the anomalies' size, strength and spatial extent: where an anomaly is indicative of an archaeological feature, such as the main defence ditch at Drumlanrig fort or ditches of likely enclosures at Neart na Gaoithe (Wessex Archaeology, 2015, Figs. 34, 37), that is large on all three criteria the validation is usually very positive in a general sense, if not at a detailed archaeological level. At the other end of the spectrum, excavation of a smaller, weaker anomaly often reveals a decidedly mixed picture; the potential archaeological significance of such an anomaly may have been established on excavation but some uncertainty surrounds its identity owing to the contexts it was found in being complex and small in size. Alternatively, the anomaly may turn out to be geological. In this light, archaeological expectations of what geophysical survey can deliver need to be realistic, guided by many factors including, above all, the nature of the site. Although now dated, Linford and David's (2001) assessment of the value of geophysical survey in the light of subsequent excavation of sites in south-east England, mentioned above, remains a model that could usefully have a counterpart in Scotland.

Turning now to the more common situation in which excavation has not taken place, there are some procedural and practical points to consider with interpretation in mind. Where good aerial photographs exist, they can often form a suitable and helpful point of comparison with the geophysical data, allowing, if necessary, revision of interpretation (see, for example, Cowley et al., 2019). Drawing on the experience from surveys at comparable sites and environments is another obvious route, and one that should be encouraged as access to, and dissemination of full survey reports becomes increasingly possible, notably through OASIS (the online UK-wide system for reporting archaeological investigations and linking research outputs and archives). The long-recognised issue of the importance of accessibility of raw data should receive increased attention in Scotland, as elsewhere in the UK, in the coming years. Despite good intentions, the idea of setting up a facility with known targets buried in different conditions seems to have found greater feasibility in forensic than in archaeological geophysics in the UK (e.g. https://www.keele.ac.uk/geophysics/forensicgeophysics/). On the matter of climatic effects on geophysical response there has as yet been no systematic assessment in Scotland. The results obtained by Clark (1996, Table 1) in southern England and Bonsall et al. (2014, 102, Fig. 32) in Galway, Ireland have indicated optimal resistance contrast between feature and surrounding soil occurring in spring and autumn. This should also apply widely to Scotland despite this region's contrasting lithologies with those commonly encountered elsewhere in the UK and Ireland.

Of great relevance to the experience in Scotland are the effects of one or a combination of noisy magnetic background, localised soil conditions and lack of magnetic or other contrast between an archaeological feature and the surrounding soil, all of them impacting on the ability to detect that feature. As outlined in Sect. 2.2, the way forward at Forteviot was to take a rigorous soil science approach, and this has since diversified and developed as a result of the current European Cooperation in Science and Technology network *Soil science & Archaeo-Geophysics Alliance: going beyond prospection* (SAGA) (Cuenca-Garcia et al., 2019). This approach could be trialled at several large fieldwork projects in contrasting parts of Scotland, extending those already treated by Cuenca-Garcia (2012). From its outcomes, trends in the soil characterisation data should emerge allowing an informed interpretation to be made that goes beyond what is at present very site-specific to something that has a wider explanatory basis.

But such soil characterisation data has already also been used in its own right in Scotland as a prospection method, specifically in the investigation of spatial organisation and function. Following the pioneering work of Entwistle et al. (2000) on land-use activity at the 18th–19th century township of Knockaird on the Isle of Lewis (pH, LoI and P, Ca, K and Mg analysis) and the multi-element analysis of soils at known activity spots at abandoned farms by Wilson et al. (2005), this field of investigation has diversified (https://scarf.scot/thematic/scarf-science-panel-report/4-people-and-the-environment/4-2-geoarchaeology/). Yet its fuller potential remains to be realised, for a start by harnessing it, where appropriate, with geophysical survey, as was the case at the Neolithic settlement at Crossiecrown on Orkney (Jones et al., 2010). Although many of the components of soil analysis normally require more time and are more labour intensive than a geophysical survey, the objection that multi-element analysis is too costly to merit its inclusion in a field project should be revised. Analysis of soils *in situ* or in bulk samples by portable XRF, as used at Forteviot (see Sect. 2.2), is more cost and time effective than laboratory-based ICP-ES analysis, yet the quality of the data in terms of its interpretative ability is not usually inferior. As Save et al. (2020) have shown in their varied case studies in France based on pXRF analysis, it is the individual element trends and multi-element associations rather than absolute element concentrations that are important in interpreting geochemical signatures across a floor, a building or other area where one or more activities took place.

Matters to do with training and equipment merit attention. The general applications of the subject feature in undergraduate and many postgraduate courses at those universities in Scotland offering archaeology courses. The practical element features strongly in modules within postgraduate courses at Aberdeen University and the University of the Highlands & Islands (Orkney), both of which, together with Glasgow, have in-house equipment; some of the equipment held at NERC's Geophysical Equipment Facility, hosted by Edinburgh University, has archaeological application. Sadly, the aerial photography with geophysical survey Masters course at Glasgow University, unique at its time, has not run during the last decade. As regards geoarchaeology, facilities and expertise are concentrated at Stirling and Aberdeen Universities. Overall, however, the opportunities for students to gain significant practical experience in Scotland are somewhat limited; the issue of further skills provision is a matter that the ScARF Archaeological Science Research Framework (www.scarf.scot/students), among other initiatives, is currently addressing.

4 Conclusions

This paper has set out some of the main roles that geophysics currently plays in Scottish archaeology. The picture is generally positive in the sense that the demand for surveys is being met, if not across all sectors. There is now a better appreciation of the techniques' limitations and of the need to match individual techniques to the requirements of particular archaeological targets than was previously the case. This is important because the range of terrains, from the points of view of topography and drift geology, is more challenging in Scotland than, say, in many parts of England. On the debit side, for reasons of insufficient funding and lack of access to particular instrumentation (for instance in electrical resistance imaging (soundings) and magnetic susceptibility measurement) and associated expertise, there is a tendency to rely on the 'standard' magnetic and resistance techniques and to avoid experimentation. Avenues for the dissemination of fieldwork activity are many and varied, but they do not yet extend to opportunities on the part of practitioners and archaeologists to meet and critically discuss survey results. An example would be to review geophysical responses to individual features at prehistoric sites obtained from several surveys in the light of excavation evidence, where available, in a given region. And it goes without saying that another meeting of the kind held as long ago as 2009 between the Geophysics Group of the Chartered Institute for Archaeologists (CIFA) and the Association of Local Government Archaeological Officers (ALGAO), Scotland (O'Grady, 2009) is surely overdue. In brief, geophysics in Scotland needs to raise its profile, particularly at the present time of important developments in remote sensing more widely. Furthermore, while retaining its traditional independent role in detecting subsurface remains, this is also the moment for geophysics in Scotland to play a greater role within geoarchaeology. Such a move, although not novel, would see more geophysical surveys including some aspect of soil characterisation, in the first instance to progress from simply recording imperfect responses of the kind alluded to above to *explaining* them in physicochemical terms. At another level, it would encourage greater integration of geophysical and geochemical survey, with the former taking the lead in locating areas of activity followed by the latter identifying the potential functions of those areas.

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Part XVII
Turkey

The Place of Archaeo-Geophysics in Archaeological and Cultural Heritage Site Investigations in Turkey

Mahmut Göktuğ Drahor and Meriç Aziz Berge

Abstract The first examples of archaeo-geophysical investigations in the territory of Turkey, are seen in the 1960s. Archaeo-geophysical studies, which came to an important place in archaeological site investigations and documentation of cultural heritage sites after the 1990s, have taken place in many legislations in the country today. Recently, the employment of non-destructive geophysical techniques in Turkey's archaeological sites has been drastically increasing. This chapter presents the history of archaeo-geophysical studies, methodological developments, educational and commercial advances. Additionally, widespread commercial applications, how archaeological site types are handled, verification of the relationship between geophysics and excavation results, and good practice examples are also summarised. In addition to the soil variations encountered in archaeological sites, the interpretation of the results of the geophysical techniques used in the determination of the archaeological context, which is highly complex due to ancient earthquakes in archaeological sites in Turkey, is also discussed in this chapter. Although archaeo-geophysics is an essential part of the study of archaeological and cultural heritage sites in Turkey, soil prospecting is limited and there appears to be a lack of integration in comparing geophysical results with the soil prospecting results.

1 Introduction

The land of Turkey has contained various archaeological settlements since the Palaeolithic age. The overall stages of evolution of the last hunters-gatherers that are thought to be in the transition phase to agricultural activity and animal husbandry were clearly observed in the archaeological excavations conducted in the south-eastern part of Anatolia in Turkey. Recently, it has become clear that an uninterrupted transition has been observed from the cultic centres of the first settlements of the Epipalaeolithic age towards the settlements of the Pre-Pottery Neolithic (PPN) age (Özkaya, 2009; Asouti & Fuller, 2012; Asouti, 2017; Boyd, 2018; Kodaş et al.,

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2020). Thus, with the emergence of Göbeklitepe and similar settlements (Karahantepe, Nevali Çori, Hallam Çemi, etc.), all phases of human evolution from the Epipaleolithic to the Neolithic period (from 11,500 BC to 8000 BC) became identifiable in this region. Furthermore, many cities in today's Turkey contain extensive archaeological remains from the Neolithic period to the Ottoman period.

The Anatolia have been inhabited by various civilisations since the Epipaleolithic ages and thus have various settlement patterns. They start from the first settlements on the rock shelters in the Epipalaeolithic age, moving to the formation of the first cities that emerged in the höyüks (tell or multi-layered settlement) and from there to the emergence of organised urban centres. Thus, there are highly variable settings spanning from single-layer settlements covering large areas to multi-layered settlements. In addition to these, the existence of very different cultures reveals diversity in grave and cemetery customs.

The land of Turkey consists of different geological formations. Particularly, this geography, whose lands were formed during the Neotectonic period, was also exposed to major tectonic effects from the Quaternary and Holocene. These features cause very different soil types to be seen in terms of archaeological settlement. The wealth of natural resources has supported the long-term settlement in the region. However, active tectonic effects and different geomorphological events cause various soil characteristics to emerge in areas where archaeological sites are located, and thus different soil types cover the archaeological context. This situation may have complex effects on the data obtained from geophysical investigations. Thus, the soil effect that directly controls the success of geophysical methods could cause different results and success rates of the geophysical prospection. The fact that many settlements are exposed to earthquake effects, especially because of active tectonics, causes further complexity of the archaeological context. This situation results in a more complex image of geophysical data, as the complexity in the buried archaeological context affected by earthquakes causes lateral or vertical displacements with depth changes. Thus, important difficulties arise during the archaeological interpretation made from the geophysical data.

The Anatolian soils have an important place in testing the results of the methodologies applied in archaeo-geophysical studies. However, the soil prospecting studies conducted on Anatolian archaeological sites are limited (Dirix et al., 2013). Particularly, the semi-arid climate conditions in the summer period and thus the excessive drying of the soil is an important problem for methods directly sensitive to soil variations such as resistivity. Additionally, large erosion episodes in the soil can cause the archaeological cultural layers to be buried very deep. This situation complicates the usage of many methods and even prevents their implementation. The intensity of seismic activity causes various damage to the archaeological settlements coming from different periods. Since this situation will significantly mix the archaeological features in the buried context, it will cause much more complex geophysical results obtained than simply when an archaeological context is buried within a heterogeneous soil matrix. Horizontal and vertical displacements that occur on the walls of buried structures, especially after large earthquakes, make this situation even more dire. Apart from these, intense treasure hunting activities are another important problem for geophysical studies. Due to these factors, as soil content is significantly mixed, it ultimately decreases the success of geophysical methods. As a result, it will be important to determine the soil properties and characteristics in detail before any geophysical study. Additionally, changes in soil character and differences in buried depths will also be important in choosing the methodology to be used.

The first examples of archaeo-geophysical applications in Turkey were carried out on the tumuli of Karnıyarık Tepe (Manisa) and Nemrut Dağ (Adıyaman) in the early 1960s (Hanfmann, 1965; Goell, 1968, 1969). Especially after the 1970s, the more frequent application of geophysical methods by foreign excavation teams conducting research in Turkey and the emergence of positive results increased the usage of the methods. Within the scope of these studies, magnetometer surveys in researching some burial grounds and especially the höyük and some antique city investigations came to prominent. Additionally, the first resistivity studies conducted in limited areas by Turkish researchers during the Keban dam studies in the summer of 1968 are commendable in this regard (Yaramancı, 1970). The widespread use of archaeo-geophysical investigations in Turkey started in the late 1980s and continued until the 1990s, increasing the interest in their application (Drahor, 2011a). However, the main development emerged at the beginning of the 2000s and is still increasingly continuing today. Especially in the last decade, with the introduction of application techniques into legal regulations, the tendency of private companies to apply such applications has increased to a great extent. In this process, another important development was that the applications extend to the documentation of preservation of the cultural heritage sites apart from archaeological sites.

Starting from the beginning of the 1990s, doctorate, and master's theses conducted on the methodological development of geophysical methods used in archaeological fields were also beginning to appear. The positivity of the results of these studies allowed the increase in the projects on the subject and the usability of different techniques. The results of these studies were published in many international journals and books and started to appear in literature.

Today, ground-penetrating radar (GPR), magnetic gradiometry (hereafter magnetometry) and electrical resistivity applications are among the commonly used geophysical techniques in Turkey. In particular, researchers working at universities generally apply integrated techniques, while the private sector commonly uses GPR techniques, with some exceptions.

2 The Archaeo-Geophysical Research in Turkey and Its Impact Upon Education, Methodology and Commercial Application

The first archaeo-geophysical studies primarily focused on investigating the different fields with selected geophysical techniques and testing the success of these techniques applied (Drahor, 2011a). Later, archaeo-geophysics played an important role in Turkish archaeology using methodological advances, detailed scientific studies and multiple method trials. Because of the developments in legal procedures, especially in the protection of archaeological and cultural heritage sites, archaeo-geophysical applications have been used more effectively. Thus, the private sector applications in archaeo-geophysics were initiated and have increased extensively in the last decade.

2.1 Brief History

The first geophysical study in Turkey was conducted by American geophysicists on Nemrut dağ tumulus between 1963 and 1964 (Goell, 1968, 1969). The aim of Goell, who was the excavation team leader, was to determine the burial tomb of Antiochus I (69–36 BC), the king of Commagene. The next investigation was conducted in 1963 on Karnıyarık tepe, another important tumulus in Anatolia, to find the tomb of Giges, which was the first king of the Mermnad dynasty of Lydia. In this study, American geophysicists conducted vertical electrical resistivity sounding (VES) studies on the tumulus (Hanfmann, 1965). The first geophysical study was carried out by a team of Turkish academicians led by A. Yaramancı from İstanbul University as a part of the Keban Dam Rescue Project in 1968. In these studies, electrical resistivity profiling measurements were attempted in a limited part of the Ağın, Tepecik, and Norşuntepe höyüks, respectively (Yaramancı, 1970). After the first studies, systematic and multi-methodological investigations were carried out between 1970 and 2000 on flat settlements and höyük's (multi-layered settlement), especially to reveal settlement plans and important structures (Demircihöyük (1977), Boğazköy-Ḫattuša (1980), Hassek Höyük (1981), Halikarnassos (1988), Göltepe (1991–1992), Truva (1992), Acemhöyük (1992–1994), Metropolis (1992–1994), Çatalhöyük (1992–1993), Kerkenes (1993–2010), Miletos (1995–1996; 2003–2009), Ziyaret Tepe (1998–2004) (Becker, 1979, 1980, 1981; Becker et al., 1993; Drahor, 1993a, b, c, d, 1994a, b, 2021; Shell, 1996; Matney & Donkin, 2006; Çayırezmez et al., 2008; Summers et al., 2010; Brückner et al., 2014)). Additionally, geophysical studies were conducted between 1989 and 1994 to determine the locations of different pottery production workshop sites (Reşadiye, Hisarönü, Sinop, Gaziköy-Hoşköy) in Anatolia (Hesse, 1992; Drahor et al., 1995). Geophysical investigations were also carried out in Nemrut dağ (1989), Çiftlikkırı (1991), Argavlı (1992), Kösemtuğ (1992), Kepirtepe (1992) and Karnıyarık tepe (1993) tumulus by Turkish and foreign geophysicists at the beginning of the 1990s (Şahin, 1992; Başokur, 1993; Drahor, 1993f, 1994b; Greenewalt, 1995; Pınar & Akçığ, 1997). Many large-scale and integrated systematical geophysical investigations continued in different archaeological sites in Anatolia between 1990 and 2021. The most important examples are: Kerkenes (1993–2010), Sardis (2001, 2018–2021), Zeugma (2001–2006), Sarissa (2000–2004), Šapinuwa (2012–2019), Burgaz (1998–2007), Troia (1992–1994), Ephesos (1998–2014) Miletos (1995–2011) (Summers et al., 2010; Drahor, 2006; Drahor et al., 2007, 2008, 2015; Çayırezmez et al., 2008; Erkul et al., 2008; Seren & Ladstatter, 2011; Brückner et al., 2014). Furthermore, various magnetometer and resistivity-meter systems were tested and developed during such studies (Faßbinder, 2011 and references therein; Summers & Summers, 2012).

2.2 Methodological Developments and Academic Advances

Geophysical studies conducted in Anatolia brought some instrumental developments. One of them was the development and establishment of the Bavarian magnetometer system. In these studies, proton, caesium and CS2-system magnetometers were tested in some archaeological sites (Demircihöyük-1977, Troia-1992 and 1994, Aşağıpınar-1994, Pompeipolis-2007). Kerkenes geophysical studies were conducted using Geoscan's RM15 soil resistance meter system. However, the extremely dry soil conditions during the summer period revealed some measurement problems. As a result, a system was developed to improve data collection in such environments (Çayırezmez et al., 2008). During this time, some methodological developments and novel application examples have emerged in self-potential application, electromagnetic VLF (very low frequency), Electrical Resistivity Tomography (ERT) for multi-layered sites, and magnetometer surveys for indoor applications (Drahor, 2004; Drahor et al., 2011; Berge & Drahor, 2011a, b).

When the academic past of archaeo-geophysics in Turkey is examined, contrary to the increasing geophysical investigations in the field of archaeology, it seems that it has not been sufficiently developed. In fact, many geophysical studies of archaeological sites have been carried out by local researchers working at universities in the last decade. However, when the scientific background of the studies is examined, it is revealed that many of them are scientifically insufficient to investigate the true archaeological context. The first scientific study on archaeo-geophysics in Turkey was the doctoral thesis conducted by Mahmut Göktuğ Drahor in 1993 (Drahor, 1993e). In the following years, ~ten other doctoral theses paid attention to this subject to some extent. These include two theses that examine specific geophysical method(s) but only with a section devoted to the application of such methods in archaeology. Generally, it seems that a significant part of doctoral theses does not adequately describe the archaeological context investigated and the methodological approaches are insufficient. Additionally, the majority focuses on the application of similar methodological practices to various archaeological sites. Master's theses (52 in total) have similar characteristics. There is an increase in the number of these theses from 1993 to 2007, and after this date, except for 2 years (2011 and 2019), there is a decrease in postgraduate theses (Fig. 1a). The ratio of postgraduate theses conducted on archaeo-geophysics at the departments of geophysical engineering on all postgraduate theses on geophysics is 4.2%. Therefore, it seems that there is still not enough interest in the subject in Turkey, which has a rich archaeological heritage. While magnetometry, electrical resistivity and GPR methods are at the forefront as these topics, other methods, or their combined used, have been little explored (Fig. 1b). When the courses given in universities related to the subject are examined, it is revealed that 15 courses have been opened on this subject so far,

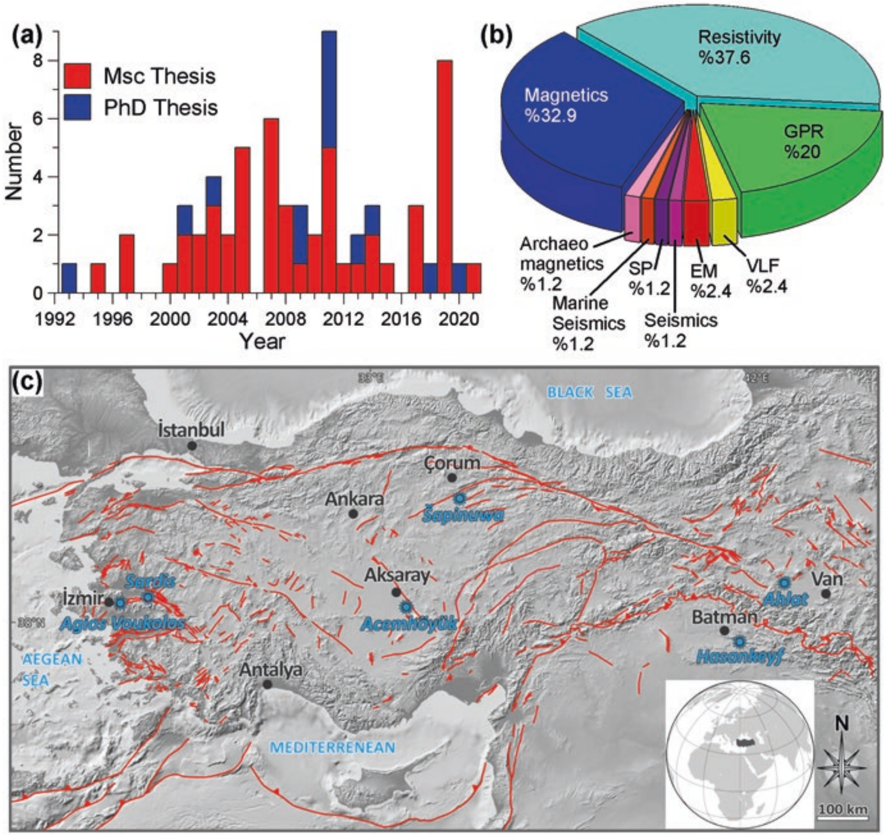

Fig. 1 (**a**) Number of postgraduate theses on archaeo-geophysics between 1993 and 2021. (**b**) Distribution of geophysical methods used in postgraduate thesis conducted on archaeo-geophysics in Turkey (GPR: ground-penetrating radar, SP: self-potential, EM: electromagnetic, VLF: very low frequency). (**c**) Active tectonic map of Turkey. The locations of the study areas associated with this chapter are overlaid on the map. (Faults are taken from Şengör et al., 1985; Bozkurt, 2001; Koçyiğit, 2003; Emre et al., 2013)

eight of them still active. Ultimately, all of them have the status of elective courses. To increase interest in the method, develop methodologies, and train students, the Research and Application Center for Near Surface Geophysics and Archaeological Prospection (CNSGAP) (2004–2020) was established under the leadership of Prof. Dr. Mahmut Göktuğ Drahor, affiliated of Dokuz Eylül University. During its activities within 16 years, the Center has contributed to many scientific and technological developments on near-surface and archaeo-geophysical research by addressing novel theoretical and practical research topics. Additionally, the Center has organised vocational training programs, meetings, symposiums, and similar events to develop scientific and technical knowledge on near-surface geophysics and archaeological prospection studies. One of them is the 9th International Conference on

Archaeological Prospection (https://www.archprospection.org/archpros11) held in Izmir between 19 and 24 September 2011. Apart from this, the Chamber of Geophysical Engineers of Turkey has also organised some courses and training programs related to this subject.

2.3 Commercial Applications in Archaeo-Geophysics and Its Impacts

Long-term agricultural activities, rapid urbanisation, industrialisation, dam-highway-railway constructions, and mining, as well as human activities such as treasure hunting, have created a negative impact on the archaeological and cultural heritage sites in Turkey. In this extremely fast process, the importance of archaeo-geophysical studies in documenting Turkey's cultural heritage is undoubtedly great. However, due to the lack of sufficient academic experts on the subject and the limited number of studies, the demand from society could not be met. The fact that it has not also an official organisation established on this subject ultimately led the private sector to show interest in this issue. The increase in interest over this subject, when considered together with the development of Turkey, led to the establishment of new companies dealing with the topic of archaeo-geophysics. Most of the private sector working on archaeo-geophysics performs only GPR surveys (aka georadar). For this reason, it seems that the term "geophysics" equals "georadar" in the administrative jargon of conservation boards and other organisations of the "Ministry of Culture and Tourism". GPR has become prominent and there has been a false perception as if it is another application different from geophysics. Based on these statements, there is a misperception among different regulatory bodies that simply conducting GPR surveys is enough to evaluate sites under development. Geophysical surveys combining different techniques are rarely considered by the private sector. On the other hand, the interest of excavation groups in subcontracting geophysical services is increasing. GPR applications are pursued in restoration and infrastructure services as per the regulations. Integrated (or combined) geophysical surveys carried out by the private sector have demonstrated potential in major highway, railway, port, pipeline and metro constructions. However, note that soil prospection is not considered in private sector applications.

3 The Place of Geophysics in the Preservation of Cultural Heritage

The place of geophysical studies is undoubtedly critical in the investigation and protection of many religious buildings, caravanserais, castles, sanctuaries and restored cultural monuments. The increase in public investment in Turkey in the last decade has directly affected the archaeological and cultural heritage sites. Especially, the development of social awareness has also increased the interest of the community in cultural heritage. Depending on these facts, intensive restoration works emerged in the process and the state provided significant financial support. Additionally, financial aid from the European Union funds contributed to the acceleration of the restoration work. Thus, restoration works in many cultural heritage sites and structures, especially religious ones, were accelerated. Naturally, the need for high-resolution geophysical studies, as a non-destructive approach, has emerged in these studies. Today, extensive GPR surveys are conducted especially on the structural elements of the interiors of buildings that are still standing, such as walls, floors and domes. Thus, in addition to the structural features of the investigated buildings, other unknown features (such as an unknown crypt) have also been revealed. Some investigations on this subject carried out in Hagia Sophia (İstanbul) are admirable (Yılmaz, 2013; Moropoulou et al., 2013; Barba et al., 2018). As a result, although the GPR method is widely used in the conservation and restoration studies of cultural heritage sites in Turkey, electrical resistivity tomography (ERT), seismic and magnetometer surveys have also demonstrated their potential (Drahor et al., 2011).

4 On the Valid Planning of Geophysical Investigations in Turkey Where Highly Variable Earth Indicators Exist

The significant earth changes and climatic differences seen in Turkey have great importance in the correct interpretation of geophysical data and its successful results. As it is known, correct planning should be made by considering these features before starting archaeo-geophysical investigations in areas where archaeological site type, soil characteristics, geomorphological effects and tectonic regimes are more variable and active. The Turkish territory is one of the most active areas in the world in terms of tectonics. This is revealed by the existence of many active faults in the country. The activity of a fault depends on the frequency of earthquake recurrence intervals on that fault. In particular, the activity within the Quaternary allows it to be classified as an active fault. Since palaeo and archaeo-seismological studies better reveal the activities in the Holocene period, the activities of this period are better known in Anatolia, especially. The general active tectonic fault map of Turkey has been created with the geological and geomorphological investigations carried out on the faults by the General Directorate of Mineral Research and Exploration (MTA) (Fig. 1c). Unfortunately, many archaeological settlements in Anatolia were established in areas near these faults and these faults had a great impact on their preservation. During the excavations in Anatolia, significant destructions are encountered in the archaeological settlements located near the active fault zones. Vertical displacements occurring in subsurface structures pose an important problem for geophysical investigations. In fact, the archaeological context of the same layer, in which displacements of up to 0.5 m are observed, can be found at different depths. This situation particularly affects GPR studies, which are interpreted as time/depth slices. Thus, GPR time/depth slices, which are thought to be taken from the same depth, extend at different depths due to deformed structural elements and cause problems in their interpretation. Before performing time/depth slice studies in such areas, a detailed analysis should be made on the processed radargrams (B-scan or reflection profiles) and it should be determined whether such a situation exists. Additionally, the archaeological context can be covered with a thick soil cover due to the old landslides, soil-debris flows, and vertical displacements result in active faulting. This situation causes significant mixing in the soil content and hinders the success of geophysical methods in determining buried archaeological structures. When the agricultural activities of recent years are added to this, a common soil erosion phenomenon is encountered in Turkey. Field types have a significant impact on geophysical investigations as well. While the PPN settlements of Anatolia are generally seen as single or multi-layered settlements on the bedrock, the Neolithic age settlements in the plains are generally multi-layered and have also very different variability in terms of size. This situation eventually leads to the formation of mounds reaching a height of about 20–25 m (Berge & Drahor, 2011a, b). Obviously, these two types of settlements are difficult areas for investigation in terms of geophysical studies, due to reasons such as the multi-layered nature of such areas, the overlapping of different archaeological layers and the bedrock effect. In particular, mono-layered and laterally spreading areas, such as Classical, Hellenistic, and Roman settlements, are better targets for geophysical investigations. However, note that the application of integrated methods would yield more useful results in cases of mono-layered settlements covered with thick alluvial or colluvial layers.

The majority of archaeological sites in Anatolia are found inside alluvial basins, and the composition of the basins consists of dense layers of clay, silt, and in some places, sandy layers, which has a significant impact on geophysical exploration. Additionally, shallow groundwater levels are another problem during geophysical studies. Apart from these, difficulties may arise in terms of electrical studies because a significant part of Anatolia has a semi-arid climatic feature and therefore the soil conditions are very dry, especially in the summer period. Furthermore, intense burned zones are encountered in the Neolithic, Bronze, and Iron Age layers. The extensive fires that make up these zones cause the archaeological context to undergo significant physical and chemical changes. As a result, before starting the geophysical studies, such problems should be thoroughly examined to decide on the method to be applied. Although magnetometer surveys, which are generally used in geophysical studies, have some problems, they generally give satisfactory results. However, the results of magnetometer surveys can be complex because of the multi-layered settlement context in the höyük areas. In electrical resistivity studies, despite excessive drying of soil conditions in summer, the problem can be solved by the emergence of advanced devices in terms of controlling the contact resistances and signal/noise ratio, and choosing a less sensitive configuration to such noise (Schmidt et al., 2020). Additionally, with the tomographic application of resistivity, it was possible to obtain models that gave excellent results and contributed greatly to the interpretation. Since GPR methods are particularly affected by dielectric permittivity and electrical conductivity, they can produce inadequate results in areas with clayey environments, near-surface groundwater, earthquake deformations, and thick colluvial cover. It should also be noted that self-potential, seismic, and induced polarisation methods can yield important results in höyük, mining-metallurgical settlements, and grave investigations (Drahor et al., 1996, 2015; Drahor, 2004).

5 Selected Field Examples Depending on the Type of Archaeological Site

In this section, the results of six different cases of multi-layered, mono-layered, grave, cultural heritage conservation and restoration studies in Turkey are presented. Two of them were selected from Western Anatolia, two from Central Anatolia and two from South-eastern Anatolia. Locations of these study areas are near the tectonically active regions (Fig. 1c).

5.1 Multi-layered Settlements

5.1.1 Acemhöyük Archaeological Site

Cases representing multi-layered settlements were selected from two different regions. The first is Acemhöyük, one of the great höyüks of Central Anatolia, which remains from the Assyrian Trade Colonies. Acemhöyük extends to 700 m in east-west direction and 600 m in north-south direction. The top of the höyük is flat and its highest point is 20 m. Excavations revealed that the shallow cultural layer was built with a regular urban orientation (NE-SW 45° and NW-SE 45°). The city is located 10 km southwest of the Tuz Gölü Fault Zone (TGFZ), an important active fault in Central Anatolia. The fault zone is a normal fault with an NW trend and active oblique slip. The settlement, which is close to the Tuz Gölü, was built on a Holocene alluvial environment (Fig. 1c). Excavations at the site began in 1962, and although there is evidence that the first settlement began at least in the Early Bronze Age (3000 BC), the most prosperous period of the settlements was during the Assyrian Trade Colonies (2000–1750 BC). Dendrochronology studies determined that the city was destroyed because of an extensive fire in about 1789 ± 50 BC. After this period, the settlement on the höyük ended and only some parts were resettled again in the Early Hellenistic period. This settlement continued until the third century AD. Because of the great fire in the Assyrian Trade Colony period, the mud brick walls of the buildings have undergone a significant physical and chemical change. In particular, mudbrick walls, which normally do not have magnetic properties, have obtained increased magnetic properties due to the thermo-remanent magnetisation that occurred because of this fire. Resistivity, self-potential, magnetometry and EM-VLF studies were conducted in this area between 1992 and 1994 (Drahor, 1994a, 2004; Drahor et al., 1996, 1999; Drahor & Kaya, 2000). An example of the results of the magnetometer surveys at these studies is given in Fig. 2a. In this study, data were collected using a Geometrics G-856 proton magnetometer that measures the total magnetic field of the earth. The sensors were held at 60 and 180 cm heights and data were obtained using the vertical gradient measurement. In the total magnetic field and gradient data, the values were very high on heavily burnt areas, walls, and other archaeological features. Corrected data were processed with different signal and image analysis techniques to obtain the most suitable images. The result of the magnetometer survey (after the inverse filter application) conducted in 1994 in the area between two different palaces (Hatipler and Sarıkaya) excavated in the 1960s and 1970s, is given in Fig. 2a. The presence of a good contrast between the traces of the burnt building elements and the soil is seen in the image. The shape of the buildings in the south is very distinctive and the amplitudes of the magnetic traces formed due to combustion on the mudbrick walls are clearly visible depending on the burning intensity. An archaeological excavation was conducted to verify the results of the magnetometer survey. The revealed structure, which was buried close to the surface, extended to a depth of 2 m. At its base, there were large burned wooden beams that went down to the floor due to a large fire (Fig. 2a, photographs given in the right-hand side). As a result of the excavations that continued in the same area in the following years, the existence of an important building complex was revealed.

5.1.2 Sardis Archaeological Site

The second example of a multi-layered archaeological settlement was selected from the Sardis area, which was the capital of the Lydian located in Western Anatolia. Sardis is located on the banks of the Paktolos River and approximately 2 miles south of the Hermus River, and it was founded on a hill on the banks of the Hermus River in the Early Lydian period (eighth century BC). Sardis, which was the last stop of the famous King Road starting from Susa, was very important in the Roman period. The city, which excessively grew during this period, spread towards the plain below. Sardis was founded on the fault scarp of the Gediz Graben, formed by east-west faults in Western Anatolia (Fig. 1c). The city has been under the influence of many earthquakes in ancient times. Since earthquakes in this region generally occurred at shallow depths, they caused significant damage to the stone structures of the settlement. The largest earthquake ever seen in Sardis occurred in AD 17.

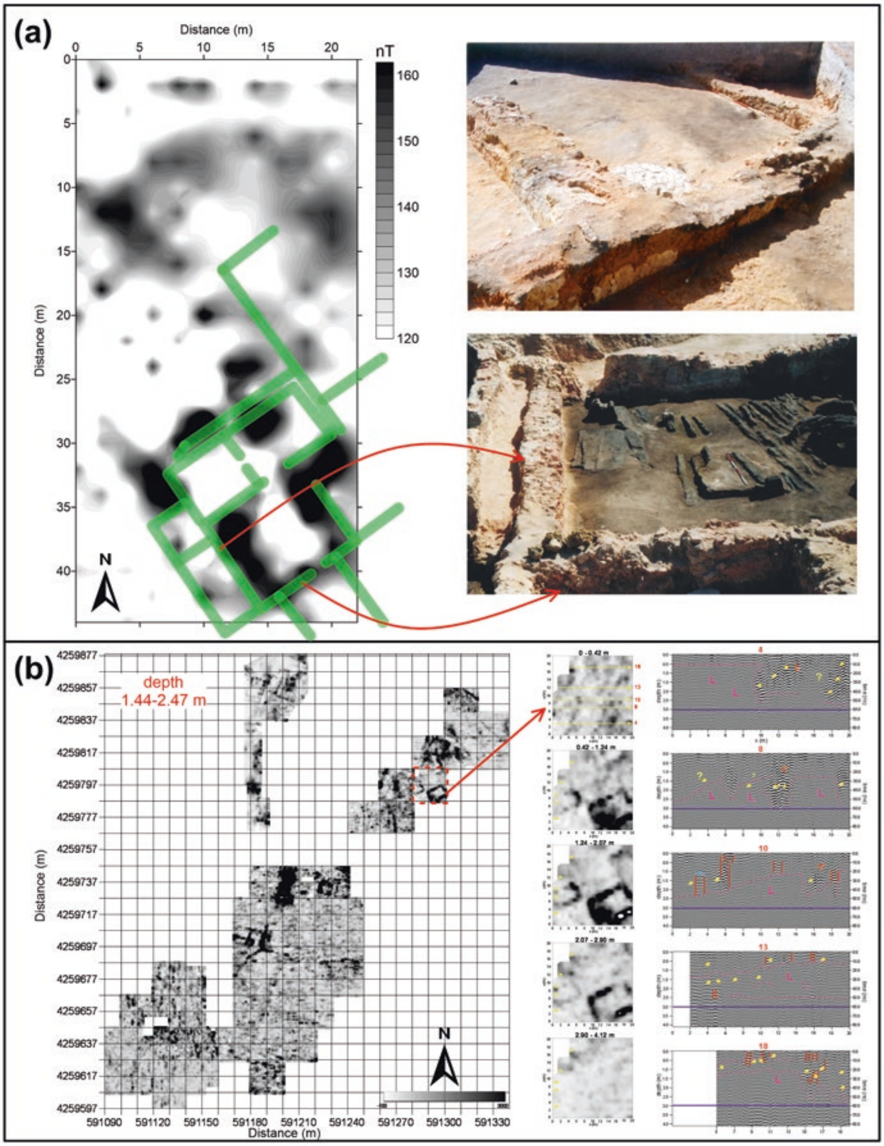

Fig. 2 (**a**) Results of the magnetometer survey and excavation photographs obtained from Acemhöyük archaeological site in Aksaray. (Modified from Drahor & Kaya, 2000). (**b**) GPR depth slices and reflection profiles obtained from Sardis archaeological site in Manisa. (Modified from Geoim Ltd., 2020)

The earthquakes in the seventh and thirteenth centuries AD also caused serious damage to the Lydian city, which was built on a weak Pliocene Sart formation composed of semi-consolidated conglomerate and sandstone materials. Additionally, the city was covered with a thick soil layer because of landslides caused by major earthquakes and soil flows caused by large erosion episodes. For this reason, it is impossible to observe any traces of structures from the early periods, except for some Roman and Byzantine structures on the surface. In the upper parts of the city, there is a thick cultural filling starting from the Early Lydian at the bottom and following the Lydian, Persian satrapy, Hellenistic, Roman and Byzantine periods. Lydian strata are buried at a depth of 7–8 m, and sometimes at a depth of more than 10 m. As a result, integrated geophysical methods are required to detect these layers. For this purpose, an integrated geophysical survey including magnetometry, ERT, VLF-resistivity, and seismic methods was conducted in Area 55 in 2001 (Drahor, 2006). As a result of these studies, Roman and Byzantine layers buried close to the surface were mapped. Since the lower layers of these structures, where significant structural deformations were observed because of major earthquakes, were not excavated, any data related to the Lydian period could not be obtained. Additionally, integrated, and large-scale geophysical studies were carried out in 2018 and 2019, in Area 49 and its surroundings, and in Area 55 and its surroundings in 2021 (Geoim Ltd., 2020). In these studies, GPR, ERT, induced polarisation tomography (IPT), seismic refraction P tomography (SRT), and multi-channel surface wave tomography (MASWT) methods were applied. In Fig. 2b, some results of the GPR investigations conducted in Area-49 and its surroundings are given. The traces of buried archaeological structures can be observed with high radar reflection amplitudes at the depth slice obtained from 1.44 to 2.47 m. The fact that the traces of the buildings have two different orientations suggests that two different settlements may have been buried at this depth. It is thought that almost N-S and E-W directional extensions are seen in the west of the area may be related to the Roman layer, and the traces extending in NW-SE and NE-SW directions in the north-eastern part of the area may be related to the possible Lydia layer. It also comes to mind that the density of the complex traces in the southern section may indicate the talus fillings formed due to earthquake-induced landslides. The images obtained from five different depth levels of the NW-SE and NE-SW oriented structure within the area surrounded by the square frame are given in the middle part of the figure. The traces of the structures here are clearly visible at three depth levels between 0.42 and 2.9 m. The radar reflection contrasts between soil and structures are quite good, and therefore the structures appear distinctly. It is interpreted that the mixed reflections in the south-western part of the large building may be due to an earthquake-related episode. Interpretations of five separate reflection profiles selected from this area are given above them. Although the traces of the structures are seen in the reflection profiles, the presence of a westward slope is mostly observed in the traces. Additionally, the changes related to the deformation in the reflection traces of the walls and interiors of the structures reveal that the layers here may have suffered significant damage because of an earthquake. When the relationship between the lossy zones indicated by “L” in the figure and the traces of structures is studied, we could suggest that a fill due to sloping slips may cover the archaeological layers.

5.2 Mono-layered Settlements

5.2.1 Šapinuwa Archaeological Site

A good example of mono-layered archaeological sites is Šapinuwa, a Hittite imperial city located on a plateau west of the Çekerek River in the Central Anatolia, surrounded on three sides by deep valleys (Fig. 1c). The foundation of the city is dated to 1400 BC, which corresponds to the Middle Kingdom period of the Hittite Empire. Šapinuwa was a religious, military, and governmental centre and had close links with Ḫattuša, the capital of the Hittite Empire. Archaeological finds have shown that the city had a sacred area where religious rituals were held during the Hittite period and that the city functioned as an important cultic centre. The city consists of two separate parts, namely Tepelerarası and Ağılönü. One of these, Tepelerarası is a residential area of an aristocratic class, while Ağılönü is a sacred area used for different religious rituals. During the excavations in the Tepelerarası area, an important archive containing more than 4000 clay cuneiform tablets in an official building was found. As a result of the excavations made in the area and readings of some cuneiform tablets, it is understood that the city consists of sacred areas, palace, military base, official buildings, and other important structures (Süel, 1995). Šapinuwa is located between the Sungurlu fault zone (SFZ), whose seismic activity has continued since the Holocene period in the north, and the Kazankaya fault zones, which are thought to have been active since the Quaternary period in the south. These active faults found within the Amasya Shear Zone are also closely related to the North Anatolian Fault Zone (NAFZ). The Šapinuwa archaeological site was built on a unit composed of carbonate, claystone, sandstone and conglomerate from the Lower Middle Eocene (MTA, 2002). Archaeological excavations and archaeoseismological studies have revealed that very strong earthquakes in Šapinuwa during the Hittite period deformed the ground and caused significant damage to the structures (Süel & Süel, 2011; Drahor et al., 2023). An area of more than 100 hectares in the Tepelerarası locality of the Šapinuwa archaeological site was imaged by the magnetometer survey (Fig. 3a, Geoim Ltd., 2018). Thus, important data related to the urban distribution in this part of the city were obtained. First, it was revealed that the city has a settlement distribution that expands in approximately NE-SW and NW-SE directions. Due to the extensive fires in the city, it was observed that high magnetic values emerged, and they generally had a regular distribution. The same area contains other important building groups apart from the excavated structures (Buildings A, B, C, and D). It is thought that this confusion is caused by the deformations that occur in the structures because of large earthquakes, in the area that generally contains regular traces, but also shows a mixed magnetic distribution. Apart from the magnetometer survey, ERT, IPT, GPR, SRT, MASWT and self-potential methods have been used in the field. The GPR method did not achieve the desired success, especially due to the significant horizontal and vertical deformations occurred by earthquakes in the archaeological layers. Another result obtained from the field and showing the effect of the changes in the soil was obtained

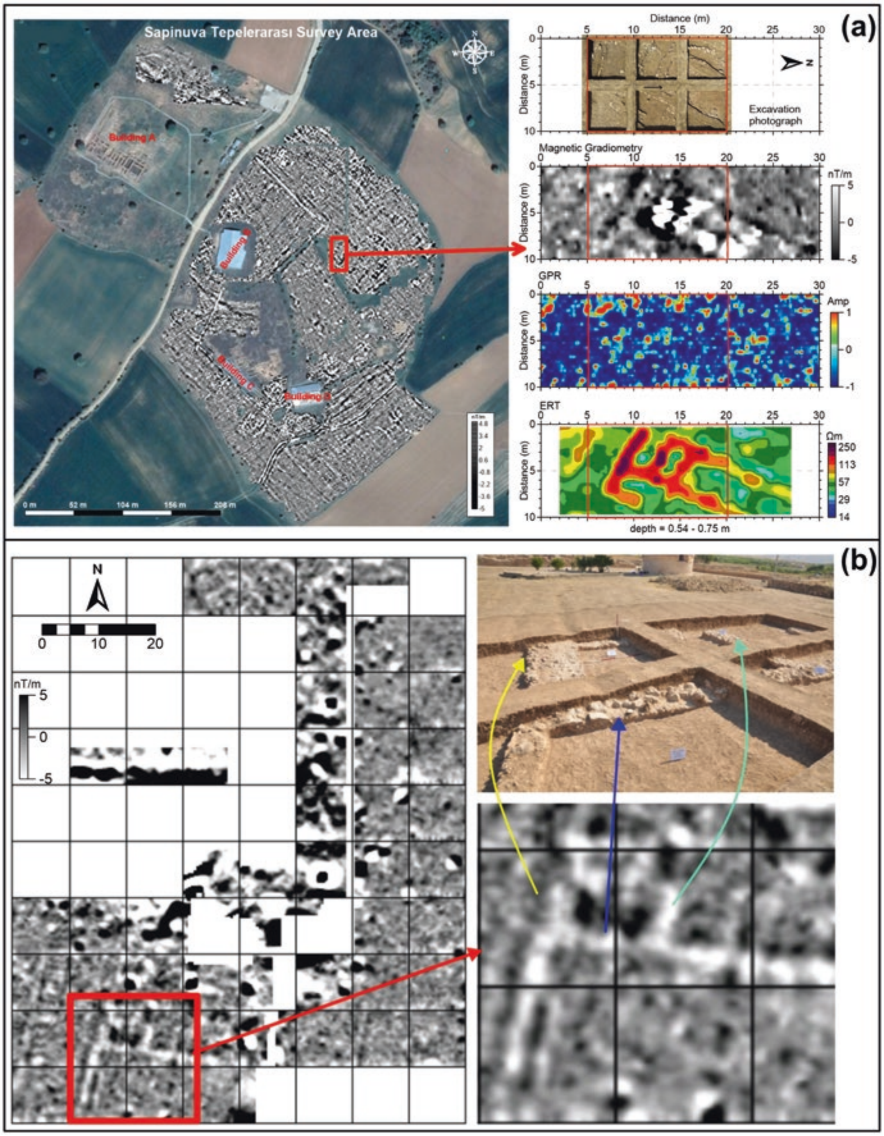

Fig. 3 (**a**) Results of the large-scale magnetometer survey, drone photograph of excavation, magnetometer image, GPR and ERT depth slices obtained from Šapinuwa archaeological site in Çorum. (Modified from Geoim Ltd., 2018). (**b**) Results of the magnetometer surveys and excavation photograph obtained from Hasankeyf archaeological site in Batman. (Modified from Geoim Ltd., 2013a)

from the H area (shown by red rectangle in Fig. 3a). In the results of the magnetometer survey, the walls of the structures made of limestone are seen with distinct negative traces. On their interior, positive magnetic traces appear with a zigzag pattern. In the ERT depth slice (0.54–0.75 m), the wall made of limestone materials was revealed. However, a successful result could not be obtained in the corresponding GPR depth slices. During the excavation in this area, the structure given in the drone photograph (upper right corner of Fig. 3a) was unearthed at the first 70 cm depth. The structure here is very compatible with the model resulted from the ERT depth slice. It has also been observed that there is a significant agreement with the results of the magnetometer survey. An important earthquake trace was revealed during the excavations as they indicated that the burnt mudbricks of the limestone walls fell towards a distinct direction (from N to S). Additionally, since the environment was very mixed due to the earthquake, the stones and the unburned mudbricks of the wall were found in a very mixed condition. For this reason, positive magnetic traces appeared with a zigzag character. Due to the earthquake, a rise towards the surface was observed in the middle part of the area, while the presence of a collapse was observed at the other two edges. This case is clearly evident in the amplitudes of images obtained from the magnetometer and ERT surveys. This result is a unique example that demonstrates the success of the results of applied geophysical methods in determining the context affected by earthquakes in archaeological sites.

5.2.2 Hasankeyf Archaeological Site

Hasankeyf and its surroundings, which have been an important settlement since the Neolithic period, were a trade and cultural centre in Mesopotamia. Within the scope of the Ilısu dam excavations, a geophysical study was conducted near the Zeynel Bey tomb related to the Akkoyunlu period (fourteenth century AD). The study area in the Tigris valley is located on a Quaternary alluvium found within the Şelmo formation from the Pliocene period on both sides of the river. This unit consists of gravel, sand, silt, and clay materials depending on the seasonal materials of the Tigris. The study area is located on the Southeast Anatolian Thrust Belt and in a region with high seismicity (Fig. 1c). During the geophysical investigation, magnetometer and GPR surveys were carried out (Geoim Ltd., 2013a). An image obtained from the magnetometer survey is given in Fig. 3b. Due to the previous restoration work conducted in the Zeynel Bey tomb and its surroundings, mixed magnetic traces have emerged in the image. However, traces of a structure with negative magnetic values are evident in the southern part of the area. This part, enclosed in the red frame of the image, can be seen in more detail on the right of the overall image. The excavation revealed the existence of a structure compatible with the results of the magnetometer survey. The materials found inside the building, which is made of limestone and buried very close to the surface, revealed that the building may belong to the Akkoyunlu period and may be related to a tomb. The structure was easily defined with sufficient magnetic contrast between the structure and the soil.

5.3 Grave Site

The study area, Ahlat Seljuk Cemetery, is located in the northwest of Lake Van in the Eastern Anatolia Region of Turkey, close to the active Süphan volcano, and it is covered with various lava and pyroclastic materials. Generally, andesite, rhyolite, basalt, cemented tuff, pumice stone and volcanic ash are observed in and around Ahlat. Additionally, the active Süphan fault is located close to the study area in the western part of Lake Van (Fig. 1c). The fact that the tomb stelae found in the study area generally collapsed in the E-W direction must be related to a great earthquake in the past. Ahlat, which was embraced by the Seljuks in 1070, became the capital of the principality established there. The cemeteries of this principality, which was one of the strongest among the first Seljuk principalities established in Eastern Anatolia, are also a unique characteristic. The study area, the Old Ahlat Cemetery, had an important place in the medieval Islamic world. There are 8169 tombstones of various types belonging to the Ahlatshahs, Ayyubids, Ilkhanids and Ottoman Periods between the twelfth and sixteenth centuries in the area. There are three types of burial structures in the cemetery. The first of these are the mausoleums, which are reminiscent of the Central Asian kurgans and are called "akıt" among the people. These tombs are called cellars in written sources. These underground structures are rectangular cellars made of cutting stones with volumes of 3.5–4 m^3 or more (Fig. 4a, photographs from previous excavation). The top of these structures is made in the form of domes. Some of these structures, which look like a pile of earth from the exterior, have collapsed or have been dug to find treasure and their interiors have been explored. The second group is sarcophagus graves with triangular forms. The sarcophaguses are 250–300 cm long and 40–50 cm wide. The third type, located uppermost sarcophagus-shaped ones with a stele on the head, is the ones seen on the surface in the area. There are various motifs on the steles, and they are made of volcanic rock (ignimbrite) unique to Ahlat. These stelae of graves are 240–300 × 60–90 × 18–20 cm dimensions. A GPR study was conducted in order to reveal the shape, location, depth and dimensions of the unknown buried tombs in the area (Geoim Ltd., 2013b). The 40–60 cm depth slice, which shows several graves in the southern part of the cemetery, is given in Fig. 4b. Two different types of tombs can be distinguished in this figure. The first one is of the "akıt" type chamber tomb, and the shape and extension of this tomb are evident in the part indicated by the red ellipse. The tomb, which is approximately 10 × 10 m in size, has a general N-S and E-W directional extension. The volumetric view of this tomb is given in Fig. 4c. In the inner part of this tomb, which continues to a depth of about 80 cm, signal losses that can represent some entrances are seen, while the high amplitude reflection traces caused by some diagonal irregularities originating from the collapsed walls are also observed. To the southeast of this tomb, one side of another "akıt" type tomb is visible. Additionally, it is thought that there is another "akıt" type tomb in the part surrounded by the orange ellipse, but it may have been destroyed due to the weakness of the traces. The area surrounded by the blue ellipse is very complex. To the south of this, a part of another "akıt" type tomb extending

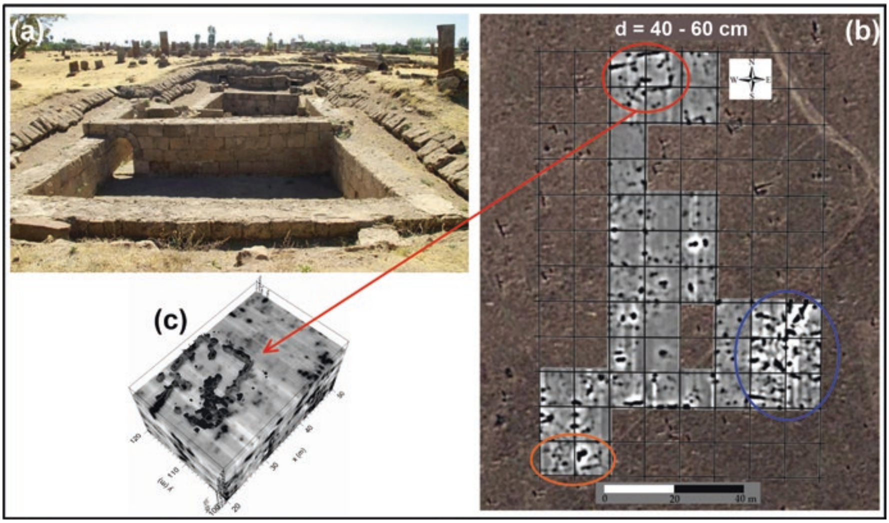

Fig. 4 (**a**) A photograph taken from previous excavations, (**b**) GPR depth slice and (**c**) volumetric GPR image obtained from Ahlat archaeological site in Bitlis. (Modified from Geoim Ltd., 2013b)

in a slightly different direction is visible. In its northern part, the density of traces with negative amplitudes suggests that there are sarcophagus type graves buried in groups and that some of them may have been destroyed. However, since the traces are smooth, it can be thought that there may be another large "akıt" type tomb below them. Apart from these, those scattered throughout the area and extending in a certain direction should show sarcophagus graves, and those scattered in different directions should show the destroyed and buried stelae. The intense negative traces seen around positive traces were interpreted as a sign of destruction due to the excavation of the soil. The GPR study revealed that the "akıt" type tombs extend to a depth of 1 m from the surface, and that sarcophagi are buried close to the surface and their overturned stelae. Since the electrical contrasts were good between the structural elements made by volcanic materials used in the graves and soil, many burials were exposed. Additionally, the reason why the sarcophaguses are seen in different directions may also be from the presence of stelae that were destroyed by a possible earthquake and collapsed in different positions.

5.4 Preservation of Cultural Heritage and Restoration Studies

Integrated geophysical studies conducted in Agios Voukolos Church, an Orthodox religious building from the nineteenth century, located in the Basmane region of the city of İzmir (Figs. 1c and 5a), are representative of their innovations and integrated applications in interior spaces. The investigation had two purposes. The first was to reveal structural damage, such as cracks that could be found beneath the floor of the church, and possible crypt-type embedded features. The second goal was to determine the subsurface features in the backyard of the church, whether there was another structure beneath it. Magnetometer, GPR and ERT were used in the investigations. It is the first time that a magnetometer survey was applied indoors (Drahor, 2011b; Drahor et al., 2011). Figure 5b shows a grayscale image of the result of the magnetometer survey taken inside the church. Significant positive magnetic values are seen in the narthex and katholikon in the results of the magnetometer survey. The twin-positive magnetic traces that emerged in the middle of the katholikon are very similar in terms of size, shape, and amplitude. Among these, a negative trace emerges. The other trace, which has a rectangular shape, is seen to the south of the twin-positive traces. These traces extend in N-S direction and cover an area of 2 × 6 m. The forms and locations of the traces suggest that several crypts may have been hidden. This study shows that positive traces may be due to the presence of crypts, tombs, and other possible burials with high magnetic values. Negative traces may result from empty cavities. In the results obtained from a bidirectional GPR study from inside the church, high radar reflection traces were observed on the magnetic anomaly zones, especially in the locations of the twin anomalies. These traces generally reach a depth of 100–150 cm. The shapes of these traces reveal that possible buried structures are located under the floor of the church. Other high-amplitude signals occur mostly at the edges of the katholikon, and they correspond to both positive and negative regions in the results of the magnetometer survey. The volumetric image of the GPR results in Fig. 5c indicates a significant abnormal region at the location of the twin anomaly. This region corresponds to the centre and

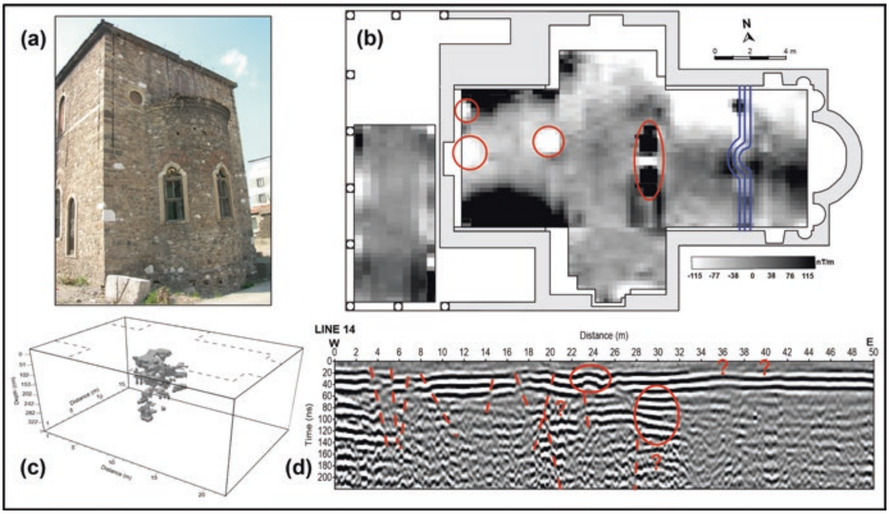

Fig. 5 (**a**) Photograph, (**b**) results of the magnetometer survey, (**c**) volumetric GPR image and **(d)** reflection profile obtained from Agios Voukolos church in İzmir. (Modified from Drahor et al., 2011)

south of the magnetic twin traces. The volumetric image shows that the deeper parts of this structure can be more clearly defined. During GPR studies in the backyard of the church, two different antennas of 100 and 500 MHz were used. Two distinct horizontal reflectors emerged in the study, which was conducted using a 100 MHz antenna to reveal the subsurface features in the deep part of the ground where the church is located (Fig. 5d). The first reflector is a high amplitude near-horizontal layer and appears between 20 and 60 ns. The dashed lines drawn on this layer, where there are some divided and wavy zones in the reflection profile, reveal that this zone may have undergone deformation. Such a record should indicate separation and subsidence in the ground due to earthquakes or other structural features. The subsurface becomes much more complex after 60 ns. Obviously, the second reflective surface, which emerged between 60 and 140 ns in the middle of the measuring line, revealed that a structure from an older building phase could be found. Similar results were obtained from ERT studies (Drahor et al., 2011). The above clearly revealed the contribution of integrated geophysical studies to cultural heritage conservation and restoration studies. Additionally, the magnetometer survey, which was used for the first time in indoor studies, showed that the method could produce useful results if there are no significant magnetic trends from the interior of monuments.

6 Conclusions and Discussions

This chapter presents a general review of archaeo-geophysical studies in Turkey. The effect of soil variability and climatic changes, tectonic effects and other similar geological changes crucially influence the success of geophysical studies in landscapes with characteristics similar to those of Anatolia. The above examples and case studies clearly demonstrate the need for detailed scientific research on these issues.

In the last decade, geophysical applications in the research of archaeological sites in Turkey have increased remarkably. This increase provides significant improvements in both the theoretical and field applications and has also an impact on the surrounding countries. The increase in the interest of the private sector in archaeological and cultural heritage investigations will also contribute to the improvement of the application methodologies and the development of new methods in the future. As Turkey is becoming one of the rising and industrialised countries of Europe and the Near East, this pace of development also poses a threat to Turkey's archaeological and cultural heritage. Against this threat, the development of research focused on geophysics and other remote sensing applications will have a significant positive impact on Cultural Heritage Management. It is expected that further technological and methodological developments will emerge in archaeo-geophysical investigations, hopefully coupled with some legal regulations for their more systematic application in the management of archaeological sites in Turkey.

Additionally, the increase in the interest of universities, private and public sectors on the topic will lead to sectoral growth and a further scientific development.

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Part XVIII
Ukraine

Geophysical Survey in Support of Archaeological Rescue Excavations at Industrial Area of Kremenchuk Magnetic Anomaly in Ukraine

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Abstract This study represents results of first archaeo-geophysical prospection at the area of Kremenchuk Magnetic Anomaly (Poltava region, Ukraine). Pre-excavation magnetometer survey, electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) measurements were performed on archaeological sites which are planned to be destroyed in near future due to development of iron ore quarries and construction of mine sites. Investigated archaeological monuments comprise settlements and burial mounds—kurgans—dated to Bronze and Early Iron Age occupying relatively high terrains in the floodplain of the Dnieper River. Based on prospection results of 18 sites and excavation of 6 ones, we evaluate the advantages and limitations of geophysical methods in confirming conclusions of visual archaeological inspection and targeting subsequent archaeological work. The recognised restrictions for geophysical methods are caused by high-gradient geomagnetic field, airborne magnetic pollution of soils and variable subsoil substrate—loess and sands. The magnetometer survey revealed an anomaly related to the remains of a large mound (the Bondari kurgan) against a background of high-gradient geomagnetic field. Large depression near the kurgan suggested its dating to the Bronze Age proved by subsequent archaeological excavations. The magnetic topsoil masks weak anomalies related to subsurface archaeological features and

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produces bright plough effects visible on the results of the magnetometer surveys. This is why, no anomalies sourced by mound of kurgan were recognised using this geophysical technique at the east from Gorishn'oplavnivskyi quarry. However, circular ditches and collapsed catacomb burials proved to cause detectable disturbance in the magnetic field. GPR measurements aided to identify the real diameter of kurgans by tracing the reflection associated with the mound-submound interface at sandy soil area. ERT results helped to clarify the structure of the large Novoselivska Mohyla kurgan. Two stages of construction were suggested from the two interpreted mounds of different resistivity. Smaller high resistivity anomalies are associated to primary and inserted burials. Magnetic anomalies caused by dwellings were found on the Bronze Age settlements as well as magnetic trace of shallow feature that was not identified during the archaeological excavations. The obtained results aid a proper understanding of the appearance of archaeo-geophysical anomalies and facilitate applying geophysical methods for archaeological needs in the region.

1 Introduction

Quarrying operations substantially change the landscape as well as adversely alter pre-existing ecosystems. Large territories are destroyed together with archaeological sites which need to be investigated as fully as possible before they disappear forever.

Geophysical methods in recent years have proved to be of great importance in acquiring data for effective archaeological heritage management and, hence, must be applied to determine best targets for excavations (Schmidt et al., 2015; Sarris, 2017).

Geophysical exploration of archaeological sites in mining provinces faces a number of specific challenges. The geology of the region can be a natural obstacle to the application of some geophysical methods (Fassbinder & Bondar, 2013; Bonsall, 2014; Rusch et al., 2020; Bondar et al., 2021a). In addition, the industrial activity noise interferes with the geophysical fields, negatively affecting measurements (Krivanek, 2001; Booth et al., 2010; Bondar et al., 2019; Polin et al., 2020; Schmidt et al., 2020). The weak contrast of physical properties of the soil and the archaeological object against the background of a high-gradient or noisy field makes archaeological objects “invisible” (Krivanek, 2001; Jrad et al., 2014).

The study deals with first archaeological prospection results in the Kremenchuk magnetic anomaly area, where large iron-ore quarries together with a sinter plant had been used since the 1970s. Since the rapid industrialisation of the region, quarrying has become an important threat to the unique archaeological heritage of the region. Alienation of new lands for quarrying of neighbouring fields, storage of dumps and construction of the tailing ponds continues.

In this chapter we evaluate the efficiency of geophysical methods in proving conclusions of visual archaeological inspection and targeting subsequent archaeological excavations to ensure the recording and mitigate the total loss of the idiosyncratic archaeological sites of the area. The article discusses the ability of geophysics to detect subsurface archaeological features against rather non-ideal survey conditions such as unfavorable magnetic geology, superficial deposits, and anthropogenic topsoil pollution. Some successful case studies are presented.

We pay much attention to the geophysical characterisation of burial monuments (kurgans), which provide the main source of information for the study of nomadic archaeological cultures of Ukrainian Steppe. A kurgan is a mound of earth raised over a grave. Large mounds can contain later graves inserted into a primary mound deposit. A few recent papers devoted to geophysical investigations on kurgans from Ukrainian steppe and forest-steppe report the capability of such minimally invasive techniques to detect these monuments even if they are partly or totally truncated by ploughing and there is no trace of them on the surface (Zöllner et al., 2008; Bondar et al., 2019, 2021b; Polin et al., 2020). Showcasing how to distinguish Bronze—Early Iron Age kurgans from natural or modern artificial elevations using geophysics is a particular objective of the chapter.

2 Location of Study Area and Environmental Settings

The region of Kremenchuk Magnetic Anomaly is located on the left bank of the Dnieper River in the forest-steppe zone of the Dnieper lowland, within the Psel and Sukhyi Kobeliachok interfluve (Fig. 1a). This territory is a part of the Ukrainian crystalline shield within the Eastern European platform, thus its landscape is flat and partially crossed by ravines. The average height above sea level is 69 m. The channel of the Dnieper River is heavily indented here, which contributed to the emergence of numerous estuaries and small islands. The climate is moderately continental.

The region comprises both natural and man-made landscapes. The iron ore deposit is located in the floodplain and on the first terrace of the Dnieper. The total area of 140 km^2 in Poltava region includes iron-ore processing industrial zone, the residential zone (the city of Gorishni Plavni and villages), transformed areas of relict landscapes and forestry areas. The soil cover is represented by sandy soils on the first fluvial terrace of the Dnieper, meadow-chernozem and chernozem formed on loess loam—on the higher areas of the lowland. Sandy soils are highly permeable and have thin (<20 cm) humic horizon A. Meadow-chernozems and chernozems have horizon A with thickness over 60 cm.

Kremenchuk Magnetic Anomaly stretches along Kryvyj Rig-Kremenchuk fault of the Ukrainian crystalline shield (Dobrokhotov, 1964; Ben’ko et al., 2000). Mining of iron ferruginous quartzites started at the beginning of 1970s at Gorishn’oplavnivskyi quarry. Now the mining complex includes also Yerystovo and Belanovo quarries, which have started being explored recently. The industry is specialised in the production of iron pellets for metallurgical needs.

Kremenchuk Magnetic Anomaly reaches tens of thousands of nanotesla on the ground surface in spots of maximum signal (Fig. 1b, c). The places of three magnetic maxima have been selected for quarrying. Gorishn’oplavnivsky maximum is

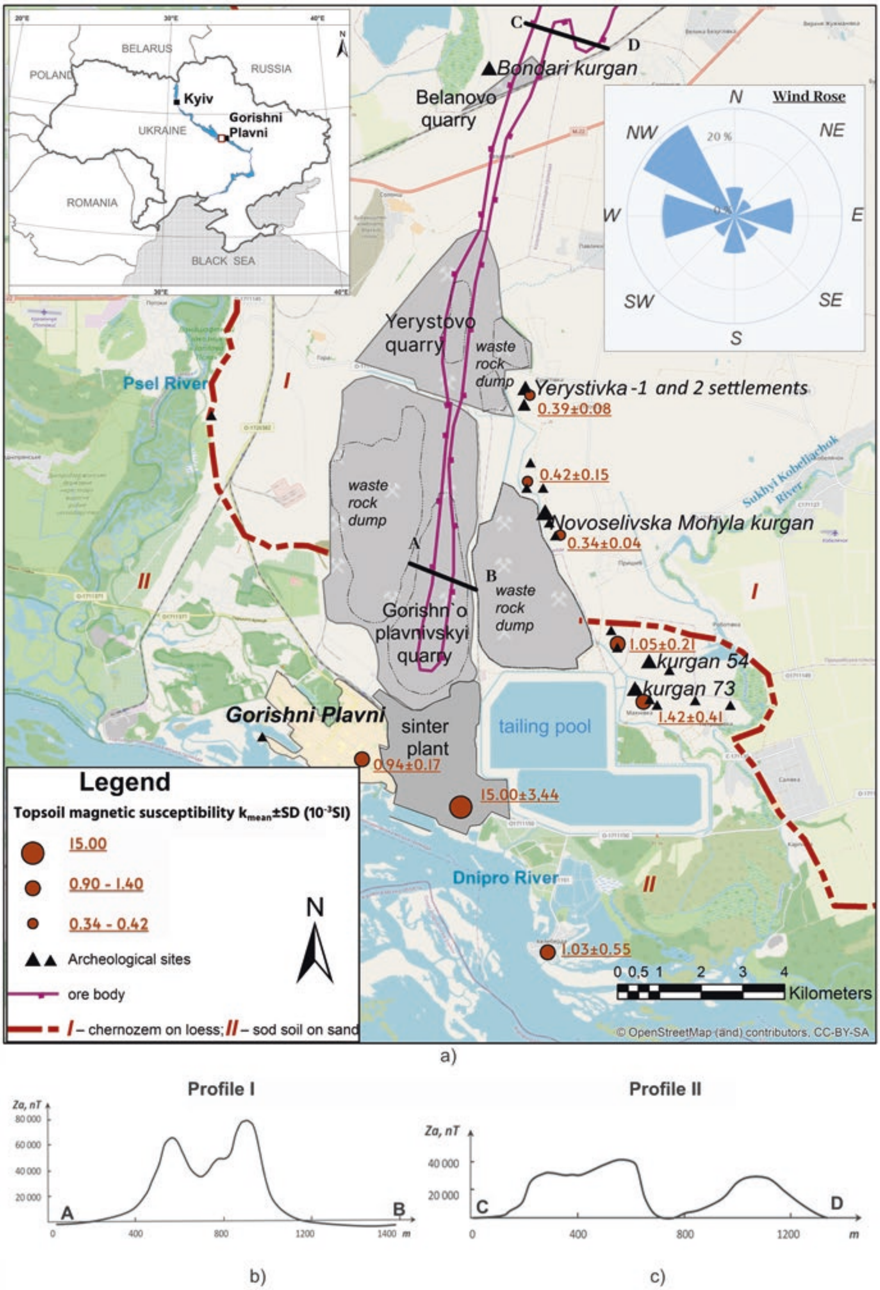

Fig. 1 Regional map of the Kremenchuk Magnetic Anomaly area showing location of the iron-ore body, quarries, main types of soil, magnetic susceptibility values of the topsoil measured at points marked with red dots, archaeological sites discussed in the article are marked with triangles and labeled (**a**). Anomalous intensity of the vertical component of the total magnetic field (Za) along transects AB (**b**) and CD (**c**). (After Krutihovskaya, 1971)

the strongest one and is characterised by a high horizontal gradient of the total field due to shallow position of the ore body (15–20 m to the surface). At the area of Yerystovo maximum the overburden makes 30–40 m, at Belanovo—more than 100 m. The shape of the magnetic anomaly is controlled by two limbs of the syncline fold at Gorishn'oplavnivskyi area (Profile 1) and by the only eastern limb combined with hinge zone preserved at Belanovo area (Krutihovskaya, 1971).

Quarries and the sinter plant located at the city of Gorishni Plavni are powerful air pollution sources at the region. Wind rose showing the distribution of wind direction (Fig. 1a) evidences that most of the time the winds blow from the northwest, transporting industrial emissions and dust from the dumps and dry beaches of the tailing ponds to the area east from the mining. After being settled on the topsoil, the dust particles change soil properties, in particular, magnetic properties (Evans & Heller, 2003; Fialová et al., 2006). This can significantly influence the results of magnetometer surveys.

3 Archaeology of the Region

The vast majority of archaeological sites in the region are dated to Bronze-Early Iron Age. The Bronze Age (mid-fourth to early first millennium BC) is characterised by the presence of cattle-breeding tribes of the Yamnaya, the Catacomb and the Timber-Grave archaeological cultures. They arranged their burials under kurgans, which became an integral part of the local landscape (Suprunenko et al., 2004; Shylov, 2007; Suprunenko & Sherstiuk, 2009). The final of the Bronze Age – the beginning of the Early Iron Age is represented by settlements of the early stage of the agricultural Belohrudovo-Chornolis culture (Bashkatov et al., 2020). In the Early Iron Age, the interfluve of Psel and Sukhyi Kobeliachok was inhabited by the Scythians (seven to four centuries BC) and Sarmatians (second century BC to third century AD) (Ben'ko et al., 2000; Kulatova, 2011).

Walkover surveys carried out at the area suggested the presence of ~130 possible kurgan groups and settlements of the Bronze—Early Iron Age (Suprunenko, 2014). Each kurgan group can contain from one to twenty kurgans of different size and degree of preservation. Small elevations of the terrain can be also due to geomorphology or associated with rather modern homesteads from the 18th to 20th centuries. On visual inspection, they are easily confused with ploughed kurgans.

4 Materials and Methods

The field measurements were conducted in 2016–2020 at 18 archaeological sites selected from the results of the walkover surveys (Suprunenko, 2014). Six sites were completely excavated by the Dnipro-Psel expedition of the Institute of Archeology of the NAS of Ukraine under the direction of Yu. Bashkatov. A flexible set of geophysical methods was used comprising high-resolution magnetometer survey (14.5 ha covered at 18 sites), electrical resistivity tomography (240 m of profiles recorded at one site) and ground penetrating radar (2650 m of profiles at 14 sites). Geophysical survey areas and individual profiles areas were georeferenced on orthoimages or topographic maps by measuring their coordinates using a GPS.

4.1 Magnetometer Survey

Magnetometer surveys can be a rapid tool for mapping subsurface archaeological structural remains. Their use at kurgan sites can provide information about inner structure and its separate elements like dromos, chambers as well as different objects on the kurgan's periphery (Smekalova et al., 2005; Parzinger et al., 2016, 2015; Fassbinder et al., 2015; Fassbinder, 2015, 2016; Bondar et al., 2019; Polin et al., 2020; Goldmann et al., 2021). This technique was used at all sites, as a means of quick investigation, although it was not always efficient. The instrument used was a caesium total field magnetometers PKM-1 (Geologorazvedka, Russia), which had a sensitivity of +/−0.01 nT. The instrument records 10 measurements per second, providing a spatial resolution of about 10 cm on the profile by normal walking speed. With traverse spacing of 0.5 m, the total intensity of the geomagnetic field was acquired with a spatial resolution of 50x10 cm.

4.2 Magnetic Susceptibility Measurements

At the vicinity of iron-ore mining and processing area, magnetic enhancement of topsoils could be due to atmospherically deposited magnetic particles of industrial origin (Fialová et al., 2006) and this can affect the results of magnetometer survey.

Weak anomalies from low contrast archaeological features could be hardly detectable against the plough effect of strongly magnetic topsoil. In order to outline such polluted areas, in-situ magnetic susceptibility (k) topsoil measurements were taken using handheld KM-7 Satis Geo kappameter at eight locations. Between 15 and 20 readings were taken from each measured point—a spot of about 4 m^2 cleaned from surface vegetation.

4.3 Electrical Resistivity Tomography

ERT can help to characterise the construction features of mounds and their relative stratigraphy (Papadopoulos et al., 2010; Tsourlos et al., 2014; Zhao et al., 2019; Hegyi et al., 2021). Apparent resistivity measurements were acquired using a one-channel device furnished with 64 brass electrodes (Khomenko et al., 2013). All profiles were made using the Wenner-Schlumberger array protocol, the electrodes were placed at every 1 m. Such distribution allowed recognition of electrical resistivity readings to a depth of about 11 m. The Wenner-Schlumberger array was chosen because it is moderately sensitive to both horizontal and vertical structures (Loke, 2009). Measured electrical data were inverted using the interpretation software Res2DINV, employing the robust least-squares optimisation technique (L1-norm) (De Groot-Hedlin & Constable, 1990; Sasaki, 1992; Loke & Barker, 1996). L1-norm tends to produce models that are piecewise constant, which is consistent with the known structure of excavated kurgans. Bad datum points and points with root mean square (RMS) error higher than 90% were removed from the final inversion. The model was accepted after four iterations with a RMS misfit lower than 5%.

4.4 Ground Penetrating Radar

GPR has been used to characterise kurgans and other archaeological mounds. A challenge to survey such sites using this technique can be related to the topographic corrections that are required to a correct interpretation of GPR data collected at relatively well-preserved mounds (Goodman et al., 2007). Other challenges can be derived from other general aspects related to the limitations of the propagation of the electromagnetic energy used in this technique, under specific soil conditions. For example, some clay-rich and highly conductive soil deposits can attenuate the propagation and reflection capacity of the GPR energy and result in a poor depth of penetration or complete failure in the detection of subsurface remains (Schneidhofer et al., 2017; Conyers, 2017; Bondar et al., 2021a). The reason to use GPR to characterise kurgans in the region was the prevalence of highly permeable sandy soils. As GPR is a highly productive technique, so it bridges the gap between magnetometer survey and ERT in cases when the first one is inefficient and the second is extremely time-consuming. The GPR system used was a VIY-3 instrument produced by Transient technologies LLC, Ukraine, equipped with shielded transmitting antennas with nominal centre frequencies of 300 MHz. Data was processed using the Synchro3 software (http://viy.ua/e/software/synchro.htm). The processing steps included zero level setting, dewow operation and wavelet filtering, windowed background removal, time gain and estimation of the average electromagnetic wave velocity by hyperbola fitting. Since the GPR profiled were collected at substantially truncated sites or flat areas around them, there was not need of topographic correction. Obtained processed reflection profiles and annotated reflections of interest were subsequently visualised to correlate them with the results of the other geophysical surveys.

5 Geophysical Results and Archaeological Evidence

Not all the expected sites or known kurgans were confirmed by the geophysical results. Often, only one or two kurgans, of an expected group of five to twenty were defined according to presence of specific geophysical anomalies. In many cases, magnetometer surveys were useful to discriminate between supposed prehistoric kurgans and elevations on the places of homesteads of 18th to 20th centuries. The latter were determined by strong magnetic anomalies from brick buildings and a lot of iron rubbish around and thus excluded from further studies. Below, we describe some case studies showcasing successful results from sites that has been validated via targeted archaeological excavations.

5.1 Detection of Kurgans Integrating Magnetometer Surveys and Complementary Techniques

The large kurgan Bondari is located in an area that soon will be destroyed according to the Belanovo quarry development plan. The maximum height of the kurgan is 4.2 m, and the diameter is about 70 m. There is a big pit at the centre of the mound, which is 3 m deep and has dimensions of 27 × 20 m. For a long time, it was considered to be a "maidan"—a saltpetre fabrication site like those that were common throughout the 17th to 19th centuries in the Poltava region (Sherstiuk, 2013). Saltpetre (or potassium nitrate for the fabrication of gunpowder) was extracted using the soil from ancient mounds. Remains of furnaces, ash dumps and other related infrastructure are usual traces of this activity in the vicinity of remnants of the destroyed kurgans (Zöllner et al., 2008; Bondar et al., 2021b).

An orthoimage of kurgan Bondari was obtained using drone-acquired photographs. A digital terrain model was derived from the orthoimage to record the mound and a large depression visible to the south-east of it (Fig. 2a). The depression is ~40 m wide and 1 m deep. It is well-known that Bronze Age kurgans were formed gradually, due to repeated earthing-up for new burials. The soil for the new mound used to be taken near the primary kurgan, resulting in the formation of a large depression, sometimes ~20–30 m wide (Mozolevs'kyi, 1990; Chernych & Daragan, 2014). As noted by B. Mozolevsky: "kurgans of the Bronze Age always stand, as in a saucer, in a deep and wide depression, the surface around the Scythian kurgan is always flat as a table". Therefore, kurgan Bondari has been dated to the Bronze Age.

The magnetometer survey of the kurgan was performed in a high-gradient field, as the site is in the near vicinity of the Belanovo iron ore deposit (Fig. 1a, b) (Dobrokhotov, 1964; Krutihovskaya, 1971). The total geomagnetic field intensity changes by over 200 nT in the NE-SW direction. However, even against such background, the magnetic anomalies associated with remnants of the mound were visible (Fig. 1b, c). Processing procedure of subtracting profile linear regression values from the measured total field values allows the exclusion of the effect from

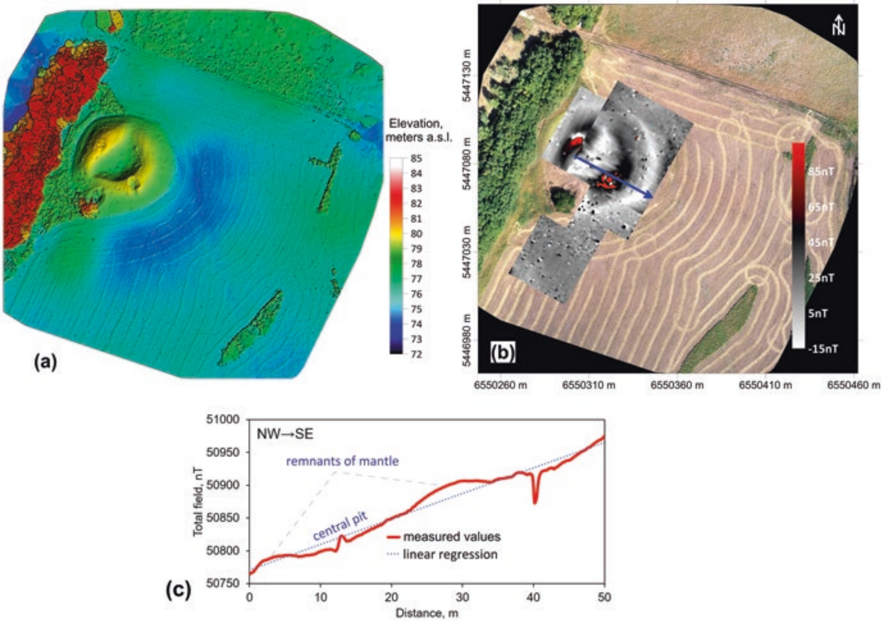

Fig. 2 Bondari kurgan (Bronze Age): (**a**) Digital terrain model; (**b**) Results of the magnetometer survey in greyscale overlying an orthoimage of the site area; (**c**) Total field profile, marked with blue line on the figure (**b**)

geological structures. The remnants of the mound caused an anomaly of up to 20 nT. Extremely high values (red) correspond to relics of the geodetic pillar and a fire point of the World War II time. No traces of saltpeter production activity were recognised in the magnetometer survey results.

Excavations proved the conclusions achieved from non-invasive study. The central pit appeared to have formed due to excavation of the central burial performed at the beginning of the twentieth century. Eleven burials of the Yamnaya and the Catacomb cultures of the Bronze Age were inserted into the mound. The individual burials did not cause magnetic anomalies.

5.2 Identification of Kurgans at Magnetically Polluted Areas

The results of the magnetometer surveys carried out at the east of the Gorishn'oplavnivskyi quarry did not detect anomalies potentially associated to kurgans' mounds. We tend to associate the reason for this with magnetic pollution of the topsoil. The in-situ magnetic susceptibility measurements revealed areas of magnetic enhancement of soil presumably due to the presence of strongly magnetic minerals of anthropogenic origin. Means and standard deviations (SD) of k value are represented on Fig. 1a. In particular, high values are observed to the east from the tailing pool.

The magnetic susceptibility of the topsoil was very high (0.8–1.4 * 10^{-3} SI) near the kurgan 73 (Fig. 1a) that was excavated at the east of the Gorishn'oplavnivskyi quarry. Targeted trench P excavated near the kurgan exposed two deposits: 0–30 cm—light pale sandy plough horizon; 30–60 cm—brown sandy subsoil (Fig. 3a, b). There was a sharp division between layers at a depth of 30 cm due to ploughing. Below, soil susceptibility decreased to 0.1 * 10^{-3} SI. Magnetic particles product of quarrying activities and spread in uppermost soil horizon by ploughing seems to be the cause of the enhancement of the uppermost deposit. Microscopic examination of thin sections extracted from the topsoil revealed fragments of ferruginous quartzite dust (a typical by-product from waste rock dumps) as well as magnetite-hematite-glassy spherules (derived from airborne ash emitted by sinter plant) (Fig. 3c, d). Although magnetometer surveys were carried out at this area, the highly magnetic topsoil masked potential anomalies derived from expected buried archaeological features. The ploughing activities carried out at these areas were also visible in the magnetometer results producing a clear stripping effect (Fig. 3a).

Kurgan 73 was 4 m high and had a slightly elongated shape because its mound was partially ploughed. Since magnetometer survey could not establish the extent of this site, several areas were explored with GPR profiles. The reflection associated with the mound and its interface with the natural underlying deposits or ancient ground surface were observed at the time of 37–40 ns (depth 1.5 m). The reflections could be attributed to different soil water saturation controlled by different porosity of the undisturbed sandy soil and mixed earth of the mound deposits. Thus, GPR measurements aided to identify the real diameter of the kurgan, which appeared to be 38 m. In the mound, a stone-carved tomb was unearthed as well as 10 more inserted inhumations dated to the Middle Bronze Age. Similar interfaces between the mound deposits-former ground surfaces were observable in the results of other GPR reflection profiles at other neighbouring kurgans.

All the more inspiring were magnetometer survey results obtained on kurgan 54 (Fig. 4), where magnetic susceptibility of the topsoil exceeds 1.0 * 10^{-3} SI. This is an example of kurgan identified from results of magnetometer survey exclusively. The survey plot occupied the top of a gently elevated area. The circular ditch was interpreted in the place of the +1.6 nT anomaly. Excavation proved a ditch with diameter of 21 m and a depth of 0.4–0.6 m which was partly destroyed by agricultural activity (Fig. 4a, b). Kurgan with a ditch is quite unusual in this region. Three inhumations of Yamnaya culture were excavated within the enclosing circular ditch, no one burial caused magnetic anomaly. Excavations revealed additional mound being constructed for new burials. The total diameter of the kurgan's mound reaches 40 m. Although the magnetic map is noisy, four anomalies with intensities 1.5–3.2 nT correspond to four excavated burials of Catacomb culture located outside the circular ditch. These burials are chronologically later than ones enclosed with the

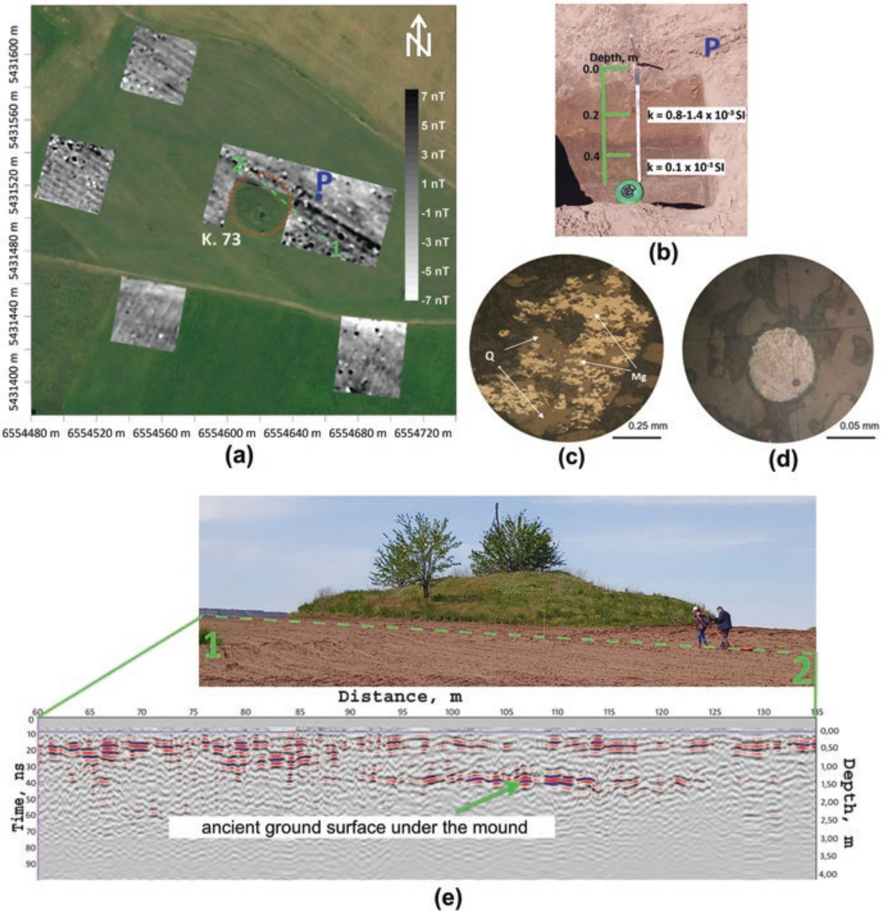

Fig. 3 Kurgan 73: (**a**) Satellite image with georeferenced magnetometer surveys results in greyscale and dynamics of the total magnetic field 50,510 ± 7.0 nT. The kurgan's mound revealed by excavation is outlined with red dotted line. The location of the soil profile is marked with P (blue dot). The GPR profile 1-2 is shown as a green line; (**b**) sandy soil profile P with magnetic susceptibility values; (c and d) thin section photographs extracted from the topsoil at P, in reflected light. Fragments of ferruginous quartzite (Q) and magnetite (Mg) are shown in (**c**). Magnetite-hematite-glassy spherule is shown in (**d**); (**e**) GPR profile 1-2 crossing a ploughed area of the kurgan's mound

ditch. They were arranged in underground chambers (catacombs), that were collapsed and filled with dark coloured soil. Figure 4c shows an example of a catacomb.

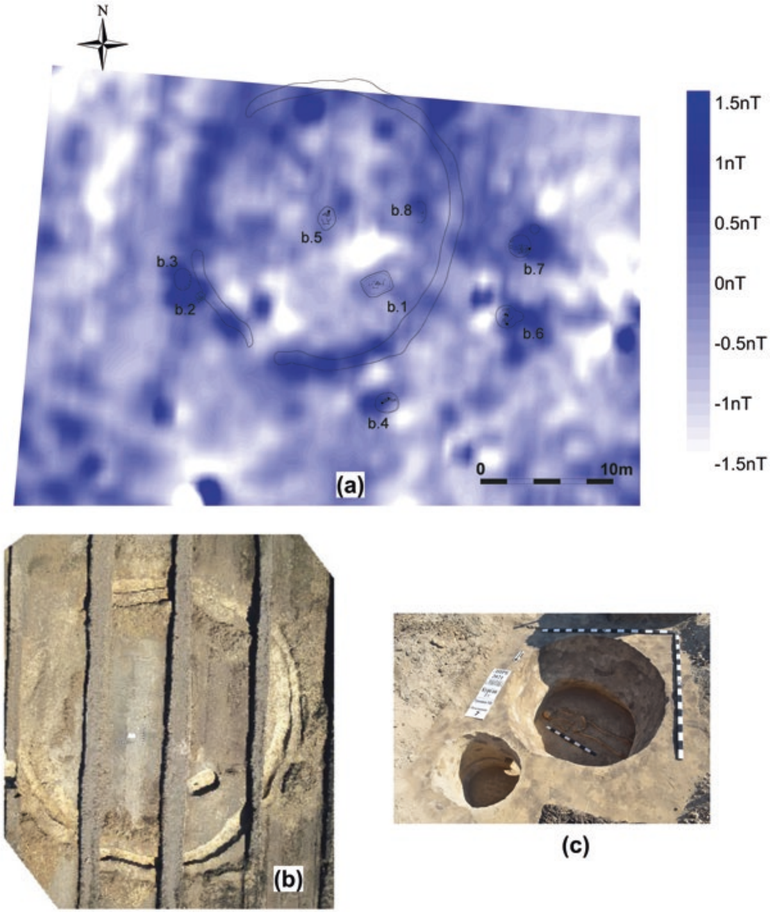

Fig. 4 Kurgan 54: (**a**) Results of the archaeological excavation overlying the results of the magnetometer survey in white-blue scale with dynamics of the total magnetic field 50,485 ± 1.5 nT; (**b**) Aerial photograph of the excavated circular ditch enclosing the Yamnaya culture kurgan mound; (**c**) Photograph of the Catacomb culture burial 7

5.3 Investigation of the Internal Structure of a Large Kurgan Using ERT

The Novoselivska Mohyla kurgan (Fig. 1a) dated to fourth to first millennium BC (Suprunenko, 2014) has a maximum height of 7.5 m and occupies a large area of 64 × 68 m. On the top of this kurgan, there was nineteenth to twentieth century cemetery which is a common aspect at these sites in the region. Since the kurgan was going to be excavated because of the development of a new waste dumping area, all graves were exhumed before the geophysical survey. Given all the open pits left after the exhumation, four ERT profiles were strategically located to investigate the internal structure of kurgan (Fig. 5a).

The results suggested the location of several structural components of the kurgan characterised by resistivity values varying from 1 to 3100 Ωm (Fig. 5b). The ERT model generally shows lower resistivity zone (<60 Ωm) corresponding to primary mound with a diameter of ~25 m. It is overlayed by secondary mound having higher

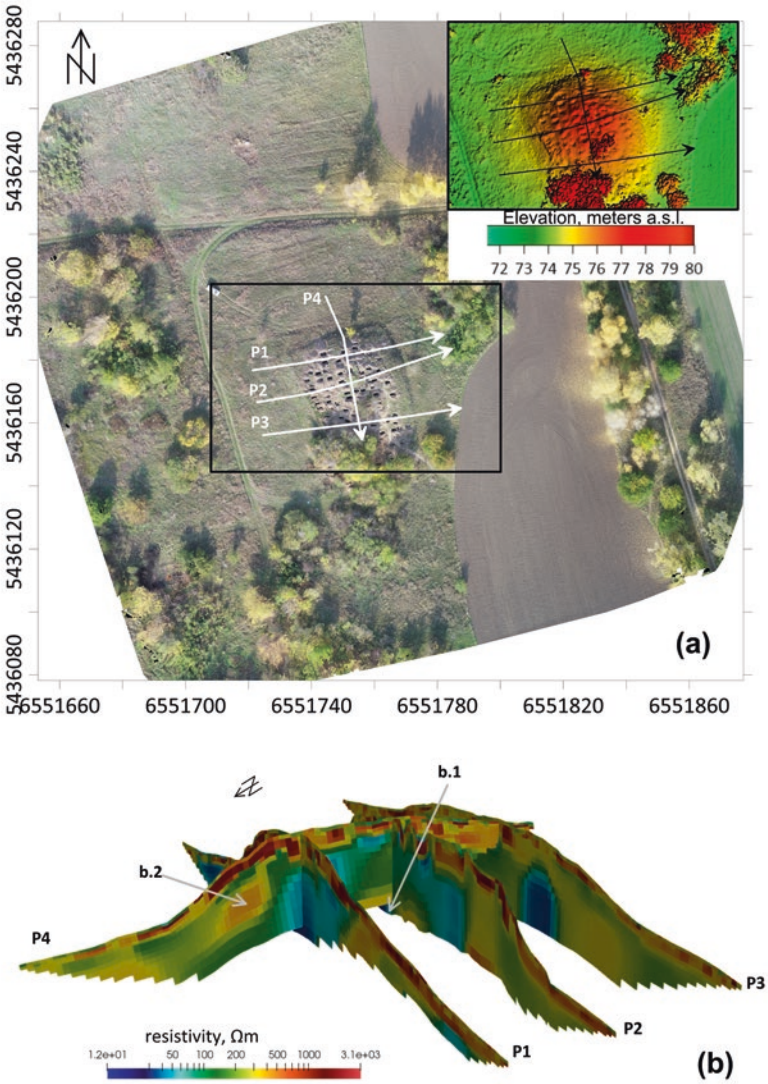

Fig. 5 Novoselivska Mohyla kurgan: (**a**) orthoimage and digital terrain model with the ERT profiles shown with arrows marked P1-P4; (**b**) ERT model of the kurgan with the location of potential burials marked as b.1 and b.2

resistivity values (100–350 Ωm). Overlying this secondary mound, very high resistivity values characterise the uppermost deposits containing the exhumed burials. At the bottom of the kurgan mound deposits, there is a high resistivity zone that may indicate the presence of initial burial (b.1 on Fig. 5b). Another possible burial is interpreted inside the primary mound (b.2 on Fig. 5b).

Although the kurgan has not been completely excavated yet, the ERT results suggested a rather complex stratigraphy of this monument, erected in several stages. This interpretation fits the hypothesis of O. Suprunenko (2014) about this pre-Scythian or Scythian kurgan, when the secondary mound was built over burial(s) inserted into the primary mound of the Eneolithic—Bronze Age.

5.4 Magnetometer Survey Mapping of Bronze Age Settlements

In 2007–2008, during visual observations for new waste dumping areas at the east from Yerystovo quarry, the settlements Yerystivka-1 and Yerystivka-2 were discovered (Suprunenko, 2014). Both settlements stretched along the watershed on a north-south direction and were located and dated by surface finds of the Early Bronze Age (Catacomb culture, 18th to 17th BC) and Late Bronze Age (Timber-Grave culture, 15th to 14th BC). Suprunenko documented on the surface of Yerystivka-1 seven ash heaps ~0.1–0.3 m high, ranging in size from 8 × 10 to 14 × 16 m. They were located in two almost parallel rows. Yerystivka-2 consists of 20 ploughed ash heaps with heights of 0.2–0.5 m and diameters of 10–21 m. Ash heaps are situated on both sides of the field road. Two of them were excavated in 2008 revealing dwellings of Belohrudovo-Chornolis culture.

A magnetometer survey was carried out on the area of 8 ha (Fig. 6a). The results at Yerystivka-1 shows several small (up to 4 m^2) low-intensity (up to +3 nT) anomalies, probably sourced by remains of ancient dwellings and farm structures. However, archaeological research has not been conducted there yet. The results at Yerystivka-2 (Fig. 6b) clearly shows the old field road, which is now ploughed out. A linear anomaly seems to correspond to an accumulation of ferruginous quartzite rubble (blue line in Fig. 6b). Anomaly 1, of oval shape, intensity of 0.7–2.3 nT and significant dimensions (60 × 90 m) was of particular interest. However, the excavation trench that targeted this anomaly did not reveal any archaeological nor natural feature.

Anomalies 2,3,4 had intensities of 3–4 nT and a size of 3–10 m (Fig. 6b). These were also targeted with excavation trenches reaching ~0.8–1.4 m depth (Fig. 6c–e) and revealed three pit-houses.

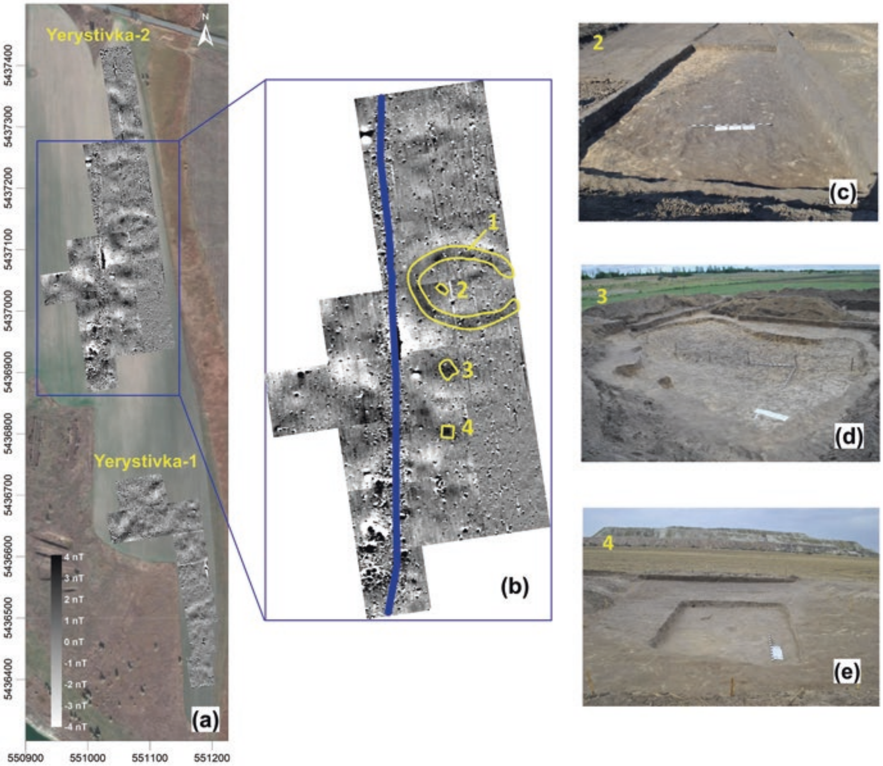

Fig. 6 Settlements Yerystivka-1 and 2: (**a**) Satellite image overlaid by the results of the magnetometer survey in greyscale and dynamics of the total magnetic field 49,760 ± 4.0 nT; (**b**) Results of the magnetometer survey at Yerystivka-2 with anomaly annotations in yellow; (**c**) Excavation results at the location of anomaly 2 (0.4 m depth); (**d**) Excavation results at the location of anomaly 3; (**e**) Excavation results at the location of anomaly 4

6 Discussion

The efficiency of geophysical techniques at each site within the region is strongly controlled by local conditions. As is shown by the example of Bondari kurgan, large mounds cause magnetic anomalies even on the background of strong geological magnetic effect due to the large amount of earth hosting magnetic minerals (Fig. 2b, c). Destruction of the mound due to looting or saltpeter production could normally be traced by the results of a magnetometer survey. Single inhumations inserted into the mound cause no disturbance in the magnetic field unlike burials in catacombs as illustrated in the case of Kurgan 54. When the catacomb collapses and the overburden is not thick enough, holes are formed on the surface of the mound, gradually refilling with soil. That is what probably happened with the detection of the catacomb burial at Kurgan 54 (Fig. 4a). Magnetic anomalies from catacomb burials as well as from kurgan's circular ditch are largely originated due to the detrital magnetic remanence of the infill (Bondar et al., 2022). Modern magnetometers are capable of detecting such archaeological features even under a rather thick layer of magnetically polluted soil. However, anthropogenic magnetic enhancement in the topsoil imposes limitations on the use of magnetometry on smaller kurgans. If a small kurgan hosts no ditch or destroyed burial, it stays invisible for magnetometer survey. However, under favourable conditions other geophysical methods could help, as shown on the example of Kurgan 73. Sandy soil facilitated determination of interface between the mound and former ground surface as well as its extent using GPR (Fig. 3e). Valuable archaeological information about internal structure of large kurgans can be obtained using ERT, as shown on example of Novoselivska Mohyla kurgan (Fig. 5b). Many kurgans with highly resistive structures, such as burials in stone-carved tombs, cromlechs, well-preserved catacombs, are often found in the Kremenchuk Magnetic Anomaly area (Suprunenko et al., 2004; Shylov, 2007).

Magnetic prospection of the settlements Yerystivka-1 and Yerystivka-2 has demonstrated good results in searching for Bronze Age dwellings and pit-houses (Fig. 6a, b). However, the excavation results targeting the large anomaly 1 did not provide any archaeological evidence (Fig. 6b). We can attribute it to a "magnetic ghost" case (i.e. an archaeological feature that is invisible during an excavation but detectable in term of their magnetic properties) (Schleifer, 2004; Leckebusch et al., 2000; Breitwieser et al., 2001; Lysenko, 2009; Simon et al., 2012). In this case, this anomaly could be related to a trace of shallow ditch, which did not reach subsoil and was backfilled with organic material with enhanced magnetic properties. It is known that decomposition of organic matter plays the key role in soil magnetic enhancement, the iron minerals stay whereas the organic matter dissolves (Schleifer, 2004).

7 Conclusions

Amongst 18 supposed archaeological sites investigated with the use of geophysical methods at the industrial area of Kremenchuk Magnetic Anomaly, nine had been confirmed to be related to Bronze—Early Iron Age. Relics of the 18th to 20th centuries were recognised under kurgan-like mounds at five sites. Four sites revealed no geophysical traces of archaeology therefore have not been recommended for excavation.

Based on the results we could determine the following geophysical anomalies related to the presence of kurgans: magnetic anomalies caused by the mound of the kurgan; magnetic anomalies caused by circular ditch or catacomb-type burials; reflections from the interface of the mound and former ground surface observable in GPR reflections profiles radargram at sites located in a sandy soil environment.

In this work, we found that cultural heritage sites in many cases can be located and characterised with the aid of geophysics under challenging anthropogenic and natural survey conditions. However, the limitations of a particular method must be considered. The enrichment of magnetic particles in the topsoil together with heavy ploughing add a lot of noise to the magnetometer survey results restraining discrimination of weak anomalies. The use of GPR is limited to recognition of earthwork at sandy soil. ERT as time- and labour-consuming technique is appropriate at large kurgans to establish the stratigraphy.

The mining of ferruginous quartzites at the Kremenchuk Magnetic Anomaly area will continue. More and more new zones will be used to develop activities related to quarrying activities. The need of archaeological investigation of this areas to ensure the recording and safeguard of this heritage from it destruction through modern development will become increasingly important in future. Therefore, the results obtained from our study will facilitate applying geophysical methods for archaeological needs and aid proper understanding of the appearance of archaeo-geophysical anomalies in the region.

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